Effect of Different Fertilization Levels on Yield and Lycopene Content of Field Tomatoes

Laura Caralampides

Department of Plant Science
Macdonald Campus of McGill University
Sainte-Anne-de-Bellevue, Québec, Canada

July 2012

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Master of Science

©Laura Caralampides, 2012

Abstract

This thesis examined the effect of nitrogen (N), phosphorus (P) and potassium (K) fertilization rates on field fresh-market tomato yield (cv. Florida 47), nutrient levels in leaves, fruits and soil, and fruit lycopene content. Yield and plant nutrient levels were not affected by N fertigation and soil nitrate level suggested leaching. The causes for leaching were site specific. High initial P levels affected plant nutrient content and soil pH influenced availability of nutrients in the soil. Yield showed a quadratic response to increasing P fertilization. High initial K soil levels affected foliar nutrients and there was no response to fertilization. However, for soils low in initial K the maximum yield was obtained with 160kg K_2O ha^{-1}. Lycopene content was maximized at 90 and 20 kg ha^{-1} of N and K, respectively for early harvests. Tomatoes harvested earlier in the season, at a more advanced ripening stage and with a shorter post-harvest period had significantly more lycopene.

Résumé

Cette thèse avait pour but d'identifier l'effet des taux de fertilisation d`azote (N), de phosphore (P) et de potassium (K) sur le rendement de tomate en champs (cv. Florida 47), la concentration en minéraux dans les feuilles, fruits et sol, ainsi que la teneur en lycopène des fruits. Le rendement et la teneur en éléments nutritifs des plantes n'ont pas été affectés par la fertigation d'azote. Aussi, le niveau de nitrates du sol suggère qu'il y a eu du lessivage. Les causes de lessivage étaient spécifiques au site. Les niveaux initiaux élevés de P ont affecté le contenu en éléments nutritifs des plants; aussi, le pH du sol a influencé la disponibilité des nutriments dans le sol. Le rendement a répondu de manière quadratique à l'augmentation des taux de fertilisation en P. Lorsque la teneur initiale en K était élevé, les concentrations foliaires étaient affectées, par contre il n'y avait pas de réponse à la fertilisation. Cependant, pour les sols à faible teneur en K le rendement maximal était obtenu avec l'application de 160kg K_2O ha^{-1}. La teneur en lycopène était maximisée à 90 et 20 kg ha^{-1} de N et K, respectivement, lors de la récolte plus hâtive. Les tomates récoltées plus tôt dans la saison, à un stade de maturation plus avancé et avec une plus courte période post-récolte avaient une plus haute teneur en lycopène.

Acknowledgements

I would like to express my sincere gratitude to my supervisors Dr. Katrine Stewart and Dr. Philippe Seguin. Katrine and Philippe provided me with constant encouragements and support, especially for initial field procedures, data analysis and text editing for my master's project at McGill University. I am also very grateful to my research advisory committee, Dr. Alan Watson, for the valuable suggestions and encouragements. I would like to thank Dr. Pierre Dutilleul for his assistance with statistical analyses and Mr. David Wees for his insightful suggestions.

I am most grateful to the technicians at the Horticultural Research Center, Michael Bleho and Jean-Pierre Laplaine, for their constant implication in the project and valuable experience in field work and field research, as well as for their friendship. As well, the Lods Research Center technician and research assistants, James Straughton, Amelie Desilets-Roy and Michael Lewis, for their technical help with my samples. Many thanks to Mr. Wucheng Liu, laboratory technician who helped me every step of the way in my lycopene analyses. Thanks to Guy Rimmer and Khosro Mousavi technicians for providing me with some material.

I would like to thank the MAPAQ (Ministère de l'Agriculture, Pecheries et Alimentations du Quebec) for the financial support making this research possible and supporting my graduate student experience. I would like to express my gratitude to: Dr. Annie Pellerin, Elizabeth Lefrancois, Christine Villeneuve and Olivier Breton-Bourgault from the MAPAQ, for organizing and helping throughout this project. I would also like to thank the scientists at the three other sites; from IRDA: Christine Landry, Laurence Simard, Julie Mainguy, from Agriculture and Agri-Food Canada, Carl Belec and from CIEL, Pierre Lafontaine, David Collyer and Stephanie Valcourt. Finally, I am great full to the chemist Dr. Patrick Dube from Laboratoire d'analyse agroenvironnemental de l'IRDA, for analysing the soil, foliar and fruit samples without which none of this project would have been possible.

A big thank you to all the summer and fall students from the 2009, 2010 and 2011 seasons at the Horticulture Research Center and my laboratory mates, many of which have become great friends.

I would like to express my warmest thankfulness to my family; my grand-parents who always believe in me no matter what and my parents Monique and Jean-Charles Caralampides who put up with my tantrums and supported me in every way possible through every step of this project. Merci à tous!

Table of Contents

List of Tables

List of Figures

List of Abbreviations

DW	Dry weight
FW	Fresh weight
N	Nitrogen
NO_3^-	Nitrate
NH_4^+	Ammonium
P	Phosphorus
P_2O_5	Phosphorus
K	Potassium
K_2O	Potassium
Al	Aluminum
Cu	Copper
Mn	Manganese
Mg	Magnesium
Ca	Calcium
Fe	Iron
Zn	Zinc

Nitrogen, phosphorus and potassium fertilizer application per treatment (kg N, P_2O_5, K_2O ha^{-1}) for the Sainte-Anne-de-Bellevue and L'Assomption sites for 2009 and 2010

	Treatment	**Sainte-Anne-de-Bellevue**	**L'Assomption**
Nitrogen experiment	T1	0-60-60	0-60-160
	T2	40-60-60	40-60-160
	T3	80-60-60	80-60-160
	T4	120-60-60	120-60-160
Phosphorus experiment	T5	130-0-60	130-0-160
	T6	130-20-60	130-20-160
	T7	130-60-60	130-60-160
	T8	130-120-60	130-120-160
Potassium experiment	T9	130-60-0	130-60-40
	T10	130-60-20	130-60-80
	T11	130-60-60	130-60-160
	T12	130-60-120	130-60-280

1. General Introduction

1.1 Introduction

Tomatoes are an important crop in Canada, the annual production in 2010 was of 492,650 metric tonnes (FAOSTAT, 2012). In the province of Quebec, the fertilization recommendations have been shown to be excessive for tomatoes (*Solanum lycopersicum*) (Tremblay and Beaudet, 2006). The excessive fertilizer applications as well as inadequate timing of application lead to fertilizer loss. Reduction in preplant fertilizer and split applications to better match nutrient availability in the soil with the plants nutrient demand would help reduce the fertilizer loss. In fact, the current nitrogen fertilization recommendation for most of North America is to apply as preplant 40% of the total recommendation, which ranges from 110 to 220 kg N ha^{-1} (Peet, 1996; Zhang et al., 2006; OMAFRA, 2010; Petzoldt, 2011; Virginia Cooperative Extension, 2010). Current recommendations in Quebec must thus be revisited.

It is difficult to split apply fertilizer using conventional fertilization methods. However, a relatively new technology that would facilitate is fertigation; a combination of fertilization and irrigation.

The effect of the individual nutrient on the plant development has another major impact on the fertilizer requirements. Nitrogen, phosphorus and potassium are critical for tomato growth and development (Jones, 2008). Nitrogen is associated with vegetative and biomass accumulation, phosphorus to seed and root development, while potassium is associated with fruit development and quality.

1.2 Hypotheses and objectives

Objectives:

1. Assess the effect of different fertilization levels of nitrogen, phosphorus and potassium on tomato growth; looking at the yield and quality.
2. Determine which level of N, P, K leads to the highest production of lycopene.
3. Determine optimum time of harvest to maximize production of lycopene.

4. Determine which ripening stage and post-harvest time leads to highest production of lycopene.

Hypotheses:

1. Higher levels of nitrogen, phosphorus and potassium will increase the yield of tomatoes.
2. Higher levels of nitrogen, phosphorus and potassium will increase the lycopene content of tomatoes.
3. Tomatoes harvested later will contain more lycopene than the tomatoes harvested earlier in the season.
4. Tomatoes harvested at a light-red ripe stage will contain more lycopene than the tomatoes harvested at the breaker stage and ripen to the light-red stage post-harvest.

2. Literature Review

2.1 The tomato crop

2.1.1 Tomato production

Tomato (*Solanum lycopersicum*) is the second most important vegetable crop next to potato. World annual production in 2010 was approximately 146 million metric tonnes of fresh fruit (FAOSTAT, 2012). The Canadian commercial production estimates for tomatoes in 2010 were 6,791 ha of tomatoes planted, and 6,623 ha that were harvested. This gives a total production of 492,650 metric tonnes, and a marketable production of 473,792 metric tonnes. Of this marketable production, 0.3% (1,593 metric tonnes) is produced in British Columbia, 1.3% (5,982 metric tonnes) in Quebec, and 98.4% (466,043 metric tonnes) in Ontario (Statistics Canada, 2011). In 2010, a decrease in the area of production and harvest was noted. In addition, a more important reduction was found in the fruit yield, especially the marketable yield. In Quebec, there are only about 500 ha of field-tomato production; the whole production being produced for the fresh market (Carrier, 2009). Tomatoes used for processing in Quebec all come from greenhouse production. In 2010, the total area of greenhouse tomato production in Quebec was estimated to be 470 ha (Statistics Canada, 2011).

2.1.2 Growth type and plant physiology

Tomatoes originate from South America, where it grows as a perennial (Jones, 1999; Heuvelink, 2005). There are two growth types: indeterminate and determinate. The indeterminate tomato plants are usually pruned to keep a single stem and require trellising (Jones, 1999). They continue their growth and produce fruits on side shoots throughout the season (Lerner, 2001). Of the two type of growth, it is the one that is the most often chosen for greenhouse production. On the other hand, the tomato cultivars that have a determinate growth are usually much small and bushier. They have a genetic makeup that has a set height (Lerner, 2001). Once it reaches this height, the growth stops and it produces flower clusters and sets fruits.

A tomato stem is about 4 cm in diameter at the base. The plant is covered with glandular and non-glandular trichomes, which are beneficial in plant defence against insects both through mechanical and chemical defence (Kang et al., 2010). The leaves are compound with a larger terminal leaflet and up to 8 lateral leaflets which can be also compound. The flowers are day neutral (Jones, 1999). The tomato flower will self-pollinate (Amati et al., 2002), however, it requires the flower to be vibrated to allow the pollen on the anthers to be released and fall on the stigma (Morse, 2009). The roots system can extent to a 1.5 m diameter and adventitious roots can develop on the stem, especially at the base (Picken et al., 1986).

2.1.3 Tomato crop management

Shoot pruning is performed usually 2 to 4 weeks after transplanting (Santos and Vallad, 2010). The shoot emerging from auxiliary buds from ground up to the first flowers are removed, leaving a single stem. This practice has been shown to sometimes increase production of large fruits (Marim et al., 2005; Cited by Preedy and Wateson, 2008). Also, the growth type influences several field management factors including for example plant spacing (None, 2010).

Irrigation is critical at the early flowering, fruit set and enlargement stages of tomato (Virginia Cooperative Extension, 2010). In field conditions, pollinators and the wind are sufficient to ensure pollination (Heuvelink, 2005). Optimal temperature conditions for pollination are between 13 and 24° C night and between 15.5 and 32° C day (Jones, 1999).

Optimal soil texture is a medium textured soil. The soil texture is a factor that can be taken in to consideration to establish better fertilizer recommendations; it is especially true for nitrogen (Peet, 1996). The drainage must be good, as this crop does not tolerate saturated soil for long periods (Jones, 1999; Kelley and Boyhan, 2010).

2.1.4 Fruit physiology

From seeding, it usually takes between 50 and 65 days for early varieties and between 85 and 95 days for late varieties for fruits to reach maturity (Jones, 1999). Tomatoes can have from 2 to 12 locules (Jones, 1999), but most popular types of tomatoes, round tomatoes, usually have only 2 and 6 (Jones, 1999; Heuvelink, 2005). The tomato fruit growth can be described using a sigmoid curve that includes three main phases (Ho and Hewitt, 1983; Gillaspy et al., 1993). The first period is a slow growth that lasts for 2-3 weeks during which the fruit uptakes only about 10% of its final weight. During this stage, the most important modification to the fruits occurs at the cellular level, where cell division takes priority over cell enlargement (Gillaspy et al., 1993). On the other hand, the second period is characterised by cell enlargement, which explains the rapid growth of the fruit. This period lasts 3 to 5 weeks, and the maximum growth (daily growth) usually occurs 20-25 days after anthesis, and most of the fruit weight is accumulated by the mature green stage (Ho and Hewitt, 1986). The final stage is mostly characterised by major metabolic changes. The change in color occurs 2-3 days after the mature green stage. As the fruit ripens, there is a transformation from chloroplast into chromoplast, associated with this is the degradation of chlorophyll and production of carotenoids and lycopene (Cheung et al., 1993; Egea et al., 2010). It was found that from the mature green stage of fruit ripeness, with the temperature held constant at 20° C, is approximately 2 days required to obtain the breaker stage, 4 days to turning, 6 days to the pink stage, 8 to light red stage, and 10 days to the red stage (Rubatzky and Yamaguchi, 1997). Also associated with the fruit ripening is the solubilisation and degradation of the cell wall (Brummell, 2006) due to the activation of a number of enzymes (Bargel and Neinhuis, 2005). The major changes that affect fruit quality listed by Grierson and Kader (1986) (summarized in Appendix A, Figure 1) include: degradation of starch, chlorophyll and toxic alkaloid α-tomatine, production of glucose, fructose, pigments (β-carotene and lycopene), and flavour and aroma compounds. It is also associated with increases in soluble pectines, in ratio of citric acid to malic acid and glutamic acid, and softening of the fruit.

2.1.5 Introduction to tomato fertilization

The tomato crop is considered a crop with major fertilization requirements (Badr et al., 2010; Samaila et al., 2011). During the vegetative stage, most of the nutrients are allocated towards growth and development of the plant (foliar), while the macronutrients as well as a number of micronutrients are being allocated to fruit production during the reproductive stage (Halbrooks and Wilcox, 1980, cited by Jones, 1999). Given that fertilization is such an important management factor that affects yield and quality of tomatoes, it has been the subject of a large number of studies. Factors studied included the effect of different macro and micronutrients on tomato production; such as yield and plant development (Pujos and Morard, 1997; Xiuming and Papadopoulos, 2004), also fruit quality (Taylor and Locascio, 2004; Moigradean et al., 2007). Other studies were conducted to understand the effect of the nutrient form and which are more efficient for the plant (Oded and Uzi, 2003; Ben-Oliel et al., 2004), the effect of different methods of application (Badr and El-Yazied, 2007; Badr et al., 2010), etc.

2.2 Fertilization and impact of excess-application of fertilizers

During the “Green Revolution”, a marked increase in yield was partly attributable to the increased use of synthetic fertilizers (Singh, 2006; Mulvaney et al., 2009). It, however, became clear later on that excessive use of fertilizers has an impact on the environment and human health. Despite the recognition of the negative effects associated with excessive fertilizer use, world consumption of fertilizers has continued to increase over the past 25 years.

Excess application of nitrogen fertilizer leads to accumulation and then loss of this nutrient in different forms. Nitrogen can be lost through ground water in the form of nitrate and nitrite leachate. It has been shown to be responsible for not only eutrophication of groundwater, but also eutrophication of estuaries and costal seas (Tilman et al., 2001). Through denitrification, nitrogen in the soil is transformed to N_2O, a greenhouse gas, which is partly responsible for climate change. Nitrogen synthetic fertilizers represent 63% of all human-related sources of reactive nitrogen (Dobermann, 2005; Cited by: Battilani et al., 2008), which results in tropospheric smog and greenhouse effect. Due to the binding capacity of phosphorus to particles compared to the high mobility of nitrogen, phosphorus is mostly associated with surface water eutrophication, particularly freshwater lakes and streams (Carpenter, 2008).

The environmental pollution caused by inefficient fertilization has evident repercussions on the well-being of humans and animals. Excess N fertilization can lead to accumulation of nitrates. The nitrates will then be transformed into nitrite through the digestive process, and this can lead to methaemoglobinemia, as well as certain cancers (Wang and Li, 2004).

Also associated with nutrient loss are economic losses. These losses affect both agricultural producers and the global population. When fertilizer is left in excess in the fields and is not up taken by the plants, it becomes input money that is not paid for by the income. Also, a growing concern is the cost associated with the technologies to treat water in order to have it suitable for drinking, and other activities (Pretty et al., 2000), or that require the development of other techniques to lessen the levels of nitrate (Batheja et al., 2009).

2.3 Fertilization recommendations for fresh market field tomatoes

In most cases, current recommendations in North America are to apply 40% of the total seasonal fertilizer as pre-plant, with recommendations ranging between 33 and 60 % (Peet, 1996; Zhang et al., 2006; OMAFRA, 2010; Petzoldt, 2011; Virginia Cooperative Extension, 2010), depending on soil texture, organic matter content, etc. Recommendations for the lower end of the range are associated with light textured soils with less than 3.2% organic matter (Peet, 1996; OMAFRA, 2010; Virginia Cooperative Extension, 2010). The total seasonal nitrogen fertilizer being applied for fresh market tomato production can range from as little as 70 kg ha^{-1} (OMAFRA, 2010) to as much as 302 kg ha^{-1} (Zhang et al., 2006). In most cases, the total nitrogen application is located between 110 and 220 kg ha^{-1} (Olson et al., 2011; Petzoldt, 2011, Virginia Cooperative Extension, 2010). Again, this is always dependent on the soil texture, soil initial fertility, weather conditions for the location and season, etc.

There have been only a limited number of studies that have investigated N fertilization requirements of tomatoes in Canada and especially Quebec. Most of the research done on this subject comes from Florida and California, where field tomatoes production is significantly larger. Currently, the recommendations and practice for field tomatoes in the province of Quebec is to apply most of the fertilizer early in the season; before crop transplant or seeding, and/or when the crops are young (CRAAQ, 2003). This is done through a limited number of soil-applied fertilizer applications. For tomatoes, the recommendation is to apply 100 kg N ha^{-1} preplant and an additional 35 kg N ha^{-1} as sidedress when fruits have reached 2.5 cm in diameter.

A study conducted by Tremblay and Beaudet (2006) showed that current fertilization recommendations for a number of vegetables for the Province of Quebec are too high for N and P fertilizer, and that they should be revisited to have allow for better nutrient use efficiency. Their conclusions were based on fertilization practices, soil tests prior to planting and after harvest, and tissue samples from live crop and residual crop were analysed. They compared the input, export and residual nutrients in the field. One of the main finding was that there was an important need to review the N fertilization recommendations for tomato.

Ontario's fresh market field grown tomato fertilization recommendations are comparable to Quebec's recommendations. OMAFRA's recommendation (2006) is to apply 35-50 kg N ha^{-1} preplant and 35-50 kg N ha^{-1} side-dressed after the first fruit set. However, unlike in Quebec, processing tomato growers are provided with a fertigation method of N application. However, these recommendations are for processing tomatoes and it is important to note that fertilizer requirements for processing tomatoes can be higher than for fresh tomatoes. This depends on a number of factors including: soil type, fertilizer application method, soil's organic matter content, cultivar (open pollinated versus hybrid varieties) (Peet, 1996; OMAFRA, 2010). As mentioned earlier, the nitrogen recommendation for fresh tomatoes in Ontario is between 70 and 100 kg ha^{-1}, while the nitrogen recommendation with soil applied fertilizers for processed tomatoes varies between 70 and 180 $kgha^{-1}$ (OMAFRA, 2010). The range is different if fertilizer is applied through fertigation.

Fertigation practices vary a lot in terms of the number of applications ranging from a couple of times in a season (B.C. Ministry of Agriculture and Lands, 2009; Petzoldt, 2010) to once a day (Olson et al., 2011). The recommendations that have a limited number of applications usually applied the same amount of fertilizer at each the step. However, when the number of applications increases, differences in the application rate throughout the fertigation period are implemented to have a better match of the plant nutrient demand at the different stages of the plant development. The major stages marked by fertilization rate changes include: one week after transplanting, fruit set and when the fruit starts to turn in color (B.C. Ministry of Agriculture, 2009; Petzoldt, 2011; Virginia Cooperative Extension, 2010). Some recommendations have a steady increase throughout the season (Virginia Cooperative Extension, 2010), while others increase more or less in a linear manner until the last few weeks of the season, when the fertilization rate is reduced (Kemble et al., 2004; Olson et al., 2011).

In general, the recommendations are to apply the total of the phosphorus as a preplant application with some exceptions (Petzoldt, 2011). The recommendations for potassium applications are less standard. Some of the recommendations suggest applying the fertilizer as a preplant (B.C. Ministry of Agriculture, 2009) while a number of others include it as part of the fertigation plan (Kemble et al., 2004; Petzoldt, 2011; Virginia Cooperative Extension, 2010) and finally others do not make the distinction in the fertilization method (Virginia Cooperative Extension, 2010). In one case, as it was the case with nitrogen recommendations, potassium fertilization rates were partially based on soil textures (Virginia Cooperative Extension, 2010).

2.4. Excess fertilization, matching plant nutrient demand and fertilizer application

Excess fertilization sometimes happens without the grower's knowledge and intention. Exterior elements such as weather and disease cannot always be controlled and can lead to excess fertilization (Singh, 2006). Even after the estimation of fertilizer requirement has been calculated, there are many other variables to take into consideration: timing of application, fertilizer source, type and frequency of irrigation etc. Inappropriate decisions regarding these variables can also lead to excess fertilization. Also, it is not uncommon that fertilizer is added in surplus as insurance (Schröder et al., 2000; Battilani et al., 2008). Since the cost of fertilizers is low compared to the income (1-2% of the gross income – Simon et al., 2002; cited in Schenk, 2006), growers are not willing to take the risk and apply more than is needed in case the soil fertility is not uniform and there is nutrient shortage.

Also, it is common practice to apply most of the seasonal fertilizer requirement in a limited number of applications prior and/or early in the plant's development cycle. Yet, this is an issue as plant requirements do not match with the nutrients that are made available to plant uptake when there is a fertilization application. At the time of the fertilization, the plant nutrient requirements are in fact much lower (Appendix A, Figure 2), which leaves a lot of residual nutrient in the soil. Any nutrient in the soil and not up taken immediately has a much higher chance of being lost through leaching, denitrification, etc. (Sanchez and Doerge, 1999; Thompson et al., 2006). A way to remedy to this matter is to apply the fertilizer in split applications and following more closely the plant nutrient demand and uptake (Appendix A, Figure 3) and to have fewer nutrients susceptible to being lost (Doerge et al., 1991; Cited by Sanchez and Doerge, 1999). This not only does it reduce the amount of N subjected to losses, it also increases the nutrient uptake efficiency (Alva et al., 2006). A number of studies done on different crops, compared solely preplant application to a combination of preplant with multiple post-planting fertilizations. The combinations, which allow the fertilization to be more spread out throughout the crop's development, showed an increase in yield regardless of the fertilization method used post-harvest (Sibler et al, 2003; Savić et al., 2006). The combination preplant fertilization and fertigation increases nutrient use efficiency since banding the fertilizer at preplant provides the nutrients to the limited rooting system at the time, and when the roots have developed, frequent application of fertilizer can better fit the plant nutrient demand with fertigation (Alva et al., 2006). These results were also observed with tomatoes (Locascio et al., 1997; Shedeed et al., 2009).

2.5. Typical nutrient uptake in tomato plants

Applying high fertilization rates is especially a concern early in the plant's ontogenesis because for most crops the nutrient demand at that time is low as nutrient uptake follows biomass production. The nutrient uptake for tomatoes is relatively low prior to flowering, at which time nutrient demand increases until it reaches a peak during fruit set and early fruit bulking (Hartz and Hochmuth, 1996).

Tapia and Gutierrez (1997) followed the dry weight accumulation and nutrient (N, P, and K) uptake of tomato plants throughout their growth (from 30 to 148 days after emergence) for different tissues: roots, leaves, stems, and fruits. Plant demand and nutrient uptake closely followed plant biomass production (Appendix A, Figures 4, 5, 6, and 7). There was no clear distribution pattern early in the ontogenesis (from 1st cluster to 4th cluster). However, the transition phase that followed had a distinct demand for N from the leaves (vegetative phase), followed by a clear pattern of N being mostly allocated to fruit production with just under 60% of N demand going for fruits. At the same time, the stem N demand remained the same, and the N allocated to leaves was reduced by 10% (Appendix A, Figure 5). Phosphorus was mostly allocated to the fruits, and the decrease in leaves and stem P allocation followed a similar patterns that of the N (Appendix A, Figures 5 and 6). Potassium uptake and allocation was for stems and leaves. When fruits began their accelerated growth, most of the K was allocated to the fruits (Appendix A, Figure 7). Over all, during the stage when the fruits begin their accelerated growth, K was the nutrient that was the most demanded by the plant followed by N and P. At that time, 47, 65, and 56% of the N, P, and K respectively were uptaken by the plant. Taking into account the lag phase between fertilizer application and nutrient availability, the uptake pattern of the nutrients helps create a fertilization plan for which the fertilization rates match the crops nutrient uptake and distribution.

2.6. Effect of nitrogen, phosphorus and potassium fertilization on tomato plants and fruits

2.6.1 Nitrogen

Some early nitrogen fertilizer is needed for young seedlings (Bosland and Votava, 2000). Nitrogen fertilization affects vegetative growth and biomass accumulation, as it is associated to increasing photosynthate source capacity (Tei et al., 2002). The growth stage and environmental conditions should be taken into considerations to apply the optimal N rate, which should match the nutrient plant demand. However, during the vegetative stage, growers usually tend to restrain their N application since too high levels can lead to excess vegetative growth. In fact, it promotes vegetative growth over reproductive growth and causes: a delay in fruit growth, a reduction in yields, an increase disease along with insect damage, and create poor flower development, fruit set and fruit size (Bosland and Votava, 2000; OMAFRA, 2001; cited by Heuvelink, 2005). This is especially true in sub-optimal conditions such as periods of high rainfall and humidity. At fruits set and into the reproductive growth, N levels are raised to promote fruit production.

Deficiency in N result in a stunted plant with paler looking leaves. Due to nutrient mobility within the plant, the older leaves show deficiency first. The flowers take on a deeper shade of yellow and in severe cases of N deficiency they drop and the remaining fruits are smaller, thus affecting the yield. Toxicity due to excess fertilization results in dark green leafage. Flower clusters are more numerous but bud abortion increases. It also inhibits flower development, fruit setting and formation, increase susceptibility to lodging, disease and insect invasion. (Jones, 1999)

2.6.2 Phosphorus

Phosphorus is another macronutrient that is essential to crops, although in much smaller quantities than N. It is associated with early root development and architecture especially when P levels are low (Heuvelink, 2005). It has also been shown to affect flower and seed production (Menary and Staden, 1976; Lau and Stephenson, 1994). Phosphorus deficiency hinders the photosynthesis capacity of tomato plants, especially under lower than optimal temperatures (Zhou et al., 2009).

Deficiency symptoms include a decrease in leaf expansion and leaf area and number. One of the most visible symptoms is the color of the leaves going to a dark green and then turning purplish, usually starting with the older leaves. On the other hand phosphorus excess is associated with micronutrients (zinc, copper, and iron) deficiency (Jones, 1999; Cited in Heuvelink, 2005). Fertilization with phosphorus fertilizer is usually done through conventional fertilization methods: preplant broadcast (Bosland and Votava, 2000; Suojala et al., 2006). The reason for this is that traditional phosphorus fertilizers do not dissolve easily and thus, fertigation is not suggested because the fertilizer can block the system. Precipitation of phosphorus with calcium or magnesium can occur when they are found in high concentrations in the water (Burt, 1998).

2.6.3 Potassium

Excess fertilization of potassium can lead to crop luxury K uptake without profitable economic return (Zhang et al., 2009). Deficiency symptoms include marginal chlorosis of the older leaves and stunted growth (Jones 2008). Zhang and al. (2009) found that both green fruit and blossom-end rot fruit yield decreased with increasing application of K fertilizer when no drip irrigation was applied. However, with drip irrigation, increasing K fertilization rates created an increase in marketable yield. In fact, K fertilization has been associated with increased fruit quality, plant growth and yield. A positive correlation was shown between increased rates of potassium and fruit weight and number of flowers and fruits. About, two-thirds of the K uptake is allocated to fruits (Hidetoshi, 2007). Potassium also increases production of beneficial compounds such as protein, ascorbic acid, lycopene, total soluble solids, titratable acidity, and reduces sugar levels (Si-smail et al., 2007; Almeselmani et al., 2010). It was also shown to reduce the internal white tissues and increase the redness of fruits, thus reducing the incidence of yellow shoulder in tomato fruits (Gunter, 2010). Finally, it was shown to have a positive impact on the number of stems per plant, stem diameter, and plant height (Si-Smail et al., 2007).

2.7. Irrigation and fertigation

Global warming and increasing world population are two worldwide issues, which are in direct association with the increasing concern that is water use efficiency (Brace, 2007). Increasing droughts have been associated with global warming. To allow agriculture to continue, irrigation is a key element. However, water is becoming a valued commodity especially with increasing populations. Water use efficiency is a major goal. In the past, the use of certain improved irrigation technologies has been shown to improve water use efficiency.

2.7.1 Irrigation

A major step forward in the better management of water and fertilizer was the development of drip irrigation. In a 1999 workshop on irrigation and fertigation of processing tomatoes (Bieche, 1999), it was highlighted that out of the current three irrigation methods (furrow, sprinkling and drip irrigation), drip irrigation had the best water use efficiency. Drip irrigation reduces water loss by having the water brought in slowly and directly to the root zone (Tan et al., 2009). Tomatoes, also showed a 20% increase in yield when drip irrigated compared to furrow irrigation, and this was partly explained by better moisture regime at the root zone (Hebbar et al., 2004). Tu et al (2004) in Southwestern Ontario also obtained a higher yield in drip irrigated tomatoes than tomatoes that only received rainwater. Drip irrigation also reduces the labour and management cost mainly by removing large metal pipes which make field work and machinery use more difficult In arid and semi-arid regions, when comparing with furrow irrigation, drip irrigation was shown to have less production of nitrous oxides, especially N_2O, a greenhouse gas (Sanchez-Martin et al., 2008).

2.7.2 Fertigation

Another step toward better use of resources was the development of the fertigation technology. Fertigation is the combination of two known processes: fertilization and irrigation. The nutrient that is most applied by fertigation is nitrogen (Burt et al., 1998). Fertilizer is either dissolved or simply injected (liquid form) in the irrigation water. Just like irrigation, it can be applied to the plant through furrow water, sprinkler fertigation or drip-fertigation. As for drip irrigation, drip-fertigation is more efficient than the other fertigation methods in most of the same ways, including a more adequate distribution of the fertilizer.

2.7.2.1 Split application

As mentioned previously, split application of fertilizer reduces the risk of nutrient loss (Sanchez and Doerge, 1999). Drip fertigation allows split application well into the growing season, and throughout plant growth stages (Qawasmi et al., 1999; Salo et al., 2002). This cannot be done as easily with side dressing as machinery cannot enter the field after the plants reach a certain height.

2.7.2.2 Flexibility

Fertigation allows for a quicker response to the regime of fertilization, which changes with the plant growth stage. Once the system is set up it can be done automatically with timers. The plant can be fertilized from a few times a day to a few times a season with this method. It also allows to apply the application of fertilizer according the climate in order to prevent losses in nutrients and have the appropriate water regime.

2.7.2.3 Impact on input cost

Fertigation can reduce the fertilizer cost by reducing the requirements in squash (*Cucurbita* spp.) (Mohammad, 2004), Chinese cabbage (*Brassica rapa*) (Ueta et al., 2009), and lettuce (*Lactuca sativa*) (Monaghan et al., 2010). However, two studies in Harrow, ON, showed opposite results, where by using fertigation, nutrient requirements are higher. One of the studies looked at the production of processing tomatoes and the other looked at bell peppers (Zhang et al, 2010 a, b). Both studies found that with fertigation compared to the current recommendation for soil applied fertilization, there was a higher need for fertilizer.

2.7.2.4 Impact on yield

Yield is also positively affected by fertigation method of fertilization. A number of crops potato (Mohammad et al., 1999), pepper (Qawasmi et al., 1999), broccoli (Thompson et al., 2002), have been shown to have higher yields with fertigation compared with both a non-irrigated control and combinations of drip irrigation and broadcast N application.

In Ontario, the effects of drip irrigation and drip fertigation, on the yield processing tomatoes were observed (Tan et al; 2009). Two soil types were used, a light loamy sand and a clay loam (heavy soil). In all cases, there was significantly higher marketable yield with drip irrigation and drip fertigation than the control (between 14% and 47% higher yields). Light soil had a higher increases in yield compared to the heavy soil.

Hebbar et al. (2004) conducted a study in India, where a tomato crop was subjected to different irrigation methods (furrow and drip), fertilization methods (broadcast, drip fertigation with NPK soluble fertilizers, drip fertigation with normal fertilizers, drip fertigation with NK only, subsurface drip-fertigation) and two different fertilization rates (100% and 75% of the recommended fertilization rates with drip-fertigation). Drip irrigation increased the yield by 19.9% compared to furrow irrigation. Also, the tomato yield under water-soluble fertilizer fertigation was 79.27 Mg ha^{-1} while with drip irrigation and soil applied fertilizer the yield was down to 71.92 Mg ha^{-1}.

2.7.2.5 Impact of nutrient uptake efficiency

Tan et al (2009) looked at N and P uptake efficiency. Drip irrigation and/or fertigation showed 64 and 35% increase in the P and N use efficiency respectively on the light texture soil and a 35 and 12% increase in the coarse texture soil. Shedeed (2009) obtained similar results.

2.7.2.6 Impact on water loss (runoff, leaching and evaporation)

Drip fertigation reduces water loss due to runoff (Bieche, 1999) as the nutrient solution is applied directly to the plant. It can reduce water lost by evaporation compared with sprinkler application, and overall it reduces evaporation especially with the use of plastic mulch as it traps the moisture under the mulch. It also reduces the need for water as it goes directly to the root zone. Under optimal conditions, fertigation can reduce the water and nutrients lost through leaching (Dangler and Locascio, 1990; Locascio et al., 1997; Kafkafi, 2005; Tan et al., 2009).

2.8 Beneficial compounds in tomatoes

Tomatoes contain a number of health-beneficial compounds, such as high potassium content, vitamins, and carotenoids. About 75-83% of the total carotenoids in tomatoes is in the form of lycopene. This makes tomatoes a fruit of recent interest for a number of studies on beneficial properties associated with the consumption of tomatoes for their lycopene content. Lycopene, which acts as a natural defence pathway, an antioxidant and antimutagenic agent (Preedy and Watson, 2008). This makes tomatoes a beneficial fruit for the consumption especially and these characteristics are especially important, as it is a highly consumed product. Between 1970 and 2008, in the United States there was a decline in all canned vegetable consumption except for mushrooms and tomatoes (Buzby and al., 2010). In fact, processing tomatoes are second only to potatoes in terms of national per capita vegetable consumption in the United States (Plummer, 1999). In 2001, in Canada, excluding potatoes, tomato was the second most consumed fresh vegetable (Agriculture and Agri-Food Canada, 2002).

2.9. Lycopene

Lycopene is a carotenoid pigment, a secondary metabolite, in fruits and vegetables, bacteria, fungi, and algae (Jones and Porter, 1999; cited by Collins et al., 2006). In plants lycopene compounds are synthesized through the extension of the normal isoprenoid pathway, in the chloroplast and chromoplast of the cells. Eight isoprene units (5-carbon atoms) fuse to form the lycopene molecule (40-carbon atom; Heuvelink, 2005) a straight chain of carbon-hydrogen linkage made of 11 conjugated and 2 non-conjugated double bonds (Rao and Agarwal, 2000; Shi, 2000; Boileau et al., 2002). The lycopene molecule is lipophilic and highly unsaturated. Due to the numerous conjugated double bonds, the molecule can undergo isomerisation and produce various *cis* isomers. Tomatoes have a high level of lycopene although this varies depending on the type of processing to which the fruit has been subjected. The form most present in fresh tomatoes is the all-*trans* isomer (Chasse et al., 2001). The *cis* isomers are primarily found in processed and stored foods (Rao and Agarwal, 2000; Shi, 2000). T*rans* form is poorly absorbed while the *cis* has better rates of absorption by the human body (Stahl and Sies, 1992).

2.10. Health benefits of lycopene

The numerous conjugated double bonds characteristic of the carotenoids and more specifically lycopene makes it one of the most important antioxidants due to its strong single oxygen-quenching capacity (Di Mascio et al., 1989). Reactive oxygen species (ROS) have been found to be implicated in the development of a number of chronic diseases (Halliwell, 1994; Witzlum, 1994; Ames et al., 1995; Pincemail, 1995). *In vitro* studies demonstrated that lycopene inhibits two ROS, namely hydrogen peroxide and nitrogen dioxide (Bohm et al., 1995; Lu et al., 1995). Mortensen et al. (1997) using pulse radiolysis reported that lycopene scavenged nitrogen dioxide, thiyl and sulphonyl radicals. Due to its antioxidant properties lycopene is believed to be a major protector of critical biomolecules such as lipids, low-density lipoproteins (LDL), proteins and DNA (Agarwal and Rao, 1988 (a,b); Pool-Zobel et al., 1997).

Recent studies have shown that quenching free radicals is not the only way lycopene could be beneficial to human health. Lycopene has been found to stop the proliferation of various cancer cell lines. Fornelli et al. (2007) showed that lycopene had an inhibitory effect on MCF-7 cell growth, a cell line of breast cancer. Similarly, Wu and al., (2007) reported that lycopene was shown to trap a platelet-derived growth factor (PDGF) which stimulates proliferation and migration of melanoma cells by binding with it.

2.11 Pre-harvest factors that affect lycopene production in tomatoes

2.11.1 Variety

Lycopene production varies among varieties from 4.3 to 173 mg kg^{-1} (Barrett and Anthon, 2001; Kuti and Konuru, 2005). Forty varieties of cherry, cluster, and round tomatoes, were tested in greenhouse and field conditions by Kuti and Konuru (2005). Cherry tomatoes had higher lycopene content than round or clustered tomatoes. Round tomatoes had higher lycopene content in greenhouse conditions than in field conditions, and the opposite was true for cherry tomatoes. Also, there is a marked difference between lycopene content in yellow tomatoes; 5 mg kg^{-1} and deep-red tomatoes; more than 50 mg kg-1 (Scott and Hart, 1995).

2.11.2 Temperature

Krumbein et al., (2006) showed that the optimal range for lycopene biosynthesis was between 20 to 24°C. Temperatures higher than 30 °C or lower than 12°C lead to the inhibition of lycopene production (Dumas et al., 2003). However, the temperature of the fruit is dependent on the cover or shading due to foliage and better represents lycopene content (Helyes et al., 2007). There can be a 10°C difference between fruits that are directly exposed to solar radiation and fruits that are shaded (Brandt, 2006). Numerous fruits on a cluster creating high competition between fruits off set the temperature's effect on lycopene content. Thus, even at higher temperatures, if there is a lot of competition, the lycopene content will be decreased compared to when there is low competition where there is an increased content in lycopene production (Gautier et al., 2005).

2.11.3 Quantity and quality of light

Solar radiation was shown to be a major factor positively affecting lycopene production in tomatoes (Toor et al., 2006). Low light intensity creates uneven ripeness of the fruits (Raymundo et al, 1976). Light quality also affects lycopene production. Red light increases lycopene formation (Thomas and Jen, 1975; Alba et al., 2000). In fact, Alba et al (2000) considered that lycopene production is regulated by localized phytochromes, as tomato fruits subjected to red light for a brief period had an increase in lycopene production from 3.7 to 8.7 mg/ 100g, which was then reduced to 5.2 mg/100g when subjected to far-red light. In 2005, Gautier et al., showed that when tomatoes were subjected to different light spectra, blue light increased in lycopene content.

2.11.4 Stage of ripeness of the fruit

A color grid was created to classify the stage of ripeness of tomato fruits. The basic grid includes: immature green, mature green, breaker, turning, pink, light red and red-ripe (Grierson and Kader, 1986; Sargent and Moretti, 2002). These different stages are associated with different levels of redness of the fruits. Color indexes were also developed to distinguish different colors according to numerical standards. This is done using colorimeters that measure colors along L*, a*, and b* axes, which represent different grades from white to black, green to red and blue to yellow, respectively (Camelo and Gómez, 2004). The two axes that are most used for determining tomato ripeness are a* and b* axes (green to red and blue to yellow respectively). a* is a good indicator of the color change: lycopene synthesis. Fish et al. (2002) showed that at the green stage the value of a* will be negative and increases to a positive value at the full red stage creating a positive correlation. More precision comes from using their ratio either a*/b* or $(a^*/b^*)^2$. Values of 2.0 and above are considered excellent color of tomato paste when using the a*/b* ratio, while anything less than 1.8 is considered poor and unacceptable (Barreiro et al., 1997)

As fruit mature they not only change in color but also in their chemical composition. There is a noted decrease in the chlorophyll content and an increase in the carotenoid content (Brandt et al., 2006; Carrillo-Lopez and Yahia, 2010). From the lowest content in lycopene, there is an increase of more than 500-fold (Fraser et al. 1994).The lycopene content starts to increase at breaker stage. From the breaker stage to the turning stage, there is about 3 times increase in the lycopene level (Brandt et al., 2006). In fact, the lycopene content increased from 10 µg/100 g FW at breaker to 4600 µg/100 g FW at the firm red stage and up to 7050 µg/100 g FW at the overripe stage (Fraser et al., 1994).

2.11.5 Fertilization (nitrogen, phosphorus and potassium)

Nitrogen fertilization has inconsistent effects towards lycopene production. Kobryń and Hallmann (2004) observed no significant difference between nitrogen treatments. Aziz (1968) observes a negative correlation between lycopene content and nitrogen fertilization. This would be consistent with the fact that secondary metabolites without a nitrogen atom, such as lycopene, would be favoured by N-limiting conditions (Dorais et al., 2008). As well, with increasing nitrogen fertilization comes increasing vegetative growth, which in turn would increase shading thus reducing the solar radiation and temperature for the fruits, which reduce the lycopene content. However, Montagu and Goh (1990) observed increased lycopene concentrations by an average of 30% with different nitrogen rates that went up to 600 kg N ha^{-1} in a pot experiment. Klein et al. (2005) also observed a higher lycopene content when plants were subjected to organic nitrogen fertilization.

Under hydroponics experiments, it was shown that increasing rates of phosphorus fertilization (from 0 to 100 mg P l^{-1}) increases lycopene content in tomato fruits (Saito and Kano, 1970). However, Oke et al. (2005) showed that there was no effect of phosphorus fertilization on the lycopene content of tomatoes. In a review, Dorais et al. (2008) tried to justify the inconsistency in the results with climatic factors and growing seasons, but mention that usually, increases in phosphorus rates would increase lycopene concentration.

Finally, potassium seems to be consistent in increasing lycopene production. Trudel and Ozbun (1971) noted a 40% increase in lycopene content in a pot experiment when the nutrient solution increased from 0 to 8 mM. Fanasca et al. (2006) showed that between high calcium, potassium, and magnesium solutions, the high potassium solutions resulted in the tomatoes that had the highest content of antioxidants, especially lycopene. When subjected to 150, 300, and 450 mg K l^{-1}, the lycopene content in three cultivars was positively correlated with increasing rates of K (Serio et al., 2007). In a soilless culture, different concentrations of potassium were tested and once more, the plant subjected to the highest potassium concentration had the highest lycopene content (Ramírez et al., 2009).

2.12. Post-harvest factors that affect lycopene production in tomatoes

2.12.1 Temperature

At storage temperatures of 15 and 25°C, the tomatoes had 3-fold greater lycopene content than when stored at 7°C.In fact, at 7°C lycopene production was inhibited (Toor and Savage, 2006). Similar results were obtained by Javanmardi and Kubota (2006), when they compared the lycopene content of tomatoes stored at room temperature (25-27°C) for 7 days, and tomatoes stored at 12°C for 7 days then at 5°C for another 7 days. The tomatoes at room temperature experienced a significant increase in lycopene content, while the tomatoes at 12°C had a lower content in lycopene, which stayed constant for the 7-day period and then decreased but stayed constant when the temperature was put at 5°C for 7 days.

2.12.2 Differences in tissue type

Differences in lycopene content were also found in the different layers of a tomato fruit (Sharma and Le Maguer, 1996; Carrillo-Lopez and Yahia, 2010). The skin of the tomato fruit usually has the more lycopene (about 5 times more) than the pulp of the tomato (Marković et al., 2010). The pulp of the tomato has a lycopene content ranging from 64.6-107 mg kg^{-1}. The wet insoluble fraction represented 354-536 mg kg^{-1}, while the soluble faction represented 0.074-0.34 mg kg^{-1} (Sharma and Le Maguer, 1996).

2.12.3 Post-harvest ripening and vine ripening

Giovanelli et al. (1999) observed that lycopene content in vine-ripened tomatoes increase linearly compared to the exponential increase in lycopene content in post-harvest ripened tomatoes. The exponential increase mostly started when the index color was at $a^*/b^* = 1$. However, it is only after a^*/b^* equalled 2 that the post-harvest tomatoes had a higher content in lycopene than the vine-ripened tomatoes.

3. Materials and Methods

3.1 Fertilization experiment

3.1.1 Site conditions and plant material (Sainte-Anne-de-Bellevue)

The experiment was conducted during the summers of 2009 and 2010 at the Horticulture Research Center, Macdonald Campus, McGill University, Sainte-Anne-de-Bellevue, Quebec (lat. 45º 26'N long. 73º 56'W). The soil was a Gleyed Eluviated Eutric Brunisol (31% sand, 32% clay, 37% silt) which was fall-ploughed and spring-harrowed. Tomatoes were planted following sweet corn in 2009 and pepper in 2010. Soil fertility at the onset of experimentation was 792 kg P ha^{-1} and 458 kg K ha^{-1} as determined by soil tests (Soil Test Laboratory McGill University, Sainte-Anne-de-Bellevue, QC, Canada).

Preplant fertilizers mono-ammonium phosphate (MAP: 11-52-0), calcium ammonium nitrate (CAN: 27-0-0), and potash (0-0-60 Agros Centre Fertibec, Inc., St-Rémi, Qc, Canada) were applied on the 18 May 2009 and on 24 May 2010. The granular fertilizers were worked into the soil with a rake manually. Approximately a week prior to transplanting, beds (6 m x 1.1 m and 0.12 m high) were made using a plastic mulch layer and bed maker (Model 2550, Rain-Flo Irrigation, East Earl, PA, USA). The machine laid drip irrigation tape (T-Tape 0.015mm with holes at 30.48cm and an out flow of 4.17 LPM/100m, T-Systems International, Dan Diego, CA, USA supplied by Récoltech, St-Rémi, QC, Canada) in the center of the bed and it was covered with 1.1mm black polyethylene (CLIMAGR, Récoltech, St-Rémi, QC, Canada). In 2009, beds were 2.0 m center to center and there was 0.5 m between treatments. In 2010, spacing between the rows was increased from 2 to 2.25 m to facilitate machinery use. Also, between the main treatments rows, where the irrigation lines were placed on the soil surface, a 1 m distance was implemented to allow easier access to the field during fertigation/ irrigation sessions and at harvest.

Transplants of tomato cv. Florida 47 (Stokes Seeds, Thorold, ON, Canada) were grown at Les Serres Lefort (Ste-Clothide, QC, Canada). Transplants were grown under natural daylight and a constant air temperature of 23-24 °C for the first week after seeding and 21 °C for the next 6 weeks. Tomatoes were seeded into 128-cell Styrofoam tray containing peat-based growing substrate Terreau Sunshine Mix (Sun Gro Horticulture, Vancouver, BC, Canada). At the cotyledons stage, seedlings were watered as required and fertilized daily with 100 ppm N, 11 ppm P, and 83 ppm K.

Tomatoes were transplanted using a mechanical transplanter (Rain-Flo Transplanter Model 1600, Rain-Flo Irrigation, East Earl, PA, USA). At the 4 true leaf stage, on 27 May 2009 and 4 June 2010 the plants were transplanted into a single row with 0.45 m between plants. Each transplant received 150 mL of water but no transplanting solution.

3.1.2 Treatments and experimental design (Sainte-Anne-de-Bellevue)

The experimental design used was a randomized complete block with split-plot restriction and 3 replications. The main plots were the elements: nitrogen (N), phosphorus (P), and potassium (K). Each element had four fertilization levels, which were randomly applied as sub-plots giving a total of twelve treatments (T1 –T12). All plots received a constant 50 kg ha^{-1} preplant broadcast N. A first set of 4 treatments (T1-T4) had varying levels of nitrogen, which was supplied by fertigation (0-40-80-120 kg N ha^{-1}), while phosphorus and potassium levels were held constant at 60 kg ha^{-1} for both. The second set of treatments (T5-T8) had varying levels of phosphorus (0-20-60-120 kg P_2O_5 ha^{-1}) while nitrogen and potassium levels were held constant at 130 kg N ha^{-1} and 60 kg K_2O ha^{-1} respectively. Finally, the third set of treatments (T9-T12) had varying levels of potassium (0-20-60-120 kg K_2O ha^{-1}) while N and P_2O_5 levels were held constant at 60 kg P_2O_5 ha^{-1} and 130 kg N ha^{-1}.

Nitrogen in the form of soluble granular ammonium nitrate 34-0-0 (Plant Products Co Ltd / Plant-Prod Québec, Laval, QC, Canada) was applied via the irrigation system. All treatments received calcium via the irrigation system at the rate of 5 kg Ca ha^{-1} from the appearance of the first fruit until the end of August. Calcium was applied in the form of Oligo-Calstick (13% Ca) (SynAgri, Saint-Isidore-de-Laprairie, QC, Canada).

Each treatment plot consisted of three 6 m long rows. The outer two rows served as guard plants. In the center row, the middle six plants were harvested.

3.1.3 Site conditions, plant material, treatments, and experimental design (L'Assomption)

The experimental design at the CIEL (Carrefour Industriel et Expérimental de Lanaudière) site in L'Assomption (lat. 45º 56'N long. 73º 19'W) was the same as the one previous described for Sainte-Anne-de-Bellevue. The soil texture in both years was a loamy sand. In 2009, the soil fertility at the onset was 611 kg P $ha^{-1}$and 245 kg K ha^{-1}, while in 2010, the soil P and K levels were 465 and 194 kg ha^{-1} respectively. For the potassium fertilization component of the experiment, due to the lower initial levels of potassium a new higher range of fertilizer dosage was used (40, 80, 160, and 280 kg K_2O ha^{-1}). The nitrogen and phosphorus fertilization rate were constant at 130 kg ha^{-1} and 60 kg ha^{-1} respectively. For the nitrogen fertilization, the same range of rates was used as in Sainte-Anne-de-Bellevue (i.e., 50, 90, 130, and 170 kg N ha^{-1}), while the potassium and phosphorus levels were constant at 160 and 60 kg ha^{-1} respectively. Finally, for the phosphorus fertilization, the range used was the same as in Sainte-Anne-de-Bellevue (i.e., 0, 20, 60, and 120 kg P_2O_5 ha^{-1}), while the nitrogen and potassium fertilization rate were constant at 130 and 160 kg ha^{-1} respectively.

3.1.4 Fertigation schedule

3.1.4.1 Fertigation schedule for 2009 season

The fertigation schedules at both sites are presented in Table 3.1. The separation according to plant development stages was done to match the plant changes in nutrient demand throughout its growth (Tapia et Gutierrez, 1997).

3.1.4.2 Fertigation schedule for 2010 season

The total quantity of fertilizer applied in each treatment was the same as the 2009 season. However, in order to better respond to plants nutrient demand, the fertigation schedule was modified (Table 3.2). Twenty percent of the allocated nitrogen was applied between transplantation and the formation of the first fruit (approximately 4 weeks). In the next two week period 15% N applied and then, 50% from the two weeks after the formation of the first fruits to the first weeks of harvest (5 weeks), and the final 15% until end of August/ beginning of September (2 weeks).

3.1.5 Irrigation system

The injector was a Mazzei 283 (Récoltech, Saint-Remi, QC, Canada) (Mazzei Injector Corp., Bakersfield, CA, USA) which works by pressure differential. It was mounted on a pipe (from 3.8 cm before the injector to 2.5 cm after) with valves before and after the injector. This pipe was then attached to a main source pipe (3.8 cm) in parallel. On the main pipe a valve was placed between the connections to the injector, to controls the flow of water into the field as well as to create the pressure differential, which can be read on the two manometers that were added on either side of the injector line. On the main line following the second manometer there was a pressure reducer to reduce pressure to 82.74 kPa.

The main line ran parallel to the plants on the outside of the last row, which ended with a valve to flush the system (Figure 3.1). To this main line were connected 9 x 2.5 cm secondary lines (2.5 cm) that ran perpendicularly to the plants/mulches/drip-tapes. They represent the 3 lines (N, P, K) repeated 3 times (three blocks) and they were equipped with valves at the beginning (right after the connection from the main line) and their end (after the last row). The end valves were there again used to flush the system. Finally, these lines were connected to the drip tapes, which were cut and closed at the end of each 6 m allocated to a treatment. The connecters from the secondary lines to the drip tapes were equipped with valves for all the N lines and for the treatments T5 and T9, which were the controls for K and P. The rest of the connecters were simple connecters that allowed free flow from the secondary lines into the drip-tapes.

3.1.5.1 Irrigation schedule

Irrigation was applied based on tensiometer readings when the soil reached 60% field capacity at a depth of 30 cm, where the majority of the roots are located (OMAFRA, 1990).

3.1.5.1.1 2009

Irrigation was based on crop requirements, which was assumed to be primarily influenced by nitrogen fertilization levels. Thus, tensiometers were mostly placed in treatments with different levels nitrogen fertilization. Two tensiometers per three sub-plot, per block were used to identify the irrigation needs. Thus, 2 tensiometers were placed in each of the following treatments: T1, T2, T3 and T4. Since T6 to T8 (part of the phosphorus experiment) and T10 to T12 (part of the potassium experiment) received the same amounts of nitrogen as T3, their water requirements were based on the calculation of irrigation requirements from the tensiometers placed in the T3 sub-plots. Finally, T5 and T9 each had two tensiometers, as they were the treatments that received the lowest dosage of P and K, respectively and might have required less irrigation water. However, no irrigation was required during the season.

3.1.5.1.2 2010

Additional irrigation was required twice in the 2010 season. The field were irrigated for periods of 90 minutes. Irrigation took place during a dry period of the summer, on 6 July and 15 July 2010. The need for irrigation was based on the number of days without precipitation (i.e., a minimum of five days with less than 10 mm in rainfall) and the very high heat during that period (i.e., greater than20°C).

3.1.6 Field operations

3.1.6.1 Training

Tomato plants were trained using the Florida weave system (Cutler, 1997). Rebar posts (La Forge Arboit Inc., L'Assomption, QC, Canada) 1 cm in diameter were placed after every second plant to support the crop. Training began when plants reached a height of 30 cm. A string was tied around each rebar post and around the individual plants at a height of 20 cm from the soil surface. Additional strings were added when the plants reached heights of 35 and 50 centimetres, respectively. Tomatoes were suckered as required to remove excessive foliage. In 2010, the stakes were sterilized with a solution of KleenGrow (Plant Prod., Laval, QC, Canada) prior to use.

3.1.7 Weeding

Weeds were manually removed from the planting holes in the mulch twice during the season. Weeding between rows was done mechanically every three weeks using a rototiller (Kubota, Osaka, Japan).

3.1.8 Pest and Disease control

3.1.8.1 2009

Tomatoes were sprayed twice in Sainte-Anne-de-Bellevue with Bravo 500 [Fungicide group M, Chlorothalonil, (Tetrachloroisophthalonitrile)]. The first spray had a concentration of 400ml/8L and was performed when initial symptoms of possible fungal disease were observed in the field. The second spray was with a solution of Bravo 500 (100ml) (Contains: Chlorothalonil,) and Kocide 101 [(fungicide/bactericide- AI: Copper hydroxide)] (25g) in 10L of water. Both products were obtained from Équipement Lavalé (St-Joseph du Lac, QC, Canada).

3.1.8.2 2010

In Sainte-Anne-de-Bellevue, in order to control flea beetles (Coleoptera: Chrysomelidae) Sevin XLR (Carbaryl) (Équipement Lavalé, St-Joseph du Lac, QC, Canada) was sprayed once at a rate of 1.25 mL/L.

3.1.9 Data collection

3.1.9.1 Meteorological data

For Sainte-Anne-de-Bellevue, data of minimum, maximum and mean temperature, and total precipitation were retrieved from the Environment of Canada website, National Climate Data and information Archive (Environment Canada, 2012). The data were retrieved from the weather station of Ste-Anne-de-Bellevue 1, Quebec, Canada, which is located at approximately 2.2 km away from the experimental field. The data was collected from 1 April to 1 October of both years. For L'Assomption similar data was collected from onsite weather station from 1 May to 1 September.

3.1.9.2 Soil Sampling

3.1.9.2.1 2009

Soil samples were taken in early to mid-May in the spring and early October in the fall. At the onset of the experiment, the main plots were sampled at a depth of 20 cm for pH, Mehlich-III solution, and organic matter. For each main plot, six samples were taken randomly across the plot, mixed, a 300 g subsample being preserved for analyses. The subsample was then air dried. Soil samples for nitrate analysis were taken from the N main plots. Three samples were taken at 2 depths of 0-30 and 30-60 cm for each plot. The samples were mixed and sub samples of 300 g were frozen. Six soil samples were taken from each block for soil texture. A 300 g composite sample was air-dried. A single soil sample was taken from each block to determine soil density. A hollow cylinder (7.75 cm high and 8.3 cm in diameter) for a volume of 419.3 cm^3 was placed on the soil surface and was pressed into the soil until the soil inside the cylinder was levelled with the top of the cylinder. The cylinder was removed and the soil core weighed, oven dried at 105°C for 24 hours and reweighed. Soil density was calculated using the following formula:

Density (g/cm^3) = Weight of dry soil (g) / Volume of the cylinder ($\pi r^2 h$)

In October, after the end of the experiment the soil was sampled in the experimental row but away from the drip tapeline where the fertiliser concentration would be expected to be much higher. Samples were taken beside plants used for yield determinations. Four soil samples for nitrate analysis, taken at 2 depths (0-30 and 30-60 cm) were mixed and a 300 g sub sample was frozen. Mehlich-III analyses were done on each of the phosphorus and potassium treatment. Four soil samples were taken at a depth of 0-20 cm in each plot these samples were mixed and a 300 g sub sample was air-dried. All soil analyses were conducted at the IRDA Laboratory of Agro-Environmental Analysis in Quebec City, QC, Canada. The Mehlich-III was analysed using the Inductively Coupled Plasma (ICP) method (McQuaker et al., 1979) and nitrate was analysed using the official method for the Province of Quebec; titrimetric analysis (CEAEQ and MAPAQ, 2003).

3.1.9.2.2 2010

Based on the 2009 results, a number of changes were made to the soil sampling protocol. Soil samples were dried 3 to 4 days after collection to prevent any modification in nitrate analysis results. During air drying the soil was mixed and sieved on a daily basis to ensure uniformity of the sample. Soil density samples were taken from test rows under the mulch at fruit set. At the end of season sampling was done mid-September.

3.1.9.3 Foliar sampling

Foliar sampling was done using a modified version of the protocol of Tremblay et al. (2001). The youngest fully expanded leaf from 4 tomato plants in the central experimental row was harvested from each plot. In Sainte-Anne-de-Bellevue, this was done on 19 July 2009 and 9 July 2010. In L'Assomption, the foliar sampling was done on 24 July 2009 and 20 July 2010. The leaves from all blocks were combined for a treatment sample. Leaves were chopped, weighed and 150 g were put in paper bags which were then oven dried at 70°C (≈24 hours) and reweighed. The method used by IRDA Laboratory for Agro-Environmentral Analysis in Quebec City, QC, Canada, was the Kjeldahl digestion method through wet sulphuric analysis (Persson, 2008).

3.1.9.4 Yield

Six tomato plants in the center four meters of the experimental row were harvested weekly. In Saint-Anne-de-Bellevue, in 2009, harvest started on 12 August and ended 17 October for a total of 11 harvests and in 2010; the tomatoes were harvested 5 times between 11 of August and 2 September. Between 25 August and 2 September, the field was infected with late blight (*Phytophthora infestans*). All fruit were harvested and the plants destroyed. In L'Assomption, harvest started on 26 August and ended 13 October for a total of 7 harvests, while in 2010, harvests started 11 August and ended 8 October for a total of 9 harvests.

In both field seasons, with the exception of the final harvest when all fruits were removed, fruit were harvested at the breaker stage when there was a definite change in color from green to pink or red on the blossom end of the fruit (Sargent and Moretti, 2002). Canadian standards (OMAFRA, 2011) were used to grade the quality of the fruit and grading for the size was based on Quebec fresh market tomato standards (Les Maraîchers P A Cousineau & fils, Sainte-Clothilde, QC, personal communication).

Fruits were classified as marketable or non-marketable. Marketable tomatoes were separated in two classes: 1st class, which had no or very little damage (i.e., less than 5 bacterial spots) was also separated according to size into two groups: small (6 cm to 7.6 cm) or medium-large (>7.6cm). The 2nd class had to be bigger than 6 cm, and fruits were categorized according to their damage (blossom-end rot, physiological, gray wall, uneven maturation, others). Fruits were judged non-marketable if less than 6 cm in diameter, damaged or diseased.

3.1.9.5 Sampling fruit biomass

In each block, five tomatoes were selected per plot, giving a total of 15 tomatoes per treatment. Once harvested, the tomatoes were quartered and a 500g subsample was put into Cryovac bag and oven dried at 70°C. Finally, the moisture and nutrient content were determined. In Sainte-Anne-de-Bellevue, in 2009, this was done on 8 September, and in 2010 it was done on the last harvest date on 2 September. In L'Assomption, it was done on 24 September 2009 and on 3 September 2010. The method of analysis used was the same as for the foliar samples.

3.2 Lycopene experiment

3.2.1 Fruit sampling and sample preparation in 2009

Six tomatoes per treatment per block were harvested on 8 and 23 September at the red-ripe stage, when more that 90% of the skin was red (Sargent and Moretti, 2002).Tomatoes were quartered and then blended for 3 minutes in a countertop blender. A 40±5 ml sample of the reconstituted tomato puree was transferred into a 50 m centrifuge tube (Fisherbrand, Non-sterile, Polypropylene, NJ, USA) and wrapped in aluminum foil to protect from exposure to light. Samples were then frozen at -20 °C. The samples were removed from the freezer the night before analysis to thaw and then were weighed.

The analysis was done according to a modified version of the protocol described by Sadler et al (1990). A 1±0.1 g of reconstituted tomato as weighed and put in a vial (30 ml, Fisherbrand, 25*95mm, screw thread with rubber-lined cap, NJ, USA). Then, 20 ml of hexane-acetone-ethanol (10:5:5) (EMD Chemical Inc., Gibbstown, NJ, USA) was added to the vial, which was mixed for 10 min on a shaking incubator (MaxQ4000, Thermo Scientific, orbital shaking speed 300rpm). Water (3 ml) was added followed by another 5 min of agitation. The solution separated into distinct polar (13 ml) and nonpolar (10 ml) layers. From the upper phase where hexane and lycopene are found, 1.5 ml was centrifuged (Micromax Thermo IEC, Needham heights, MA, USA) for 10 min at 10,000×g and then 1.0 ml was transferred to a High Pressure Liquid Chromatography (HPLC) vial (National Scientific, Rockwood, TN). Twenty μl was used for HPLC analyses.

Lycopene was separated by HPLC using a Varian system (Walnut Creek, CA, USA) equipped with a ProStar 210 solvent delivery system, a Model 410 autosampler, and a ProStar 330 PDA detector. Separation was carried out on a reverse phase column (5 μm, 4.6 × 250 mm, Phenomenex, Torrance, CA, USA). The flow rate of the column was 1.0 ml min^{-1}. Mobile phase used was a solution made of methanol: tetrahydrofuran (THF): water in a ratio of 67:27:6 (Fisher Scientific. Fair Lawn. NJ, USA). Detection was made at 447 nm. A lycopene standard (Sigma Aldrich, St. Louis, MO, USA) was diluted with THF stabilised with 0.025% Butylated hydroxytoluene (w/v) and used to prepare calibration curves. The content of lycopene in the samples was quantified based on the resulting curves.

3.2.2 Fruit sampling in 2010

Due to crop failure at the Sainte-Anne-de-Bellevue site, tomatoes used for lycopene analysis were taken from the L’Assomption site. Fruits were harvested at both the breaker and light-red stages on 17 September. Then they were left to ripen until they reached the red stage, 10 and 17 days.

3.3 Statistical Analysis

The experimental design in the field was set up as a randomized complete block design with split-plot restriction to facilitate fieldwork and allow for a smaller size field. The data was however analyzed as separate randomized complete block designs (RCBD) for each nutrient using the General Linear Model procedure (GLM) in SAS (v. 9.2, SAS Institute, Cary, NC, USA). Regression analyses were carried out using Proc REG in SAS (v. 9.2, SAS Institute, Cary, NC, USA). Linear and quadratic regression coefficients were tested. When the quadratic coefficient was significant, both linear and quadratic were kept in the equation. Statistical significance level was set at 0.10 for all tests. The treatment means for the soil samples post-harvest were separated using Fisher's protected least significant difference (LSD) test ($P<0.05$). The statistical significance of the differences between the onset soil tests and the post-season nutrients content of each fertilization treatment were also tested using Dunnett's test ($P<0.05$); the initial levels being used as the control.

Table 3.1 Weekly application of nitrogen fertiliser through fertigation to tomato (cv. Florida 47)

Week	Stage	Fertigation dose (%)	Treatment weekly dosage (kg N ha^{-1})			
			T1	T2	T3	T4
1	Transplant – first fruit	5	0	2	4	6
2		7.5	0	3	6	9
3, 4, 5, 6	First fruits - Harvest	37.5	0	3.75	7.5	11.25
7, 8, 9, 10	Harvest – End of August	50	0	4	8	12

Table 3.2 Weekly application of nitrogen fertiliser through fertigation according to different tomato (cv. Florida 47) growth stages

Week	Stage	Fertigation dose (%)	Treatment weekly dosage (kg N ha^{-1})			
			T1	T2	T3	T4
1, 2, 3, 4	Transplant to the formation of the first fruit	20	0	2	4	6
5, 6	Two (2) weeks after the formation of the first fruits	15	0	3	6	9
7	From the two weeks after the formation of the first fruits to the first weeks of harvest (5 weeks)	10	0	4	8	12
8, 9, 10		37.5	0	5	10	15

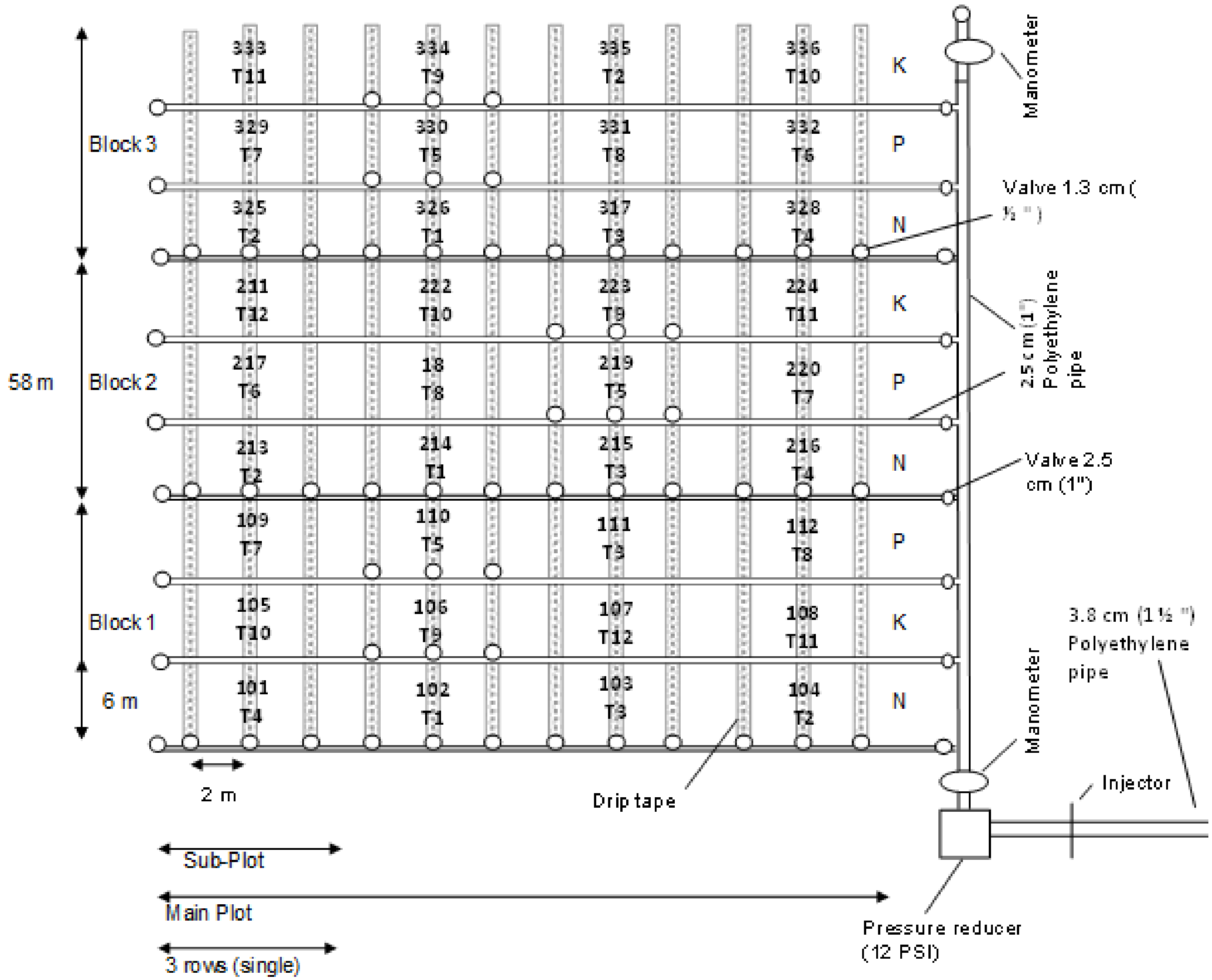

Figure 3.1: Layout of the tomato fertigation experiment located at McGill University, Macdonald Campus in Sainte-Anne-de-Bellevue, Quebec

4. Results and discussion

4.1 Fertilization Experiment

4.1.1 Nitrogen experiment

4.1.1.1 L'Assomption

The 2010 season was warmer and wetter than 2009 particularly at the end of the growing season (Table 4.5). Total precipitation was much greater in 2010 than in 2009. May and June of 2009 had more precipitation than in 2010 however, the rest of the summer and early fall were much dryer. In 2010, August and September had received almost 4 times more rain than 2009.

In 2009, increasing the nitrogen (N) fertilization level resulted in a slight but not statistically significant decrease in early yield (Table 4.1). Both in 2009 and 2010, the highest N rates produced the highest yield but these were not significantly different from the two lower rates (Table 4.1 and 4.2). In 2009, the early harvest of both the total and marketable yield represented close to a quarter of the total harvest (Table 4.1), while in 2010, the early harvests represented a little under half the total harvest (Table 4.2). This difference could be accounted for by the fact that there were 3 early harvest dates and 4 later dates in 2009 versus 3 early and 2 late in 2010.

Increasing N rates did not affect the percentage marketable yield for both 2009 and 2010. In 2009 the percentage marketable yield was greater than 80% while in 2010, it was lower; being 75% (Tables 4.1; 4.2). The lower marketable yield in 2010 could be in part explained by the high daily mean temperatures at the end of the first week of July. In fact, for 4 days the daily mean temperature was above 27°C, with maximum daily temperatures going up to 36°C and remaining above 30°C for almost 10 days in a row (Appendix B, Table 2). In growth chamber conditions, a reduction in fruit number and weight has been associated with increase in temperatures from 25 to 29°C (Peet et al., 1997). Similar effects have been observed with field tomatoes in Florida (Zotarelli et al., 2009).

At the onset of the 2009 experiment, the soil nitrate (NO_3^-) content at a shallow depth; between 0 and 30 cm, was significantly higher than at the end of the season (Table 4.3).

Fertilization levels affected soil NO_3^- content post-season as increases in N fertilization rates resulted in an increase of residual N. The three lower fertilization rate did not affect the NO_3^- content in the lower portion of the soil profile (30-60 cm), however significantly higher amounts of NO_3^- accumulated in deeper layers with the highest fertilization rate (170 kg N ha^{-1}). In 2010, there was no effect of level of N fertilization on shallow NO_3^- soil content, nor was there a difference in the contrast between pre- and post-season soil NO_3^- content at that particular depth; between 0 and 30cm. However, the fertilizer seemed to have penetrated the soil deeper as the post-season NO_3^- content was greater than at the onset of the season, except for the lowest application rate, which had comparable NO_3^- content to the onset content.

The foliar and fruit samples could not be analysed statistically as they were the result of pooling three repetitions per treatment. At fruit set, the foliar N content of the youngest fully mature leaf on a dry weight basis was similar among all treatments both in 2009 and 2010 (Tables 4.4). The N content in the foliar biomass of 2010 was slightly higher than in 2009. In 2009, the N levels were in the lower half of the N sufficiency rate at the time of early fruit set which is between 2.5–4 %, and in 2010, it was in the middle of the range (Maynard and Hochmuth, 2007). This sufficiency range was created to help farmers determine nutrient status of the crop during the season and make appropriate fertilization decisions to obtain adequate growth of the crop. As for the foliar biomass, the fruit N content on a dry weight basis did not seem to be affected by increasing N fertilization levels both in 2009 and 2010 (Table 4.4). The mean N content in the dried fruits was 1.8%.

The lack of variation in the foliar N accumulation at fruit set could be associated with a lack of variation in accumulation of N pre-sampling. From the anthesis of the fifth flower to the end of the onthogenic cycle, the leaves still require from 32 to 22% of the total N demand respectively (Tapia and Gutierrez, 1997). Sampling was prior to the fifth flower at the anthesis stage thus, it is possible that following sampling, N uptake varied with fertilization rates for the leaves. Considering that there could have been no effect on N content in leaves post-sampling and there was no difference in fruit N content, the uptake of N could have been similar for all the fertilizer treatments. The amount of fertilizer uptake would be between the range 50 and 90 kg N ha^{-1}. As applying 50 kg N ha^{-1} was associated with a post-season reduction in soil NO_3^- at a shallow depth, and fertilization of 90 kg N ha^{-1} and more, at a deeper depth, was associated with an accumulation of NO_3^- that could suggest leaching of excess fertilizer.

Regarding the soil NO_3^- content in 2009, a combination of two factors could explain the accumulation of NO_3^- with increasing fertilization rate at the shallow depth compared to the onset, while at a deeper depth only the highest fertilization rate affected the NO_3^- soil content. It is important to note that it is recommended to consider the first 60 cm of the soil profile since N can leach into deeper layers with precipitation (Schroder et al.,, 2000). The first factor to explain the distribution of NO_3^- is the rooting system. Although roots are mainly located in the first 30 cm, the tomato root system can reach a depth of 1.5 m (Jones, 2008). Therefore, the plant roots could easily have removed the N that had moved in the deeper layer, as the L'Assomption soil was a coarse textured soil, in which roots grow deeper (Wang et al., 2008). A second factor affecting NO_3^- distribution in the soil is the wetting pattern. There could also simply not have had enough water either from the rainfall or from fertigation / irrigation for the three lower application rates to leach the nutrients in the lower soil profile as it was the case with 170 kg N ha$^{-1.}$ This could be due to the higher N application, but could also be linked to the wetting pattern and the nutrient distribution in the soil during fertigation / irrigation. No nutrient can bind to sand, and NO_3^- being a negative ion it is not bound to clay particles, which have a negative surface; therefore NO_3^- moves with the water flow (Solomon et al. 2004). In a number of soil textures including coarse texture soil, it creates a higher concentration of NO_3^- at the boundary of the wetting pattern with almost no NO_3^- close to the source of N fertilizer application (Bar-Yosef and Sheilkhoslami, 1976; Li et al., 2003). In addition, it was shown that increasing volume of fertigation / irrigation did not affect the lateral spread of the water and NO_3^-; it did however increase the wetted depth (Li et al., 2003). This is especially important as in this experiment, there was only one mother solution for the fertigation and the difference between application rates was obtained by applying more or less of that solution, thus the treatments with the highest fertilization rates received a greater volume of solution.

In 2010, the weather conditions and more specifically the high rain pattern could partly explain the lack of variation in yield and N uptake by the plant, the accumulation of NO_3^- post-season at a deeper depth and finally, and the lack of difference in soil NO_3^- levels with increasing fertilization rates. It is most likely that there was some leaching. Sand particles that make up the major part of a coarse textured soil, as the one at the L'Assomption site, have very little retaining power on nutrients and allows the nutrients to move faster in and through the soil layers (Solomon et al., 2004). Rutkovienė et al. (2004) observed similar results and added that about 45% of the mineral N is leached out immediately upon application. In August 2010 there was 120 mm more of rain than in 2009 and September received 121 mm more than in 2009. This water moved the NO_3^- through the soil profile into the deeper layers where it accumulated. The risk of leaching happening in a coarse textured soils when high N rates is combined with intense precipitation is high and not uncommon (Bergstrom and Brink, 1986; Knox and Moody, 1991; McNeal et al., 1995; cited in Zotarelli et al., 2007). Even though the rainfall in 2010 was high, the initial soil NO_3^- content as well as the applied N were high enough to maintain a high NO_3^- content in the upper soil layer.

4.1.1.2 Sainte-Anne-de-Bellevue

In Sainte-Anne-de-Bellevue, for both years, the fresh market tomato yield was not affected by increasing N application rates (Tables 4.6 and 4.7). Although not significant, a maximum yield of 79 Mg kg^{-1} was produced with an application rate of 130kg N ha^{-1}. As in L'Assomption, the early harvests in 2009 represented about half the total harvest for both the marketable and yield (Table 4.6), while in 2010, it represented less than a sixth of the marketable and total yield (Table 4.7). This difference can be explained by the difference in the number of harvests between the two years. In 2009, there were five harvests for the early harvest and an additional six harvests were made to sum at eleven total harvests. Since there was one more harvest done in the later part of the season, and the early harvest represents half the total harvest, it implies that the early harvests had a slightly higher yield than the later ones.

In 2009, the percentage of marketable yield was higher early in the season and reduced in the later part of the season as the total harvest had a slightly lower marketable yield percentage (Table 4.6). This can be explained by the last harvest which represented between 21 and 62% of the total yield (data not shown). At the time of the last harvest the tomatoes were all green and had suffered cold injury and were considered unmarketable.

The 2010 season ended abruptly, as the field was infected with late blight *(Phytophthora infestans*). The development of the disease is favoured by high humidity and warm days and cool nights (Howard and al., 1994). The higher temperatures, precipitation and humidity that characterised the 2010 season (Table 4.8) were the perfect conditions for spreading diseases, including late blight (Gabor and Weibe, 1997). In fact, fruits with the first signs of late blight were harvested on August 18th. The disease produces brownish black lesions on the stem and petioles. The fruit had brownish-green lesions and a greasy rough appearance. The symptoms appeared about a week and a half after the site had received over 70mm of rain in one day and the mean temperature never dropped below 15°C (Appendix B, Table 4). Two weeks after the first fruit was diagnosed, the entire field was infected. The disease is known to spread quickly and the spores can travel long distances by wind (Jones, 1999; Heuvelink, 2005).The remaining tomatoes were harvested in a final total harvest.

In 2010, the last harvest date (September 2nd) represented between 72 to 96% of the total tomato yield (data not shown). It represented such a high portion of the yield due to the fact that it was done earlier in the season, when the yield was close to the maximum and included all the tomatoes as it was the final harvest (due to the late blight). Yet, the yield was much lesser in 2010 than in 2009 because the last harvest was so early in the season; it was in early September instead of mid-October. The high percentage of marketable yield was due to the fact that for the last total harvest marketable tomatoes with late blight were still classified as marketable even thought they were infected with the disease (Table 4.8). This was done to better represent what the yield would have been had the late blight not happened.

At fruit set, the youngest fully mature leaves of all treatments had similar N content for both years (Table 4.9). In 2009, the mean of the treatments (3.8 % DW) was slightly lower than in 2010 (4.0 % DW). These N percentages were at the higher end of the limit of the adequate rang (2.0-4.0 %) of the N content (Maynard and Hochmuth, 2007, Kelley and Boyhan, 2010). Nitrogen fertilization continued after the sampling period, this could possibly result in luxury consumption of this nutrient. High N fertilization is associated with increased vegetative growth. In turn, this often leads to increased disease in the crops and can also lead to a reduction in yield (Jones, 1999, Heuvelink, 2005). The N content of fruits DW was similar amongst N treatments. In 2009 there was 1.9% N while in 2010 it was approximately 2.7 %. There was higher accumulation of N in the tomato plant grown at the Sainte-Anne-de-Bellevue site than in the L'Assomption site in 2009 (Tables 4.4 and 4.9). This could be due to the higher N soil content, which facilitated the uptake of the nutrient. It seemed that the N content in the dried fruits was higher in 2010 than 2009. This is in conjunction with Davies and al (1981); that ammonium-N content decreased with ripeness increasing. In 2010, the fruit biomass was sampled at the final harvest. Some of the tomatoes that were used for the fruit biomass were still at the green and yellow green stage. Thus, the fruits in 2010 were less ripe, than the ones that were harvest in 2009 at breaker stage.

In 2009, increasing N application rate from 50 to 170 kg ha^{-1}did not affect the NO_3^- content of the soil, nor did it change from the onset (Table 4.10). However, there was an accumulation of NO_3^- in the shallow layer of the soil profile. This accumulation was not affected by the fertilization rate as Dunnett's test showed that there was no significant difference in the contrast between the soil NO_3^- content of each N application rates and the one from the onset. Similarly, in 2010, at the deeper layer, there was an accumulation of NO_3^- that was not affected by the fertilization rate. At a shallower depth, there was a significantly higher accumulation of NO_3^- when 50 kg N $ha^{-1}$was applied, however, it was not significantly different from the NO_3^- soil levels with higher N fertilization rates.

In 2009, there was most likely not enough water either in the form of precipitation and fertigation / irrigation to have the NO_3^- move into the deeper layers. In fact, there was less precipitation in the later part of the summer in 2009 (Table 4.8), which could have caused $NO3^-$ to remain in the shallow part of the soil. The 2010 soil NO_3^- results can partially be explained the fact that sampling was done early in the season when fertigation was still ongoing and was at the highest concentration of N application (Table 3.6). It could also be attributed to the movement of the NO_3^-, which follows the water flow and accumulates towards the boundary of the wetting pattern. This was also observed in loamy textured soil by Li et al., (2003) who noted that using ammonium nitrate fertilizer, applying a smaller volume of ammonium nitrate resulted in a higher concentration of NO_3^- at the boundary of the wet front. This could partly explain why solely the lowest N rate had a significant accumulation of NO_3^- and although not significant, there seemed to be a decrease in NO_3^- with increasing fertilization in the shallow layer. There was also an accumulation of NO_3^- in the deeper layers, which could be linked to the flushing duration and the fertigation-irrigation sequence. For the experiment, eliminating the water variable between all the treatments implied adjusting their water application post-fertigation. Flushing is essential to clean the system, however, it should not be excessive as this leads to nutrient leaching. In fact, the optimum duration should be half the time of the duration of fertilizer injection (Fares and Abbas, 2009). The fertigation strategy used impacts the distribution of NO_3^- in the soil (Li et al., 2004). Li and coworkers (2004) tested four combinations of fertigation –irrigation; they obtained the most NO_3^- in the shallowest part of the soil profile with: (1:2:1) water–fertigation–water, followed by (1:2:1) fertigation–water–fertigation, (1:4:3) water–fertigation –water. Finally, the combination that had the least amount of NO_3^- in the 0-20cm depth was (1:1) fertigation–water. In contrast, at a depth of 20-30cm, the order of the combinations that had the most NO_3^- were opposite to that at the 0-20 cm depth. Hanson et al, (2005) had similar results; less NO_3^- leached when injection time was at the end of a long irrigation period rather than at the beginning or the middle of it. Since in Sainte-Anne-de-Bellevue, the irrigation water was added post-fertigation, it allowed the NO_3^- to move deeper in the soil profile. Also, Sogbedji et al., (2000) found that the concentration of NO_3^- leached was high and not affected by the fertilizer application rate when the field had high NO_3^- soil levels; this was for both a clay loam soil and a loamy sand soil.

The extractant (2M KCl) used for the N soil analysis content not only extracts NO_3^- but also exchangeable ammonium (NH_4^+) (Griffin et al., 2009). In this experiment, only the NO_3^- was quantified (Tables 4.3 and 4.10). However, there is more N in the soil in the form of exchangeable NH_4^+ ions and organic N. There is therefore even more N in the Sainte-Anne-de-Bellevue site than the L'Assomption site due to the soil texture. In fact, L'Assomption in 2009 had at the onset 6.3% of the soil that was N; in Sainte-Anne-de-

Bellevue it represented 20% of the soil (data not shown). In 2010, in L'Assomption the total N was similar (6.2%) while in Sainte-Anne-de-Bellevue it was slightly lower; 17% (data not shown). Fertilizers with NH_4^+ as the major source of N can be toxic to plants or even cause blossom end rot (Dekock et al., 1979; Jones, 1999), however, NH_4^+ is the form of N that is more readily uptaken by the plants benefiting its initial stages of growth and development (Jones, 1999). The fertilizer used in this experiment was ammonium nitrate, thus there would be no counter effect due to NH_4^+ being the major source of N. Also, the initial soil N content was higher in Sainte-Anne-de-Bellevue than in L'Assomption, thus, the higher NH_4^+ content could help increase the initial growth of the plant, thus giving a higher yield.

As mentioned previously, the NO_3^- concentration is higher towards the wetting boundary (Li et al., 2004), on the other hand, NH_4^+ is higher in concentrations close to the source of N. This is due to the binding action of the positively charged ion to the negatively charged exchange sites on the clay. This is important considering the soil texture at the Sainte-Anne-de-Bellevue site, which had a considerable amount of clay.

The high soil N background in Sainte-Anne-de-Bellevue, could explain the lack of effect increasing N fertilization had on the yield. It is possible that the soil was sufficient to answer to the plant demand and any added fertilizer was surplus fertilizer. A study similar to the current one was published by Heeb and coworkers (2005) who showed that applying more than 750 mg N plant^{-1} week^{-1} did not significantly increase the marketable yield of tomatoes plants grown in plots in a greenhouse. In the current experiment, from the beginning of fertigation, the highest fertilization rate of the first fertigation stage (Table 3.1 and 3.2), had a rate that corresponded to a higher rate than 750 mg N plant^{-1} week^{-1}. In fact, applying 5.5 kg ha^{-1}week^{-1} corresponds to 750 mg N plant^{-1} week^{-1}. Therefore, from the second set of rates, the highest two fertilization rates were above the 750 mg N plant^{-1} week^{-1}. This could explain why there is no increase in the marketable yield for these application rates in both 2009 and 2010, this is the case for both the L'Assomption and Sainte-Anne-de-Bellevue site. Another study by Magdoff et al., (1990) established that with higher soil N levels than 20-30 mg N kg^{-1} there was rarely any yield improvement in corn production. Considering that the fertilizer recommendations for tomatoes in Quebec is 135 kg N ha^{-1} and corn is between 120 and 170 kg N ha^{-1} (CRAAQ, 2003). The requirement for tomatoes represents the lower part of the corn recommendations; thus this soil fertility could be representative for tomatoes as well. In this case, the Sainte-Anne-de-Bellevue in 2010 is close to 20 mg N kg^{-1} (Table 4.10), which could explain why there was no improvement in yield.

One important point that has to be taken into consideration is that there was no control or zero application of N since there is always a 50 kg N ha^{-1} preplant application. In Sainte-Anne-de-Bellevue both years, there was a lot of vegetative growth, more than in L'Assomption (data not shown). This could indicate that there was over fertilization of N, which has been shown to at times result in no significant increase in yield (Grant et al., 2004). Thus, having a control, no N applied regardless of the method of application could perhaps show effects on the yield. Since there was no response to the fertilization range used, it should be expanded to not only include a zero fertilization control treatment, but also higher application rates. The current yield results show no effect to N application rate, even with the highest application rate there is no optimum, plateau or reduction in the yield as there would be in the case of an over application of N. These responses would happen if the fertilization rate was so high that the plant uptake was directed towards vegetative growth instead of reproductive growth and thus affecting the yield (Heeb et al., 2005). In addition, some studies have shown that fertigation can require more N than the conventional fertilization method (Zhang et al., 2010 a, b). The plant demand in N increased due to the increase in yield caused by the use of the fertigation method.

A gross range of the yield for fresh market field tomatoes is between 28 and 90 Mg ha^{-1} (Heuvelink, 2005; Jones, 2008). The mean fresh-market tomato yield in the United States is 31 Mg ha^{-1} (USDA, 1997; Maynard and Hochmuth, 1997; cited by Jones, 2008). Cultivar choice, climatic factors, soil characteristics, management practices, etc. are some of the factors that explain the wide range in the yield (Jones, 2008). Adding new best management practices and new technologies improved the yield. For example, using drip irrigation, polyethylene mulch and fertigation, Abdul-Baki and Spence (1992) reported yields of 84 t FW ha^{-1} (76 Mg ha^{-1}) for fresh market field tomatoes on a sandy soil with 90 kg N ha^{-1}.

A three-year experiment on sandy soil in Florida tested three N rates (176, 220, 230 kg N ha^{-1}) fertigated in fresh-market tomatoes (Zotarelli et al., 2009). The cultivar used was Florida 47, the same as for this study. Applying higher fertilization rates than 176 kg N ha^{-1} had no effect on the yield. However, an increase in the yield was noted over the years. The first year, the yield of the three fertilization rates was between 31 and 35 Mg FW ha^{-1} and increased to 73 and 85 Mg FW ha^{-1} in the last year. The difference in yield over the years was attributed to differences in climatic factors: rainfall, temperature and solar radiation. This difference in the yield can be compared to the ones in this study. In L'Assomption, in both 2009 and 2010, the yields are low yet not as low as in 2005 in Florida which used the same cultivar on a similar type of soil with higher rates of N fertilization that in this experiment. However, high yields were also obtained in Sainte-Anne-de Bellevue in 2009; the best yielding year (71 to 79 Mg FW ha^{-1}) of the two years for this site was within the range of Zotarelli's highest yielding year (73 to 85 kg N ha^{-1}). The climatic conditions as well as soil characteristics associated with the two sites and years created the variation in the yield over the years and sites.

Table 4.1 The effect of nitrogen fertilization levels on early and total tomato yields in 2009 in L'Assomption

Treatment (kg N ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
50	13087	11522	88.0
90	12912	10532	81.6
130	12300	11561	94.0
170	8891	7314	82.3
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvest			
50	53099	43303	81.6
90	54263	41967	77.3
130	55614	43593	78.4
170	58556	45269	77.3
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.2 The effect of nitrogen fertilization levels on early and total tomato yields in 2010 in L'Assomption

Treatment (kg N ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
50	23400	15779	67.4
90	20537	15662	76.2
130	25285	19937	78.9
170	27168	21004	77.3
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
50	44009	29404	66.8
90	46410	33696	72.6
130	57017	41300	72.4
170	64267	46154	71.8
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not signifiant

Table 4.3 The effect of nitrogen fertilization levels on foliar and fruit biomass of tomato in L'Assomption for 2009 and 2010

Year	Treatment ($kg\ N\ ha^{-1}$)	N (%)	
		Foliar +	Fruit ++
2009	50	2.53	1.48
	90	3.12	1.85
	130	2.81	2.04
	170	3.53	1.84
2010	50	2.94	1.85
	90	3.36	1.73
	130	3.47	1.88
	170	3.09	1.78

+ At fruit set, on a dry weight basis
++ At harvest, on a dry weight basis

Table 4.4 The effect of nitrogen fertilization levels on foliar and fruit biomass of tomato in L'Assomption for 2009 and 2010

Year	Treatment ($kg\ N\ ha^{-1}$)	N (%)	
		Foliar +	Fruit ++
2009	50	2.53	1.48
	90	3.12	1.85
	130	2.81	2.04
	170	3.53	1.84
2010	50	2.94	1.85
	90	3.36	1.73
	130	3.47	1.88
	170	3.09	1.78

+ At fruit set, on a dry weight basis
++ At harvest, on a dry weight basis

Table 4.5 Average temperature (° C) and precipitation (mm) May to September during the 2009 and 2010 growing seasons in L'Assomption Quebec

Month	Temperature (° C)		Precipitation (mm)	
	2009	2010	2009	2010
May	13.2	15.2	92.2	44.4
June	17.5	17.7	130.2	109.6
July	18.9	22.4	119.0	128.2
August	20.0	19.9	49.2	166.4
September	14.7	15.2	40.0	161.1
Seasonal Mean	16.9	18.1	86.1	146.3

Table 4.6 The effect of nitrogen fertilization levels on early and total tomato yields in 2009 in Sainte-Anne-de-Bellevue

Treatment (kg N ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
50	39660	31932	80.5
90	41456	35611	85.9
130	40740	31827	78.1
170	40259	33839	84.1
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
50	71388	50821	71.2
90	72237	54703	75.6
130	79487	49876	62.7
170	77172	50456	65.4
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.7 The effect of nitrogen fertilization levels on early and total tomato yields in 2010 in Sainte-Anne-de-Bellevue

Treatment (kg N ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
50	5015	4318	86.1
90	3434	2611	76.0
130	4899	2770	56.6
170	2392	1744	72.9
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
50	41481	35456	85.5
90	43237	36131	83.6
130	40230	32439	80.6
170	42995	37849	88.0
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.8 Average temperature (° C) and precipitation (mm) May to October during the 2009 and 2010 growing seasons in Sainte-Anne-de-Bellevue, Quebec

Month	Temperature (° C)			Precipitation (mm)		
	2009	2010	Avg 1971-2000	2009	2010	Avg 1971-2000
May	12.2	15.4*	16.2	79.0	33.8*	71.4
June	17.4	18.0	18.1	68.8	160.4	88.6
July	19.5	22.5	21.0	127.6	60.6*	93.6
August	20.1	20.2	19.8	81.6	162.6	104.2
September	14.5	15.8	14.6	42.8	157.6	96.0
October	6.7	8.5*	8.1	99.6	90.0*	77.2
Seasonal Mean	15.1	16.7*	15.8	83.2	110.8*	88.5

*Estimated

Table 4.9 The effect of nitrogen fertilization levels on foliar and fruit biomass of tomato in Sainte-Anne-de-Bellevue for 2009 and 2010

		N (%)	
Year	Treatment ($kg\ N\ ha^{-1}$)	Foliar +	Fruit ++
2009	50	3.85	1.76
	90	3.5	1.84
	130	3.38	1.95
	170	3.97	1.94
2010	50	3.94	2.85
	90	3.88	2.55
	130	4.11	2.36
	170	4.00	2.86

+ At fruit set, on a dry weight basis
++ At harvest, on a dry weight basis

Table 4.10 The effect of nitrogen fertilization levels on nitrate content ($mg\ NO_3^-\ kg^{-1}$) at two depths of soil in Sainte-Anne-de-Bellevue for 2009 and 2010

Treatment ($kg\ N\ ha^{-1}$)	Nitrate content ($mg\ NO_3^-\ kg^{-1}$)			
	2009		2010	
Depth	0-30 cm	30-60 cm	0-30 cm	30-60 cm
	Pre-season			
Main plot	6.83	3.36	15.6	7.4
	Post-season			
50	14.26 n/s	5.47 n/s	44.9 n/s *	14.4 n/s
90	8.53 n/s	6.24 n/s	32.6 n/s	23.8 n/s
130	12.32 n/s	4.66 n/s	31.9 n/s	16.1 n/s
170	13.06 n/s	3.51 n/s	30.7 n/s	13.4 n/s

Method of analysis: KCl 2 M
Post-season means followed by different letters are significantly different (P< 0.05)
* indicates a significant difference in the comparison of post-season treatments against the pre-season (p< 0.05)
n/s : not significant (Refers to the comparison of N treatments post-season)

4.1.2 Potassium Experiment

4.1.2.1 L'Assomption

A quadratic regression (Figure 4.1) describes the 2009 fresh market tomato yield response to potassium (K) fertilization. The yield increases from 57 to 62 Mg FW ha^{-1} with increasing potassium application rates from 40 to 160 kg K_2O ha^{-1} (Table 4.11). A further increase in fertilization resulted in a reduction in the yield to 55 Mg ha^{-1}. An estimated maximum yield of 61Mg ha^{-1} would be obtained with an application rate of 149 kg K_2O ha^{-1}. Similar results were obtained for marketable yield (Figure 4.2). The marketable yield increased from 46 to 52 Mg FW ha^{-1} with increasing application rates from 40 to 160 kg ha^{-1}; further increase in the fertilization resulted in a reduction in yield to 46 Mg ha^{-1} with 280 kg K2O ha^{-1} (Table 4.11). The estimated maximum would be 51 Mg ha^{-1} with an application rate of 162 kg ha^{-1}. However, in 2010, both the marketable and total yield did not respond to increasing K_2O rates (Table 4.12).

It was observed in the nitrogen (N) experiment that the early yield in 2009 represented close to 25% of the total harvest while in 2010 it represented a little under 50% (Tables 4.1 and 4.2). For the K experiment, similar results were observed. In 2009, early yield represented between 15 and 23% (Table 4.11) while in 2010 it was between 45% and 61% of the total harvest (Table 4.12). The difference can be attributed to the number of early and late harvests of both years. Even considering this, the early harvest had a much smaller yield than the later harvests. This is linked to the biomass production curve of a tomato plant, which follows a sigmoid pattern in time. First it follows an exponential growth phase with a constant relative growth rate followed by a linear growth (Heuvelink, 2005).

For the 2009 early yields and the 2009 and 2010 total yields, the percentage marketable yield was not affected by the increasing rates of K_2O fertilization (Tables 4.11 and 4.12). Marketable yield accounted for 90% of the early yields and 82% and 70% of the total yields for 2009 and 2010, respectively (Table 4.11). In 2010, the early percentage of marketable yield had a quadratic response to increasing K fertilization rates (Figure 4.3). The percentage marketable yield increased from 76 to 83% with increasing fertilization rates from 40 to 160 kg K_2O ha^{-1}; further increase in fertilization resulted in a decrease in the marketable percentage (Table 4.12). An estimated maximum marketable percentage of 83% would be obtained with an application rate of 170 kg K_2O ha^{-1}.

In 2009, applying 40 kg K_2O ha^{-1}; the lowest fertilization rate, resulted in lower K available post-season compared with the initial level (Table 4.13). In addition, increasing K application rates resulted in a significant increase of soil K levels. Potassium levels in the soil can have an influence not only on the K concentration in the crop; it also influences the uptake of other nutrients such as calcium (Ca) and magnesium (Mg) (Marschner, 2011). In fact, for a number of crops including tomatoes, inappropriate K fertilization levels can lead to the deficiency of these nutrients (Kabu and Toop, 1970; Pujos and Morard, 1997; Gunes et al., 1998). Thus, the need for their analysis is especially justified for this experiment. Applying increasing levels of K did not affect the soil Ca content nor was there a difference between the Ca soil content post-season from the onset of the experiment. This lack of effect could be linked to the fact that Ca was applied weekly at a rate of 5 kg ha^{-1} starting at first fruit set. Using Dunnett's test, Mg levels post-season were found to be significantly lower than the level at the onset of the experiment. However, Mg soil levels were not affected by increasing K fertilization rates. In 2010, K application rates showed no effect on the K, Ca and Mg levels (Table 4.13). Nor was there a difference between the initial levels and the post-season levels of each of the three nutrients.

The foliar and fruit samples from three repetitions per treatment were pooled and therefore could not be analysed statistically. In 2009, the leaf K content was overall slightly lower than in 2010 (Table 4.14). However, for both years, there seemed to be an increase in K content with increasing K fertilization. The Ca level in the leaves was similar for all the K fertilization rates. In 2009, the Mg level in the leaves decreased with increasing K fertilization. This was not observed in 2010. The K levels obtained at the L'Assomption site were compared to the sufficient nutrient rate for adequate plant growth and production; in 2009 it was below the sufficiency range of 2.5-4% (Maynard and Hochmuth, 2007), and in 2010 it was within the range. This could be due to initial soil levels being low. The Ca levels for the highest K fertilization rates were lower than the sufficiency range (1.0-2.0 %) and for the lower K rates were at the lower limit of the range. Finally, the Mg levels seemed to decrease in concentration with increasing levels of K. The lowest percentage was at the limit of the sufficiency range of 0.3%. In 2009, there seemed to be a slight increase in K and Mg dried fruit content with increasing K application rates. These trends were not observed in 2010. The Ca content of the dried fruits for both 2009 and 2010 was similar among t the K treatments.

In 2009, the highest yield was obtained with the second highest potassium fertilization rate; 160 kg K_2O ha^{-1} (Figure4.1). At that same rate, K soil levels started to accumulate and the higher rate resulted in significantly higher residual K (Table 4.13). Also, similar results were found for the foliar K content (Table 4.14). In 2010, there was a similar although not significant trend. This suggests that with this particular site and environmental conditions, applying 160 kg K_2O ha^{-1} would give the maximum yield. This K application rate is lower than the recommendation for the Province of Quebec for 200 kg K_2O ha^{-1} for soil with K levels between 101 and 200 kg ha^{-1} which included the soil K level in 2009 (155 kg K ha^{-1}) and in 2010 (147 kg K ha^{-1}) (CRAAQ, 2003). It is however, higher than the 0-120 lb $acre^{-1}$ (0-134 kg ha^{-1}) of K_2O recommended in California. This recommendation can be increased to 60 to 220 pounds per acre (67-224 kg ha^{-1}) when ammonium-acetate-extractable potassium was less than 150 ppm. This would be equal to 156 ppm (or 156 mg kg^{-1}) with the Mehlich3 extraction method, as it was the case in this experiment. This value is less than what was obtained both in 2009 and 2010 at the onset of the experiment thus, the fertilization recommendation would be between 67 and 224 kg ha^{-1} for the L'Assomption site (Le Strange et al. 2000), which included 160 kg ha^{-1}. It can be hypothesized that important K losses to leaching would happen with the higher application rate than the 160 kg K_2O ha^{-1}. Also, lower application rates than 160 kg K_2O ha^{-1} would not be sufficient for the plant demand. In fact, this was observed when the foliar K content was at the lower limit of the sufficiency range, and the yield that was not optimal. It was also shown in 2009 as there was a decrease in the K soil content compared with that at the onset of the experiment.

It has been found that outdoor tomato crops that yield between 40-50 t ha^{-1} (40 000-50 000 kg ha^{-1}) have a K demand between 150 and 300 kg K_2O ha^{-1} (67-133 ppm K_2O) (Halliday and Trenkel, 1992 and Jones, 1999; cited by Heuvelink, 2005). Using these numbers (which might not be the same values as for this experiment as we do not have the total vegetative uptake of each nutrients), as well as the fertilizer application rate and the soil K levels in the soil at the onset and post-season, a “loss” nutrient amount can be estimated. By adding the onset soil K content to the added fertilizer application rate, a total available K was obtained. By subtracting from this we value the soil K content post-season we can estimate the K that has either been up taken by the plant or lost In 2009, this value ranged from 57 and 117 mg K_2O kg^{-1} with increasing K application rate. Since, the plant K removal range is between 67-133 mg kg^{-1}, for the lower application rates, there was not much potassium loss and the loss increased with increasing application rates. Sandy soils are prone to have more leaching than a loamy or clay soil (Askegaard and Eriksen, 2000; Ulen, 1999; cited in Alfaro et al., 2004; Maynard and Hochmuth, 2007). However, it was noted that the fruit K content in 2010, seemed to increase with increasing potassium fertilization rate, this could therefore reduce the lost K as it would be up taken by the crop.

Soil Ca levels were not affected by increasing K fertilization levels due to the fact that starting at fruit set calcium fertilization (5 kg ha^{-1}) was done on a weekly basis. The lack of accumulation of Ca in the soil could imply that it was completely taken up by the plants and/ or be lost through leaching. Calcium is immobile in plants, and there is a very limited amount of this nutrient that is translocated from the leaves to the fruits (Heuvelink, 2005). Therefore, it gives information on the current state of the nutrient in plants, but does not allow us to draw any conclusions on fruit Ca content. The foliar samples (Table 4.14) contained sufficient amounts of Ca. In fact, Maynard and Hochmuth (2007) noted that is difficult to relate crop removal values to fertilizer requirements due to the fact that more often than not, these types of plant analysis are done on sites that have very fertile soils. This can be misleading as the plant are then subjected to more than enough nutrients from the soil itself and added nutrients in the form of fertilizer will be taken up as a “luxury consumption”. This leads to an overestimation of the true crop removal values and plant nutrient requirement. Calcium soil levels for both years were low. Yet, even with the smaller foliar Ca content, it is possible that is it more than enough go the plant need. Also, the weekly Ca fertilization reduced the likelihood of having a shortage of Ca in the fruit (Table 4.14). There is also the high possibility that some Ca was leached, since there was already sufficient Ca content at the time of foliar sampling and following that, Ca was added on a weekly basis. Calcium cations represent 90% of the cations being leached into the ground water followed by Mg, K and sodium (Na) cations respectively in a sandy soil (Hansen & Pedersen, 1975; cited in Jakobsen, 1993). Plant uptake or leaching could also have been associated with the soil Mg levels which were significantly lower than the onset levels for 2009 and was found as a trend in 2010; especially as no Mg fertilizer was added.

Heuvelink (2005) compiled data from Halliday and Trenkel, 1992, Jones, 1999, and OMAFRA, 2001, concerning nutrient demand and uptake from tomatoes grown outdoor (yield 40-50 t ha^{-1}) and in the greenhouse (100 t ha^{-1}). There was no value for Ca uptake of outdoor tomatoes while for the greenhouse crop it was 45 kg ha^{-1}. Magnesium uptake was 20-30 kg ha^{-1} (11.4 ppm) outdoor and 290 kg ha^{-1} for greenhouses. This Mg uptake for the outdoor crops is about the same as the difference between onset and post-season Mg soil levels for the 2010 season. This could suggest that no Mg was lost through leaching. In 2009, the difference was more than 11.4 ppm, which could imply leaching. The rainfall pattern is a possible explanation for the difference between the two years. In 2009, the first two months had much more rain than 2010for the same months (Table 4.5). This period of time was when the plants were either yet transplanted or very small and when nutrients are more likely to be leached due to the limited retention from the roots and the nutrient demand. Similar results were observed with broccoli and an N preplant fertilizer (Feller and Fink, 2005).

4.1.2.2 Sainte-Anne-de-Bellevue

There was no effect of increasing K fertilization rates on the early and total yields of fresh market tomatoes grown at the Sainte-Anne-de-Bellevue site for both 2009 and 2010 (Tables 4.15 and 4.16). The fertilization rates tested in Sainte-Anne-de-Bellevue: 0, 20, 60 and 120 kg K_2O ha^{-1} were lower than the ones in L'Assomption: 40, 80, 160 and 280 kg K_2O ha^{-1}. This was due to the pre-sampling soil potassium levels, which were considered high in Sainte-Anne-de-Bellevue and low in L'Assomption. This is a typical approach for K and P fertilization; when the soil levels are high to reduce the application rates (Heuvelink, 2005).

As it was the case in the N experiment (Tables 4.1 and 4.2), in 2009, the early yield represented about half the total harvest, while the early marketable yield represented 60% of the total marketable yield (Table 4.15). In 2010, the early harvests represent less than 14% of the sum of both the total and marketable yield (Table 4.16). The difference between the years could be partly due to the difference in the number of harvests at make up the early and late harvests as it was described in the N experiment. As well as the loss of the field early in the season due to late blight in 2010.

In 2009, the percentage of early marketable yield had linear regression response to increasing in K fertilization (Figure 4.4). The percentage of marketable yield increased from 78 to 89% with increasing K fertilization rates from 0 to 60 kg ha^{-1}; further increase in the fertilization rate resulted in a slight reduction in the percentage to 85% (Table 4.15). This effect was not found for the total of the harvests of that year. The later harvest had a 20% lower marketable percentage than the early harvest. In 2010, it was the opposite effect , the early harvest had a lower marketable percentage than the later harvests (Table 4.16). Also, it was not affected by increasing K fertilization rates.

Sainte-Anne-de-Bellevue had higher levels of soil K, Ca and Mg levels (Table 4.17) than in L'Assomption (Table 4.13). In fact, the onset K levels for both years were above 150 mg kg^{-1} (160 and 190 kg K_2O ha^{-1} for 2009 and 2010 respectively). In California, it was noted that a yield response to soil levels higher than 150 mg K_2O kg^{-1} was unlikely (Reisenauer, 1979; Maynard and Hochmuth, 2007). In both years, the K, Ca and Mg soil levels were not affected by increasing K fertilization levels, nor were they found to be different from the onset levels. The lack of effect on the yield as well as soil nutrient levels associated with increasing K fertilization could imply that initial soil fertility levels were sufficient for the plant demand and may not have needed additional K fertilization (Maynard and Hochmuth, 2007). In that case, any additional fertilizer would either be taken up by the plant as an extra (Maynard and Hochmuth, 2007) or lost from the soil (Jakobsen, 1993).

Yet, in Quebec (CRAAQ, 2003) for a soil K level of 165.3 mg kg^{-1} (or 370 kg ha^{-1}) which is considered medium K soil fertility, the recommendations is to apply 120 kg K $ha^{-1}$and for 191.0 mg K kg^{-1} (or 427 kg K ha^{-1}); an adequate range, to apply 80 kg ha^{-1}.

Therefore, in both years following the current recommendations the soil seemed to have been over fertilized. The K content of the youngest fully matured leaf at fruit set ranged between 25 and 32 and 31-34 g K kg^{-1} for 2009 and 2010 , respectively (Table 4.18). The levels were within the lower half of the K sufficiency range, which is between 2.5-4.0% (Maynard and Hochmuth, 2007). For both years there did not seem to be any trend in the accumulation of K with increasing fertilization rates. In 2009, the Ca levels in the leaves were found to be in the lower half of the sufficiency range for Ca (1.0 - 2.0 %) and did not seem to be influenced by the K application rates. However, in 2010, although not significant, both Ca and Mg levels increased with increasing K levels from 0 to 60 kg K_2O ha^{-1}; then decreased. The Ca content was slightly below the middle of the sufficiency range and the Mg content was well within the sufficiency range (0.25-0.50%). The dried fruits harvested in the fall of both years showed similar K and Mg content among the different rates of K fertilization. Similarly, in 2009, the Ca content was affected by increasing K rates. However, in 2010, there seemed to be an increase in the Ca content. Potassium did not appear to be accumulated in the plants in different concentrations spending on the K fertilization application rates. Therefore, there is a possibility that the K added was lost.

Potassium is a cation that is not considered mobile in the soil (Maynard and Hochmuth, 2007). Thus, in order for leaching to occur, the soil needs to be either have an unfavorable activity ratio of K and Ca as the soil depth increases or if the soil is saturated in K (Jakobsen, 1993). In this experiment, it was impossible to know if the activity ratio of K:Ca was favorable for leaching, as the soil samples were done only at one depth. On the other hand, unless it is in a saturated state, Ca, Mg and Na will be leached out of the soil prior to K as they bind to the soil to a lesser extent. The Mehlich 3 method, which was used in the current experiment, allowed us to quantify only the extractable or plant available macro- and micro-nutrients. It could be hypothesised that the more K, Ca and Mg detected the more likely the soil is already saturated and what was detected were ions that were not able to cling to the soil particles. The levels of K, Ca and Mg were higher in Sainte-Anne-de-Bellevue than in L'Assomption (Table 4.13, 4.17). All K, Ca and Mg ions were in their exchangeable state, it is therefore more likely to have saturation of the soils with each of these ions.

As mentioned previously, it has been evaluated that an outdoor tomato crop that produces a yield between 40 and 50 Mg ha^{-1} will take up K and Mg in the range of 150-300 and 20-30 kg ha^{-1}; respectively (Halliday and Trenkel, 1992; Jones, 1999; cited by Heuvelink, 2005). Calcium is required, but with optimal soil pH it is not usually specified considering the requirements are in very low concentration (Jones, 2008). In 2009, for all the fertilizer application rates (0, 20, 60 and 120 kg ha^{-1}) there was less K removed than the suggested range. In 2010, for application rates from 0 to 60 kg K_2O $ha^{-1}$the K removal was less than the range suggested, only at 120kg ha^{-1} was it within the range. The soil analysis might suggest that there was a lack of K uptake however; this was not found in the foliar and fruit nutrient content analysis.

Some possible explanations for this is the release of other forms of K in the soil such as non-exchangeable and mineral K. These forms can be released to exchangeable K (Ghiri et al., 2011). As mentioned previously, Mehlich 3, the soil nutrient analysis method used in the current experiment, extracts and quantifies exchangeable or available K. Thus, some of the non-exchangeable K or mineral K could have released enough K for plant uptake. Potassium associated with organic matter nutrient release is minor and in many cases not worth being mentioned for K (Copperband, 2002; CRAAQ, 2003). Soil organic matter has the same properties as the clay's CEC (cation exchange capacity) and binds cations to its negatively charged surface (Cooperband, 2002). It is however plant available and therefore was also already detected by the Mehlich3 extractant.

It has been shown that K fertilization helps increase yield. In Florida, between 1988 and 1997, a number of experiments on K fertilization were performed. Some of the results were summarised in Hochmuth and Hanlon (2000). More often than not, the soil K levels were analysed and categorized as low or very low in extracted K. The recommendations made in 1989 were revised in 1995 from 160 to 225 lbs $acres^{-1}$ (179 to 252 kg ha^{-1}) K_2O and from 130 to 150 lbs $acres^{-1}$ (146 to 168 kg ha^{-1}) K_2O for very low and low soil K levels respectively. These recommendation changes were based on the results of experiment summarised in this publication. Where the lowest maximum yield obtained from these trails was 748 cartons $acres^{-1}$ (20 959 kg ha^{-1}) and the highest maximum yield was 3 200 cartons $acres^{-1}$ (89 668 kg ha^{-1}). The mean of 13 optimal yields obtained from

K experiments in different soils, years and locations in Florida was 57 219 kg tomatoes ha^{-1}. The average is similar to the total yield that was obtained in L'Assomption in 2009, while in 2010 it was a bit lower. This was probably due to the differences in the weather conditions. In 2010, the season had much more rain than 2009 (Table 4.5), which could have played a role in both the quality and quantity of the fruits. In 2009 in Sainte-Anne-de-Bellevue, the yield were much higher than the average obtained in Florida and is most likely associated with the high soil K level. In 2010, the total yield was much lower due to the late blight infection in the field. Over all, Hochmuth and Hanlon (2000) obtained optimal yields with fertilization rates between 200 and 250 lb K_2O $acre^{-1}$ (178 and 223 kg ha^{-1}), this is much higher than the treatments in Sainte-Anne-de-Bellevue, and only the highest rate in L'Assomption was in that range. This can be explained by the much lower soil potassium fertility (< 20 mg kg^{-1}) in Florida compared with Sainte-Anne-de-Bellevue (>165 mg kg^{-1}) and even L'Assomption (>65 mg kg^{-1}).

In both years, increasing application rates were shown to affect the quality of the tomato fruits. This was shown either directly by increasing the marketable yield as it was the case with the L'Assomption in 2009, or indirectly by increasing the percentage of marketable yield, which was observed in L'Assomption in 2010 and in Sainte-Anne-de-Bellevue in 2009. This is a common benefit from increasing K fertilization (Hartz, 2005; Taber et al., 2008). Potassium increases the concentration of a number of beneficial compounds, thus improving on the quality of the fruit. It also has been found to improve on the redness of fruits (Hartz et al., 2005) and disorders such as yellow shoulder, internal white tissues and blotchy ripening (Gleason and Edmunds, 2006; Hartz et al., 1999; Hartz et al., 2005). In Sainte-Anne-de-Bellevue, this was not the decision factors that affect the yield, as there was barely any incidence of those disorders. The same is true for the L'Assomption site in 2009, where only 23 tomatoes showed yellow shoulder disorder and these were included in the marketable yield. It was in L'Assomption in 2010 that more color disorders were observed; a total of 657 tomatoes were observed to have yellow shoulders but were included as marketable tomatoes, another 14 tomatoes were observed to have other colour disorders and were discarded as non-marketable yield. However, this alone did not have had an impact on the marketable yield.

Table 4.11 The effect of potassium fertilization levels on early and total tomato yields in 2009 in L'Assomption

Treatment ($kg\ K_2O\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
40	8867	7793	87.9
80	10409	8209	78.9
160	9061	8746	96.5
280	12606	11939	94.7
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
40	57171	46025	80.5
80	58351	47193	80.9
160	61572	51642	83.9
280	54477	45622	83.7
Significant linear effect in a regression model	0.0900	n/s	n/s
Significant quadratic effect in a regression model	0.0628	0.0953	n/s

n/s: not significant

Table 4.12 The effect of potassium fertilization levels on early and total tomato yields in 2010 in L'Assomption

Treatment ($kg\ K_2O\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
40	27643	20998	74.4
80	23862	18739	78.5
160	27748	23086	83.2
280	26545	20750	78.2
Significant linear effect in a regression model	n/s	n/s	0.0034
Significant quadratic effect in a regression model	n/s	n/s	0.0048
Total harvests			
40	45177	30607	67.7
80	50431	34063	67.5
160	55926	40722	72.8
280	57924	41982	72.5
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

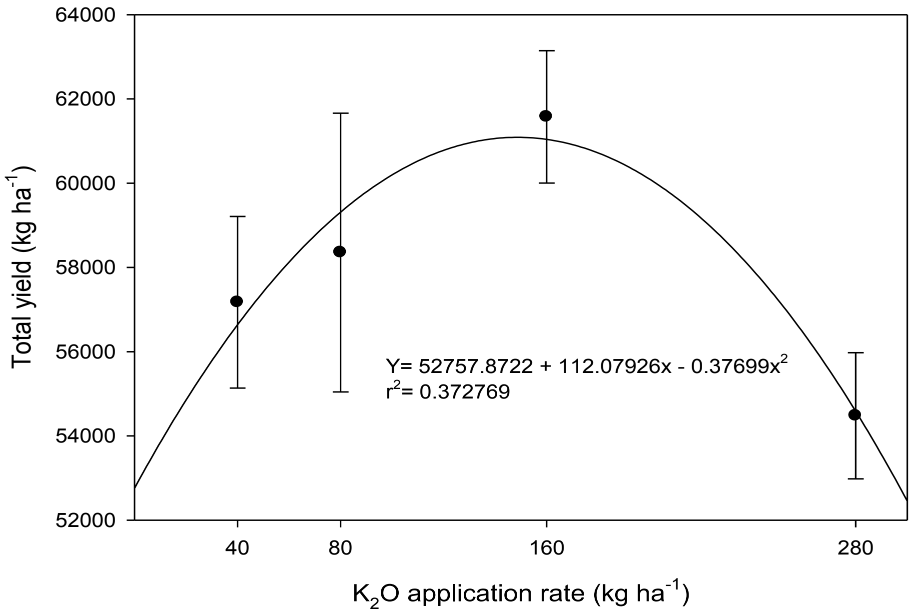

Figure 4.1 Effect of potassium fertilization levels on total yield of tomatoes grown in L'Assomption in 2009

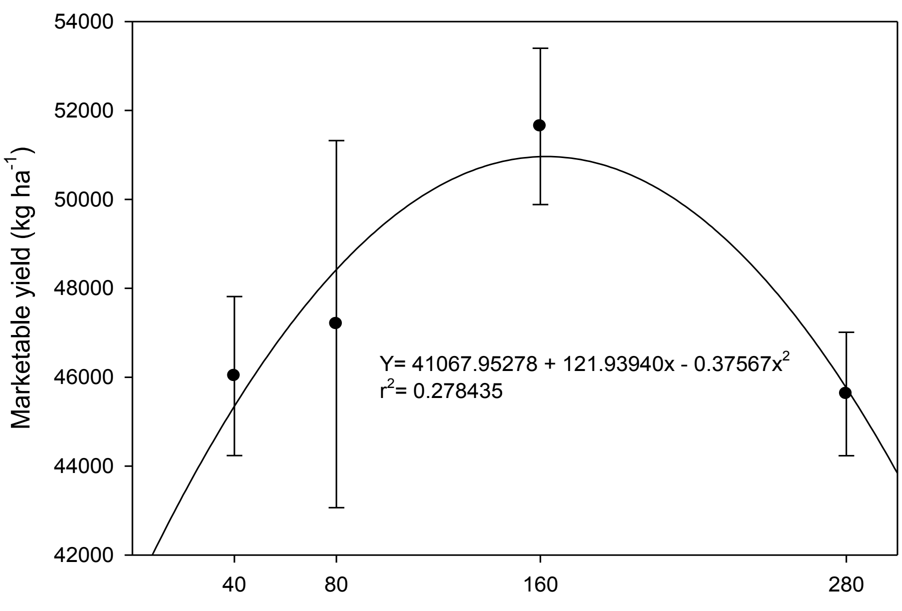

Figure 4.2 Effect of potassium fertilization levels on marketable yield of tomatoes grown in L'Assomption in 2009

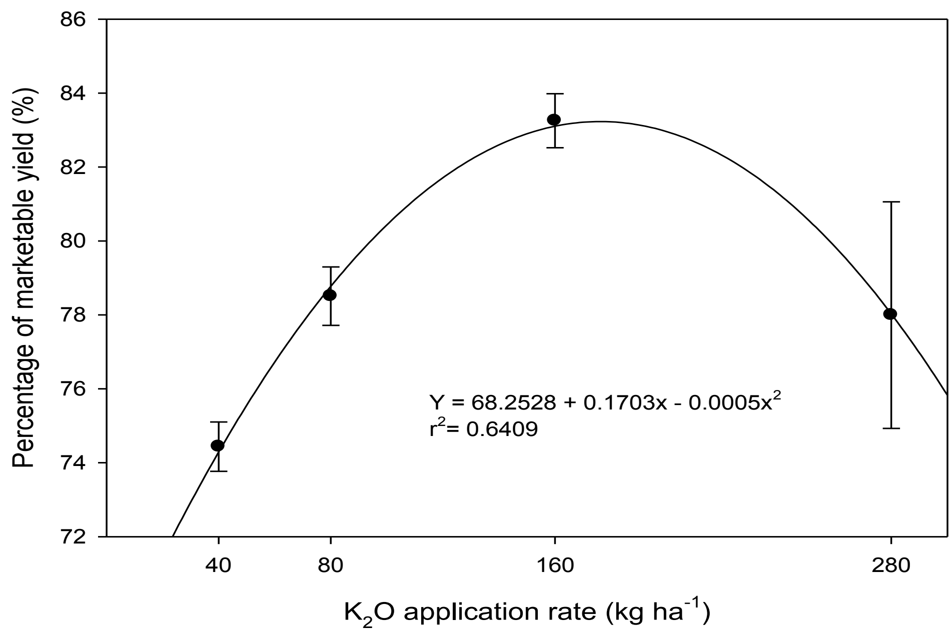

Figure 4.3 Effect of potassium fertilization levels on the early harvest of percentage of marketable yield of tomatoes grown in L'Assomption in 2010

Table 4.13 The effect of potassium fertilization levels on potassium, calcium, and magnesium content (mg kg^{-1}) in soil in L'Assomption for 2009 and 2010

		2009			2010		
	Treatment (kg K_2O ha^{-1})	Potassium (mg K kg^{-1})	Calcium (mg Ca kg^{-1})	Magnesium (mg Mg kg^{-1})	Potassium (mg K kg^{-1})	Calcium (mg Ca kg^{-1})	Magnesium (mg Mg kg^{-1})
Pre-season	Main plot	69.4	384.3	48.5	65.5	369.0	46.2
Post-season	40	30.2 a *	349.3 n/s	27.9 n/s*	31.9 n/s	361.3 n/s	34.9 n/s
	80	44.1 a	292.0 n/s	26.2 n/s*	42.2 n/s	411.7 n/s	39.0 n/s
	160	62.6 ab	305.3 n/s	22.5 n/s*	63.6 n/s	401.7 n/s	38.8 n/s
	280	77.6 b	261.0 n/s	18.4 n/s*	53.6 n/s	315.7 n/s	20.7 n/s

Method of analysis: Mehlich III
Post-season means followed by different letters are significantly different ($P < 0.05$)
* indicates a significant difference in the comparison of post-season treatments against the pre-season ($p < 0.05$)
n/s : not significant (Refers to the comparison of K_2O treatments post-season)

Table 4.14 The effect of potassium fertilization levels on foliar and fruit biomass of tomato in L'Assomption for 2009 and 2010

		Foliar †			Fruit ‡		
Year	Treatment (kg K_2O ha^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
2009	40	17873	11307	3986	28831	1366	1277
	80	19002	10254	3485	27447	1217	1330
	160	20197	9272	3336	30815	1178	1452
	280	19599	9458	3091	34619	1237	1615
2010	40	21754	13186	3855	25136	1412	1214
	80	23028	12201	3643	25867	1097	1276
	160	27522	13110	4445	24225	1321	1177
	280	28412	12563	4035	26494	1165	1193

†fruit set
‡ At harvest, on a dry weight basis

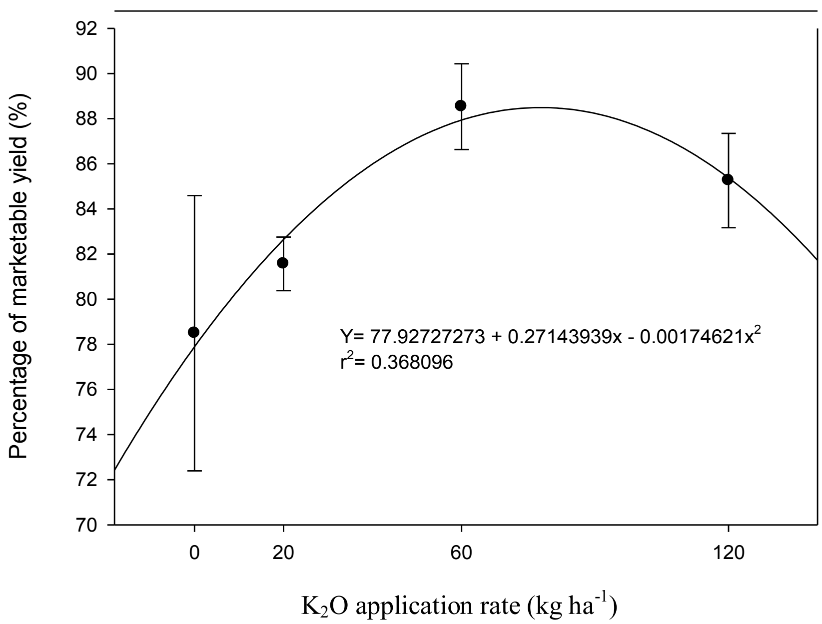

Figure 4.4 Effect of potassium fertilization levels on the early percentage of marketable yield of tomatoes grown in Sainte-Anne-de-Bellevue in 2009

Table 4.15 The effect of potassium fertilization levels on early and total tomato yields in 2009 in Sainte-Anne-de-Bellevue

Treatment ($kg\ K_2O\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
0	39024	30598	78.4
20	36296	29537	81.4
60	43284	38308	88.5
120	38710	33040	85.4
Significant linear effect in a regression model	n/s	n/s	0.0795
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
0	84518	53308	63.1
20	67836	42398	62.5
60	80302	56228	70.0
120	72531	48262	66.5
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.16 The effect of potassium fertilization levels on early and total tomato yields in 2010 in Sainte-Anne-de-Bellevue

Treatment ($kg\ K_2O\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
0	4795	3352	69.9
20	1465	861	58.8
60	5646	4559	80.8
120	3594	2809	78.2
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
0	39259	30858	78.6
20	40532	32685	80.6
60	41701	35873	86.0
120	45843	34266	74.7
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.17 The effect of potassium fertilization levels on potassium, calcium, and magnesium content (mg kg-1) in soil in Sainte-Anne-de-Bellevue for 2009 and 2010

	Treatment (kg K_2O ha^{-1})	2009 Potassium (mg K kg^{-1})	2009 Calcium (mg Ca kg^{-1})	2009 Magnesium (mg Mg kg^{-1})	2010 Potassium (mg K kg^{-1})	2010 Calcium (mg Ca kg^{-1})	2010 Magnesium (mg Mg kg^{-1})
Pre-season	Main plot	165.3	2227.0	345	191.0	1528.3	193.0
Post-season	0	137.7 n/s	2189.0 n/s	351 n/s	127.6 n/s	1317.7 n/s	159.0 n/s
	20	145.7 n/s	1904.7 n/s	316 n/s	165.7 n/s	1429.7 n/s	167.6 n/s
	60	165.3 n/s	1991.0 n/s	325 n/s	157.3 n/s	1489.7 n/s	183.0 n/s
	120	163.0 n/s	2230.0 n/s	384 n/s	114.0 n/s	1636.0 n/s	214.3 n/s

Method of analysis: Mehlich III

Post-season means followed by different letters are significantly different (P< 0.05)

* indicates a significant difference in the comparison of post-season treatments against the pre-season (p< 0.05)

n/s : not significant (Refers to the comparison of K_2O treatments post-season)

Table 4.18 The effect of potassium fertilization levels on foliar and fruit biomass of tomato in Sainte-Anne-de-Bellevue for 2009 and 2010

Year	Treatment (kg K_2O ha^{-1})	Foliar † K (mg kg^{-1})	Foliar † Ca (mg kg^{-1})	Foliar † Mg (mg kg^{-1})	Fruit ‡ K (mg kg^{-1})	Fruit ‡ Ca (mg kg^{-1})	Fruit ‡ Mg (mg kg^{-1})
2009	0	24522	12937	3891	28893	1396	1336
	20	29376	12839	4076	29797	1300	1385
	60	31931	12098	3789	30685	1407	1428
	120	27024	12131	3836	29080	1419	1407
2010	0	30935	12785	3691	35294	1227	1688
	20	34431	13539	3932	34658	1335	1681
	60	31580	15981	4278	38466	1659	1975
	120	30971	13833	3684	33251	1921	1652

†fruit set

‡ At harvest, on a dry weight basis

4.1.3 Phosphorus Experiment

4.1.3.1 L'Assomption

In 2009, the total seasonal yield of fresh field tomatoes had a quadratic response to phosphorus (P) application (Figure 4.5). Increases in P_2O_5 application rates from 0 to 60 kg P_2O_5 ha^{-1} resulted in a decrease in yield from 65 to 52 Mg ha^{-1}; further application resulting in an increase in yield to 63 Mg ha^{-1} (Table 4.19). A similar response was observed for marketable yield (Figure 4.6). Increasing P application resulted in a 30% decrease in the marketable yield from 57 Mg ha^{-1} with P_2O_5 levels increasing from 0 to 60 kg ha^{-1}. A higher application rate resulted in a higher yield; 51 Mg ha^{-1} with 120 kg P_2O_5 ha^{-1}. In contrast, in 2010, both the total and marketable yield of tomatoes did not respond to P_2O_5 fertilization (Table 4.20). Although not significant, there was a similar trend in terms of response to P application for the marketable yield.

Increasing P application rates did not significantly affect the early marketable and total yield of tomatoes both in 2009 and 2010 (Tables 4.19 and 4.20). Yet, in 2009, the two highest application rates resulted in yields almost 2 Mg ha^{-1} greater than that of the 0 and 20 kg P_2O_5 ha^{-1} rates. Similar results were observed for the marketable yield with the exception that only the 120 kg P_2O_5 ha^{-1} application rates had a higher yield. In 2010, similar results were obtained for total yield (Table 4.20). The highest yield was observed for the two highest fertilizer rates. However, no trend was observed for marketable yield.

For the 2009 nitrogen and potassium experiments in the L'Assomption site the early harvest represented close to 15% of the total harvest and in 2010 it was closer to 50% (Tables 4.1, 4.2, 4.11, and 4.12). This trend was also observed of the P experiment (Tables 4.19 and 4.20). Similarly, the early marketable yield in 2009 was between 16 and 22% of the total marketable yield, while it represented between 52 and 60% (Tables 4.19 and 4.20). The same possible reasons can explain the difference in this percentage between the years: the number of harvests dates that differs for the early and total yield.

In 2009, increasing P application rate resulted in a quadratic response for the percentage marketable yield both for the early and total harvests (Figure 4.7 and 4.8). The percentage marketable yield decreased with increasing P_2O_5 application from 0 to 60 kg ha^{-1}, supplementary application increased the percentage marketable yield. In 2010, the percentage marketable yield was not affected by P application. However, a similar trend to 2009 was observed for the total harvests. The early harvests decreased with increasing fertilization rates. Both in 2009 and in 2010, the percentage marketable yield was almost 10% higher for the early harvest compared with the total harvest.

The pre-season P soil levels were comparable in 2009 and 2010 (Table 4.21). The soil in L'Assomption was considered excessively rich according to the guidelines for the Province of Quebec (CRAAQ, 2003) since it contained more than 401 kg P ha^{-1} (511 and 510 kg P ha^{-1} for 2009 and 2010 respectively; Table 4.21). Such levels may have resulted from excess fertilization of this macronutrient, which is one of the major factors associated with P leaching. Soils prone to have P leaching are deep very sandy soils and soils very high in organic matter (Sims et al., 1998). It is not uncommon in regions where livestock production is high, as it is the case in Quebec to have such high soil P levels. Continuous manure applications based on the crop N requirements or even just as a way to dispose of manure have created high soil P level in many regions of Quebec (Daniel et al., 1994; Sharpley et al., 1994). However, the crop demand for P is much lower than nitrogen (Heuvelink, 2005) and thus, overtime, this results in accumulation of P (Kingery et al, 1994, Sharpley, 1995). Excessively high P soil levels are associated with a number of detrimental effects namely: P loss, P toxicity in the plant, and modified uptake of other nutrients (Jones, 1998b). Phosphorus loss mostly occurs through surface erosion or runoff since P is considered an immobile nutrient in the soil (Sharpley and Rekolainen, 1997). However, recent studies have shown that these are not the only ways of losing P. In fact, eutrophication, which is now major concern and is often associated with high quantities of P entering bodies of water through ground water, thus, through leaching (Simard et al., 2000; Djodjic et al., 2000, 2004; Nayak et al., 2009).

For both years, increasing P_2O_5 application rates did not result in differences in post-season soil P levels. Only in 2009, for the highest application rate of 120 kg P_2O_5 ha^{-1} was there an increase in the soil P content when compared to the pre-season P soil level. Although not significant, in 2009 there was a minor accumulation of P for all treatments compared with the pre-season.

The soil at the L'Assomption site was a sandy loam, rich in P, which did not respond to P fertilization levels, except for the highest fertilization rate for one year. These characteristics, do not allow us to draw conclusions regarding the presence or absence of leaching. Leaching has been shown to be decreased in the presence of aluminum (Al), iron (Fe) oxides (Sims et al., 1998) as well as calcium (Ca). The fact that the most important source of P for crops is inorganic orthophosphate or available P, which represents only a small portion of the soil P (Condron et al., 2005, cited in Geisseler et al., 2011), and can bind in an insoluble precipitate with cations, such as Ca, Al, or Fe (Ford, 1933; Stout et al., 1998; Stevenson and Cole, 1999, cited in Geisseler et al., 2011). The method used to analyse the presence of all the soil elements was Mehlich 3. This method only allows for the detection of plant available nutrients. Therefore, if there is precipitation or binding of the nutrients and they become unavailable, they will not be accounted for by this analysis. It is therefore important to consider the presence of these elements (i.e., Ca, Al, and Fe) in the soil. In 2009, increasing P_2O_5 application rate had no effect on the Ca soil level nor did it differ from the pre-season levels (Table 4.22). Aluminum soil levels were not affected by increasing P_2O_5 application. However, Al levels were significantly higher post-season compared to the onset of the experimentation when P fertilizer was applied. Finally, at the post-season sampling there was significantly more Fe when 120 kg P_2O_5 ha^{-1} was applied and significantly less with 20 and 60 kg P_2O_5 ha^{-1}. The 0 and 120 kg P_2O_5 ha^{-1} had significantly higher levels of Fe compared to the pre-season levels. In contrast, in 2010, increasing P_2O_5 rates did not affect Fe, Al, and Ca levels. Although it was not significant, there was less Al post-season. Phosphate binds preferably to certain cations depending on the pH. It has been shown that P usually binds to Ca at a neutral to alkaline pH and to Al and Fe oxides at an acidic pH (Hemwall, 1957; FIFA,2006). In L'Assomption in both 2009 and 2010, the soil pH was 6.0. Yet, there was an increase in the Al and Fe, which is the opposite of what was expected.

These results can be explained by a combination of two possibilities. First, there are some soils where the phosphate binds to Al and Fe oxides but the bond is not strong enough to make it insoluble and Al, Fe and P are all still available to the plant (Tran, 1990). In fact, the soil series for L'Assomption is a St-Thomas fine sand (Godbout, 1957) which is one such soil. It is a podzol characterized by its acidity as well as high leaching in the A_2

horizon. Yet it has a very limited amount of colloidal minerals. This could explain the very high soil P level. Since there is still formation of some bonds, it is not as easily leached out. Yet, it is still very much plant available and is therefore easily picked up by the Mehlich3 extraction. Secondly, there was no increase in soil P and there is an increase in Al and Fe in 2009 but not in 2010, which can be attributed to the soil P properties. The pools of water soluble (available) P are constantly replenished by the release of less-available P pools (Carter and Gregorich, 2008; Shen et al., 2011). Plant demand removed P from the soil, which was replenished by freeing more strongly bound compounds of P-Al and P-Fe, allowing for plant uptake while keeping a soil P level similar and allowing for more Al and Fe to be available. This might not have been found in the 2010 season due to climatic conditions, especially the rainfall (Table 4.5).

Other detrimental effects of high soil P level include the possibility of P toxicity in plants (Jones, 1998b). In the present experiment, both the foliar and fruit samples from three repetitions per treatment were pooled and therefore they could not be analysed statistically. In both years, the P content in the youngest fully mature leaf as well as in the fruits did not appear to be affected by the increasing P_2O_5 rates (Table 4.23). The foliar P content was within the sufficiency range (between 0.20 and 0.40 %) for adequate plant growth (Maynard and Hochmuth, 2007).

The variation in Al and Fe soil levels in 2009 and the lack of it in 2010 (Table 4.22), as well as the lower yield observed in 2010 (Tables 4.19 and 4.20) can be associated with the lower uptake of P in 2010 (Table 4.23). While the lower uptake in P reduced the yield, the P could simply have been provided by the water soluble P pool therefore not affecting P-Al or P-Fe compounds.

As noted previously, a second possible impact of high soil P content is the modification of the uptake of certain nutrients (Hochmuth and Hanlon, 2000). It can create deficiencies of Zn and Fe and toxic levels of Mn (Jones, 2008). Calcium is not a macronutrient that is affected during the uptake. However, it binds with phosphate in the soil. Although the soil Ca levels were not affected by P_2O_5 fertilization (Table 4.24), any variation early in the season could have been masked by the weekly application of Ca fertilizer starting at fruit set. Foliar sampling was done immediately prior to the start of this fertilization, allowing us to determine if P_2O_5 fertilization did affect the Ca availability. In fact, the Ca level in the leaves seemed to decrease with increasing rates of P_2O_5 (Table 4.24). This reduction in Ca content in the leaves was also observed in the dried fruits sampled towards the end of the season (data not shown). Since Ca is immobile in the plant (Heuvelink, 2005), the Ca from the leaves would not have translocated to the fruits, thus, there was still less uptake in Ca even after the fertilization in Ca was initiated. A decrease in Ca uptake with increasing P fertilization rate could have been due to precipitation of these two compounds. However, the soil pH of 6.0 makes it very improbable that the Ca would precipitate, as Ca precipitates with phosphate at a more basic pH (FIFA, 2006). Another possibility is that the uptake in Ca was similar for all treatments, but the biomass production was increased with increasing P_2O_5 application, which made the Ca less concentrated in each plant parts. The Ca sufficient ranges between 1.0 and 2.0% for the youngest fully mature leaf dry weight (DW) (Maynard and Hochmuth, 2007). The Ca content in 2009, was at the lower end of the range with the highest P_2O_5 rate resulting in 0.9% Ca content while in 2010, it was about 0.2% higher.

The sufficiency range of manganese (Mn) in the youngest fully mature leaf differs according to the source. It ranges from 30 to 100 ppm (which is the same as mg kg^{-1}) (Maynard and Hochmuth, 2007) to 40 to 200 mg kg^{-1}. According to Jones (2008), the results for both years placed the Mn content close to the middle of the range, while according to Maynard and Hochmuth (2007) it was at the border of the excess levels, with one treatment for each year in excess (Table 4.24). This high Mn content may be associated with the high soil P level, which can create excess Mn and can even lead to toxicity (Jones, 2008).

Both years, the zinc levels on a dry weight basis of the leaves was below 20 mg kg^{-1} (Table 4.24) which is the lower end of the sufficiency range (20 and 50 mg kg^{-1}) (Maynard and Hochmuth, 2007; Jones, 2008). The zinc deficiency was most likely induced by the extremely high soil P levels. Similar results have been observed by Jones, 1998 (Jones, 2008). In fact, there is a critically low level of 15 mg Zn kg^{-1} below which abnormal growth can be expected (Jones, 2008). Also, there seemed to be a decrease in Zn content with increasing P_2O_5 application rates (Table 4.24).

Iron can accumulate beyond the sufficiency range in the youngest mature leaf of the tomato without being toxic to the plant (Jones, 2008). Therefore, the fact that the leaves contented more than 100 mg kg^{-1} (Table 4.24), which is the higher limit of iron's sufficiency range might not be critical for the plants development (Maynard and Hochmuth, 2007; Jones, 2008). Iron content in the youngest fully matured leaves at fruit set did not seem affected by increasing P_2O_5 application rates. Zinc is more susceptible to becoming the first deficient nutrient when there is P excess (Jones, 2008). This can explain the lack of deficiency in Fe levels, while Zn is deficient.

4.1.3.2 Sainte-Anne-de-Bellevue

The fresh tomato total and marketable yield were not affected by increasing P_2O_5 fertilization rate both in 2009 and in 2010 at the Sainte-Anne-de-Bellevue site (Tables 4.25 and 4.26). However, a similar trend to that observed at L'Assomption in 2009 for yield (Table 4.19) was noted in the total yield in 2009; when the lowest yield was obtained by applying 60 kg P_2O_5 ha^{-1} and lower and higher rates obtained higher yields (Table 4.25).

In 2009, the early harvests represented close to half the yield at the end of the season. However, in 2010, the early harvests represented almost 10% of the total harvest. This difference is most likely due to the difference in the total number of harvest for each year as well as their separation into early or total harvest. This was even more important in 2010, when the field became infected with late blight. This infestation ended the season prematurely, resulting in a smaller number of harvests with a much larger final harvest.

For both years, there was no effect of increasing P_2O_5 application rates on the percentage of marketable yield (Tables 4.23 and 4.24). The percentage marketable yield was almost 10% higher for the early harvest that of the total harvest while it was the opposite in 2010.

The soil P level was slightly higher in 2009 than in 2010 (Table 4.27). The initial P level of 120 mg P kg^{-1} in 2009 is equal to 268 kg P ha^{-1}, which is considered a "good" level for P, while in 2010, 167 mg kg^{-1} of P represents 373 kg P ha^{-1}, a soil considered "rich" in P (CRAAQ, 2003). In 2009, the P soil levels were higher in L'Assomption than in Sainte-Anne-de-Bellevue for both years (Tables 4.21 and 4.27). In 2009, the fertilization recommendation based on initial soil P levels was 125 kg P_2O_5 ha^{-1}, while in 2010 it was 70 kg P_2O_5 ha^{-1} (CRAAQ, 2003). In both years, increasing the P_2O_5 fertilization rate did not affect soil P level post-season. In 2010, the application rate of 60 kg P_2O_5 ha^{-1} was closest to the recommendation of 70 kg ha^{-1} and it resulted in the highest, although not significantly, marketable and total yield (Table 4.26).

Soil pH can have an impact on the availability of P as well as Fe, Al and Ca (Hemwall, 1957; FIFA, 2006). In Sainte-Anne-de-Bellevue in 2009, the soil pH was at 6.5, which is considered a neutral soil and in 2010, the soil pH was at 5.8, a moderately acidic soil (Government of Alberta, 2002). In acidic soils, P can slightly adsorb to clay minerals and remains plant available, or can become plant-unavailable when it forms strong bonds with Al/Fe oxides. While in alkaline soils, P retention is dominated by precipitation reactions, although P can be adsorbed on the surface of calcium carbonate and clay minerals (FIFA, 2006; Shen et al., 2011). The pH range for which P is most available is between 6.5 to 7.5 (FIFA, 2006). However, both years, the soil level for Ca, Al and Fe were not affected by increasing P fertilization (Table 4.28).

In 2009, with a neutral pH it was expected that there would not be much adsorption of P to Ca, Al, and Fe, (Figure 4.9) which was observed (Table 4.28). Also, no different was noted between the post-season and pre-season levels. This can be explained by the fact that P can be maintained more or less constant by a chemical equilibrium in the soil (Whalen and Sampedro, 2010; Geisseler, 2011). The added P will have been picked up by the plant, bound to another ion; becoming unavailable or leached. In 2010, the soil pH was 5.8. In a slightly acidic soil, Ca content should not be affected by binding with phosphate, which is what was observed (Table 4.28). In fact, this pH value is right in the middle of the range for which P is the least available because it binds to Al (FIFA, 2006). However, the Al and Fe levels were not affected by increasing P application rate nor were they different from the initial soil levels. The soil Al level being high, it is possible that the application of P did not affect the over Al content, even though the P did in fact bind with the Al. High levels of Al, can be attributed to the low pH, which allows Al to be available (Beegle and Lingenfelter, 1995). It can also be influenced by the relatively high organic matter in the soil, which increases the amorphous nature and hence extractability of Al (Maguire and Sims, 2002). Maguire and Sims (2002) noted that the combination of low pH, OM and high Al soil content retains more the P in the soil.

The foliar and fruit P content did not seem to be affected by increasing P fertilization (Table 4.26). There was almost no difference between the 2009 and 2010 accumulation of P in the leaves. However, there was a slightly higher P content in the fruits in 2010 than in 2009. Interestingly enough, the foliar P level was considered to be above the sufficiency level of 0.20 to 0.40 % of the dried weight leaves (Maynard and Hochmuth, 2007), which is considered high however, not toxic. L'Assomption, which was extremely rich in P, was almost 2000 mg kg^{-1} higher than Sainte-Anne-de-Bellevue. This might be due to a lack of competition in the uptake of P. Also, the dried fruits were 270 mg kg^{-1} and 800 mg kg^{-1} higher in 2009 and 2010 respectively in Sainte-Anne-de-Bellevue than in L'Assomption.

In 2009, the Ca content in the dried leaves sampled at fruit set seemed to decrease with increasing P level, while in 2010 it did not seem to be affected (Table 4.30). For both years, the Ca concentration was with in the sufficiency range (1.0 to 2.0% -Maynard and Hochmuth, 2007).

For the 2009 season, it was hypothesized previously that due to a close to neutral pH (6.5) and the lack of variation in Ca content in the soil in 2009 there was not much adsorption of P to Ca. However, this hypothesis is proven wrong as there was a decrease in Ca foliar content. Another hypothesis could be that there was some formation of Ca-P compounds prior to the foliar sampling, thus resulting in the decrease of Ca with increasing P rates. At a neural pH it is not impossible to have Ca-P complex formations, they are simply not as strong or not as common (FIFA, 2006). Weekly application of Ca fertilizer starting right after the foliar sampling masked this situation in the soil and fruit biomass (data not shown) Ca content.

The Mn content was analysed as it can be affected by the soil P levels (Jones, 2008). For both years, the Mn content did not seem to be influenced by P fertilization rate (Table 4.30). In 2009, the Mn leaf content (DW) was considered at the lower limit of the sufficiency range (30 to 100 mg kg^{-1}) suggested by Maynard and Hochmuth (2007) and deficient according to Jones, (2008) (sufficiency range: 40-200 mg kg^{-1}). While in 2010, the Mn content was slightly higher, keeping the content within both sufficiency ranges (Maynard and Hochmuth, 2007; Jones, 2008). The lack of increase with increasing P fertilization rate could be due to the fact that P-Ca precipitation is usually a fast reaction that occurs shortly after water-soluble fertilizer is applied and there is a high concentration of available phosphate in the soil (Whalen and Sampedro, 2010). Thus, the supplementary P was made unavailable fast and did not affect the Mn. While the difference in the Mn content between the season could be due to the initial P availability in the soil which was higher in 2010 than 2009, thus favoring the uptake of Mn (Jones, 2008).

Zinc and Fe are microelements that decrease or become deficient in the leaves when there is P toxicity (Jones, 2008). The leaves contained excess Zn and Fe when compared to the sufficiency range of 20 to 40 mg kg^{-1} and 40 to 100 mg kg^{-1} for Zn and Fe respectively (Maynard and Hochmuth, 2007). This could indicate that although there is excess P in the leaves, it is not yet toxic and had little effect on the uptake of other nutrients (Table 4.30).

The yield response to the P fertilization remains difficult to explain. Linear regression with a positive or negative slope, a regression with a maximum or even no response to fertilizer application, are typical responses (Marschener, 1995). However, the fresh market tomato yield responded to P application and was described by a regression equation with a minimum. It was only found significant in L'Assomption in 2009. However, similar trends, although not significant, were found for L'Assomption 2010 and McGill 2009.

A possible explanation could be the plant's association with mycorrhizae. This fungi-plant symbiosis is affected by soil P levels; as available P increases, the infection of the fungi is reduces (Koide and Li, 1990;Schroeder and Janos, 2004). The association with mycorrhizae implies the plant uptake in immobile nutrients is enhanced through the hyphal system of the fungi, which can reach further in the soil than plant roots. It can also produce phosphatases making more P available for plant/ fungi uptake. On the other hand, a high portion (as much as 40 to 50%) of the C produced by plant photosynthesis is allocated to the mycorrhizae. It is possible that with the control (0 kg P_2O_5 ha^{-1}) the soil P levels were low enough that there was infection with mycorrhizae and this improved the yield by allowing the uptake of some nutrients and water, and was not hindered by the removal of the carbon compounds. These results have been observed by: Schroeder and Janos (2004). However, with increasing P_2O_5 fertilization, there was a decline in mycorrhizae infection, and the yield was reduced. Finally, with the higher rate(s), there was a sufficient amount of available P to provide for the plants and increase the yield.

It has also been shown that P fertilization had no effect on the yield of processing tomato yield when there is high soil P background (Zhang et al., 2009). Similar conditions (high soil P background) were present at both sites and this could explain the lack of variation in the yield.

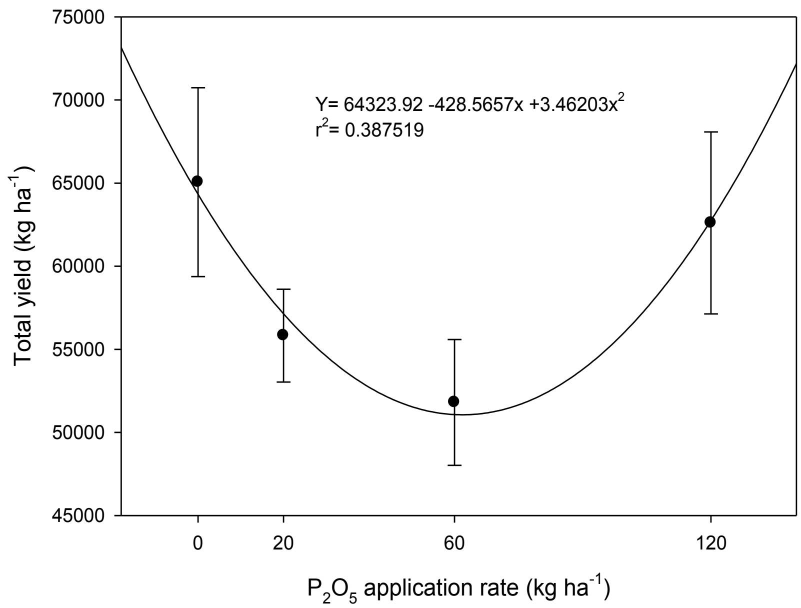

Figure 4.5: Effect of phosphorus fertilization levels on total yield of tomatoes grown in L'Assomption in 2009

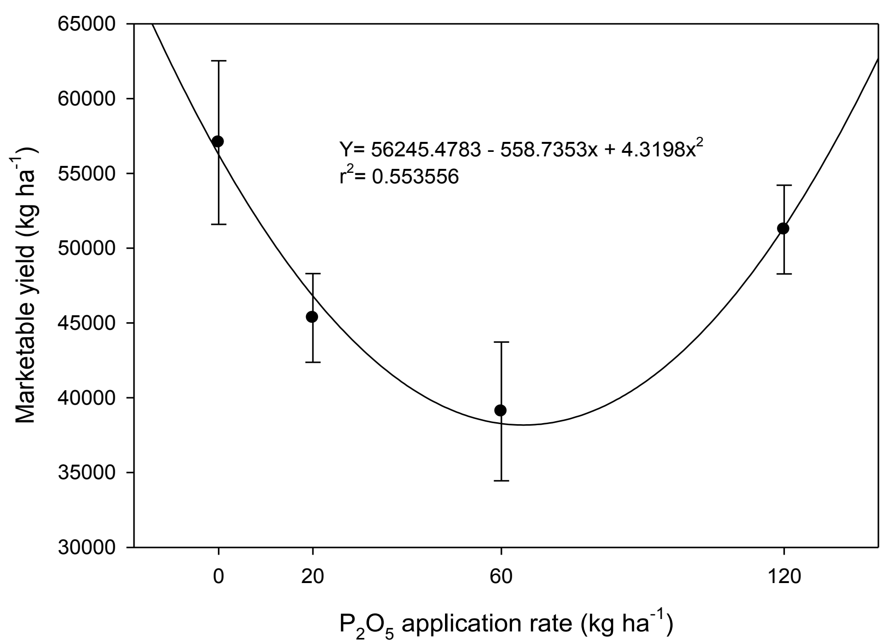

Figure 4.6: Effect of phosphorus fertilization levels on the marketable yield of tomatoes grown in L'Assomption in 2009

Table 4.19 The effect of phosphorus fertilization level on early and total tomato yields in 2009 in L'Assomption

Treatment (kg P_2O_5 ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
0	9368	8975	95.8
20	7695	7022	91.2
60	11582	8645	74.6
120	11178	10163	90.9
Significant linear effect in a regression model	n/s	n/s	0.0002
Significant quadratic effect in a regression model	n/s	n/s	0.0003
Total harvests			
0	65054	57059	87.7
20	55821	45332	81.2
60	51804	39087	75.5
120	62603	51239	81.8
Significant linear effect in a regression model	0.0453	0.0088	0.0053
Significant quadratic effect in a regression model	0.0409	0.0096	0.0076

n/s: not significant

Table 4.20 The effect of phosphorus fertilization level on early and total tomato yields in 2010 in L'Assomption

Treatment (kg P_2O_5 ha^{-1})	Total yield (kg ha^{-1})	Marketable yield (kg ha^{-1})	% marketable
Early harvests			
0	25152	21406	85.1
20	24925	19900	79.8
60	26881	20377	75.8
120	28011	20958	74.8
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
0	53577	39124	73.0
20	46711	33234	71.1
60	56790	38940	68.6
120	56202	39432	70.2
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

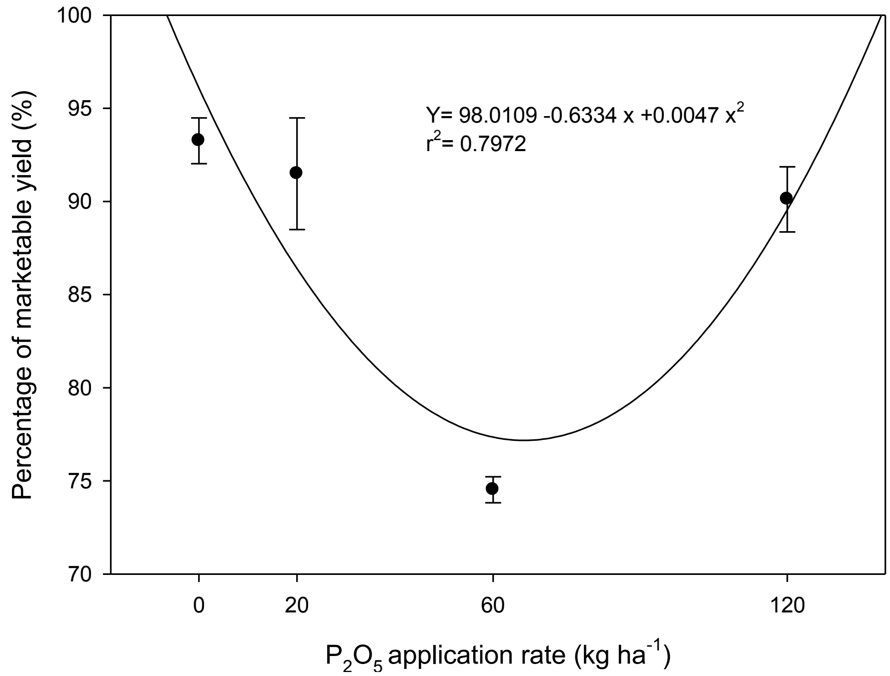

Figure 4.7: Effect of phosphorus fertilization levels on early percentage marketable yield of tomatoes grown in L'Assomption in 2009

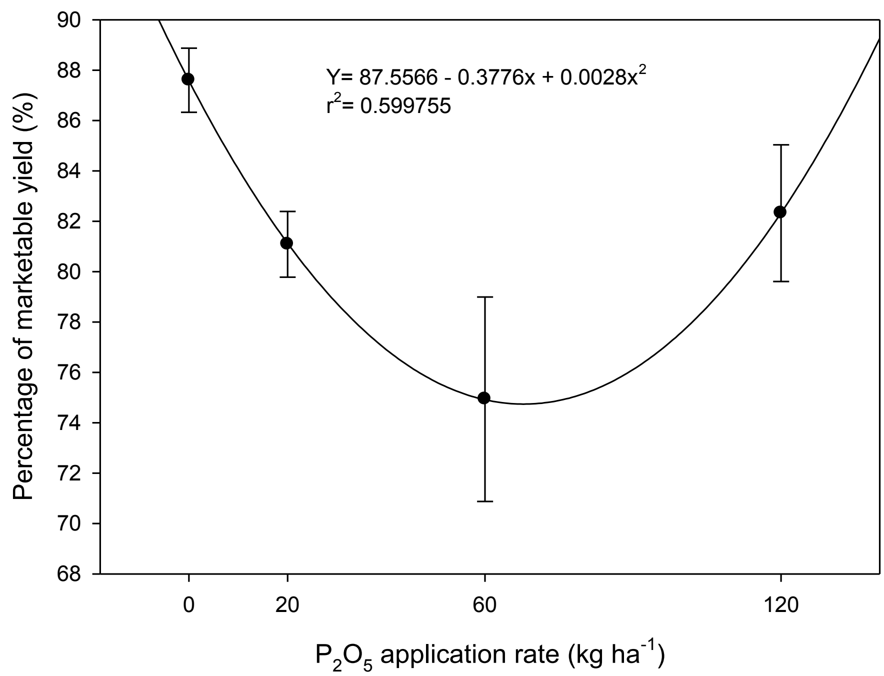

Figure 4.8: Effect of phosphorus fertilization levels on percentage marketable yield of tomatoes grown in L'Assomption in 2009

Table 4.21 The effect of phosphorus fertilization level on phosphorus content (mg P kg^{-1}) in soil in L'Assomption for 2009 and 2010

	Treatment (kg P_2O_5 ha^{-1})	Phosphorus content (mg P kg^{-1})	
		2009	2010
Pre-season	Main plot	228.0	227.7
Post-season	0	241.3 n/s	222.3 n/s
	20	234.7 n/s	226.0 n/s
	60	242.7 n/s	220.0 n/s
	120	274.3 n/s *	226.0 n/s

Method of analysis: Mehlich III
Post-season means followed by different letters are significantly different (P< 0.05)
* indicates a significant difference in the comparison of post-season treatments against the pre-season (p< 0.05)
n/s : not significant (Refers to the comparison of P_2O_5 treatments post-season)

Table 4.22 The effect of phosphorus fertilization level on calcium, aluminum and iron content (mg Ca, Al, Fe kg^{-1}) in soil in L'Assomption for 2009 and 2010

	2009			2010		
Treatment (kg P_2O_5 ha^{-1})	Calcium (mg Ca kg^{-1})	Aluminum (mg Al kg^{-1})	Iron (mg Fe kg^{-1})	Calcium (mg Ca kg^{-1})	Aluminum (mg Al kg^{-1})	Iron (mg Fe kg^{-1})
Pre-season						
Main plot	345.0	1529.3	127.7	354.0	1620.3	135.0
Post-season						
0	356.3 n/s	1591.0 n/s	141.3 ab *	355.0 n/s	1581.1 n/s	135.3 n/s
20	285.3 n/s	1636.7 n/s *	135.3 a	292.7 n/s	1586.7 n/s	134.0 n/s
60	268.7 n/s	1638.3 n/s *	137.0 a	419.0 n/s	1574.3 n/s	126.3 n/s
120	320.7 n/s	1618.0 n/s *	150.3 b *	352.7 n/s	1582.7 n/s	136.7 n/s

Method of analysis: Mehlich III
Post-season means followed by different letters are significantly different (P< 0.05)
* indicates a significant difference in the comparison of post-season treatments against the pre-season (p< 0.05)
n/s : not significant (Refers to the comparison of P_2O_5 treatments post-season)

Table 4.23 The effect of phosphorus fertilization levels on phosphorus content in foliar and fruit biomass of tomato in L'Assomption for 2009 and 2010

		Foliar †	Fruit ‡
Year	Treatment (kg P_2O_5 ha^{-1})	P (mg kg^{-1})	
2009	0	3011	2700
	20	3041	2639
	60	3078	2476
	120	2848	2633
2010	0	2758	2532
	20	2873	2167
	60	2619	2329
	120	2902	2426

†fruit set
‡ At harvest, on a dry weight basis

Table 4.24 The effect of phosphorus fertilization levels on calcium, manganese, iron and zinc content (mg kg^{-1}) of foliar biomass of tomato in L'Assomption for 2009 and 2010

Year	Treatment (kg P_2O_5 ha^{-1})	Calcium (mg Ca kg^{-1})	Manganese (mg Mn kg^{-1})	Zinc (mg Zn kg^{-1})	Iron (mg Fe kg^{-1})
2009	0	11110	76.5	17.5	144.0
	20	10296	96.0	18.2	119.0
	60	10035	103.0	18.8	121.0
	120	8728	99.5	14.9	124.0
2010	0	13820	98.8	33.5	115.0
	20	12643	120.0	17.6	97.8
	60	12614	90.4	16.2	82.1
	120	11818	76.2	15.0	91.4

At fruit set, on a dry weight basis

Table 4.25 The effect of phosphorus fertilization level on early and total tomato yields in 2009 in Sainte-Anne-de-Bellevue

Treatment ($kg\ P_2O_5\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
0	42425	35592	83.9
20	44524	40524	91.0
60	40808	35703	87.5
120	39259	34407	87.6
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
0	81849	59172	72.3
20	79191	58351	73.7
60	79679	56388	70.8
120	79919	55592	69.6
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.26 The effect of phosphorus fertilization level on early and total tomato yields in 2010 in Sainte-Anne-de-Bellevue

Treatment ($kg\ P_2O_5\ ha^{-1}$)	Total yield ($kg\ ha^{-1}$)	Marketable yield ($kg\ ha^{-1}$)	% marketable
Early harvests			
0	3901	2540	65.1
20	4724	2430	51.5
60	3725	2430	65.2
120	4307	3308	76.8
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s
Total harvests			
0	42189	32801	77.7
20	41201	32208	78.2
60	44724	36439	81.5
120	41393	34348	83.0
Significant linear effect in a regression model	n/s	n/s	n/s
Significant quadratic effect in a regression model	n/s	n/s	n/s

n/s: not significant

Table 4.27The effect of phosphorus fertilization level on phosphorus content (mg P kg^{-1}) in soil in Sainte-Anne-de-Bellevue for 2009 and 2010

Treatment (kg P_2O_5 ha^{-1})	Phosphorus content (mg P kg^{-1})	
	2009	2010
	Pre-season	
Main plot	120.0	166.7
	Post-season	
0	135.3 n/s	172.7 n/s
20	144.7 n/s	164.7 n/s
60	125.3 n/s	178.7 n/s
120	115.2 n/s	190.3 n/s

Method of analysis: Mehlich III
Post-season means followed by different letters are significantly different ($P< 0.05$)
* indicates a significant difference in the comparison of all the post-season treatments against the pre-season ($p> 0.05$)
n/s : not significant (Refers to the comparison of P_2O_5 treatments post-season)

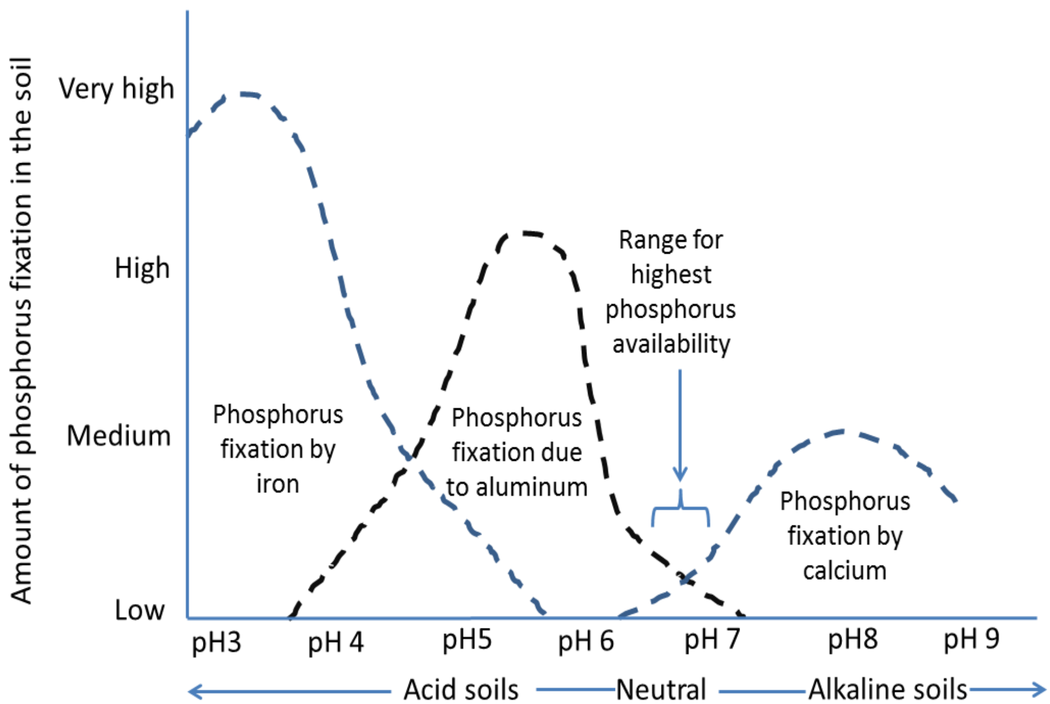

Figure 4.9 Availability of phosphorus varies with soil pH (Modified from: Fifa, 2006)

Table 4.28 The effect of phosphorus fertilization level on calcium, aluminum and iron content (mg Ca, Al, Fe kg^{-1}) in soil in Sainte-Anne-de-Bellevue for 2009 and 2010

		2009			2010		
Treatment (kg P_2O_5 ha^{-1})		Calcium content (mg Ca kg^{-1})	Aluminum content (mg Al kg^{-1})	Iron content (mg Fe kg^{-1})	Calcium content (mg Ca kg^{-1})	Aluminum content (mg Al kg^{-1})	Iron content (mg Fe kg^{-1})
Pre-season	Main plot	2156.7	963.0	188.3	1603.3	1173.3	244.3
Post-season	0	2153.0 n/s	959.7 n/s	198.0 n/s	1676.3 n/s	1171.0 n/s	239.7 n/s
	20	3013.0 n/s	959.7 n/s	219.0 n/s	1631.7 n/s	1169.0 n/s	247.7 n/s
	60	2199.3 n/s	959.3 n/s	189.0 n/s	1506.0 n/s	1153.0 n/s	238.0 n/s
	120	2278.7 n/s	976.0 n/s	197.7 n/s	1718.3 n/s	1170.0 n/s	243.7 n/s

Method of analysis: Mehlich III
Post-season means followed by different letters are significantly different (P< 0.05)
* indicates a significant difference in the comparison of post-season treatments against the pre-season (p< 0.05)
n/s : not significant (Refers to the comparison of P_2O_5 treatments post-season)

Table 4.29 The effect of phosphorus fertilization levels on foliar and fruit biomass of tomato in Sainte-Anne-de-Bellevue for 2009 and 2010

		Foliar †	Fruit ‡
Year	Treatment (kg P_2O_5 ha^{-1})	P (mg kg^{-1})	
2009	0	5331	2880
	20	3931	2831
	60	4590	3217
	120	5154	3198
2010	0	5272	3389
	20	4966	3177
	60	4839	5106
	120	4874	3763

†fruit set
‡ At harvest, on a dry weight basis

Table 4.30 The effect of phosphorus fertilization levels on calcium, manganese, iron and zinc content (mg kg^{-1}) of foliar biomass of tomato in Sainte-Anne-de-Bellevue for 2009 and 2010

Year	Treatment (kg P_2O_5 ha^{-1})	Calcium content (mg Ca kg^{-1})	Manganese content (mg Mn kg^{-1})	Zinc content (mg Zn kg^{-1})	Iron content (mg Fe kg^{-1})
2009	0	14086	32.8	33.7	114
	20	13499	38.1	26.3	119
	60	12917	36.2	26.8	136
	120	11786	39.7	29.2	105
2010	0	13903	55.5	44.8	191
	20	15028	51.8	46.6	218
	60	13398	42.7	40.7	191
	120	12290	46.7	39.1	161

At fruit set, on a dry weight basis

4.2 Lycopene experiment

4.2.1 Fertilization effect

In 2009, the lycopene content of tomatoes harvested at the earlier date had a quadratic response to increasing N fertilization levels. The maximum lycopene content (99 µg g^{-1}) was obtained by applying 90 kg N ha^{-1}; further increase in the N fertilization as well as a lower rate resulted in a decrease in lycopene. The fact that the tomatoes treated with the lowest fertilization rate had less lycopene than the other treatments was similar to that observed by De Pascale et al., (2008). Montagu and Goh (1990), and Kobryń et al., (2004) observed an increase in lycopene with increasing N fertilization rates. In fact, De Pascale et al., (2008) suggested that since lycopene was synthesized by the isoprenoid pathway, N fertilizer enhanced the enzymes in this pathway therefore increasing the lycopene concentration in the fruits. However, the lycopene content of the tomatoes harvested at the red stage on a later date was not affected by increasing nitrogen (N) fertilization (Table 4.31). That lycopene production response to N was not constant is similar to results from other studies. Dumas et al., (2003) and Dorais et al., (2008), found that secondary metabolites without N in their structure were favoured by sub-optimal N fertilization. Also, Benard et al., (2009) had similar results to the current study as there was a weak response to N fertilization that was associated with irradiance and temperature, where when one either of these conditions was not optimal, N response was reduced. Since the temperatures were lower in the week prior to the second harvest (Appendix B, Table 3), it is possible that the lycopene synthesis was not optimized.

Phosphorus fertilization did not affect the lycopene content of the tomatoes for both the early and later harvest dates (Table 4.31). Phosphorus fertilization was found to be less efficient in increasing lycopene content than N fertilization (De Pascale et al., 2008; Di Cesare et al., 2010). These results are in agreement with the results of the current experiment; as the N fertilization did not constantly affect the lycopene content, it was likely that the P fertilization would have no effect as well. Also, Bruulsema et al., (2004) and Oke et al., (2005) observed that climatic factors and the difference between growing seasons had more effect than P fertilization on the lycopene content of tomatoes.

The lycopene content was not affected by increasing potassium (K) levels in the later harvest. However, for the early harvest, the lycopene content was significantly lower for the control. The maximum lycopene content of 106 $\mu g\ g^{-1}$ was obtained by applying 20 kg ha^{-1}; further increases in the K fertilization rate resulted in a decrease in the lycopene content. Potassium fertilization is the only nutrient that showed a constant positive effect on lycopene concentration (Trudel and Ozbun, 1971). Potassium fertilization was found to promote enzymes that regulate carbohydrate metabolism and lycopene biosynthesis (Fanasca et al., 2006; Hartz et al., 1991 cited in Zdravković et al., 2007).The lack of effect for the later harvest was probably associated with climatic factors, when non-optimal conditions did not allow to the plants to respond to fertilization. However, in 2010, increase in N, P and K fertilization rates did not affect the lycopene content of fresh-market tomatoes vine or post-harvest ripened (Table 4.32).

4.2.2 Effect of time of harvest

The mean value for lycopene content from the four fertilization rates was significantly affected by the time of harvest for two of the three fertilization experiments. The lycopene content of the early harvest was not found to be significantly different from the late harvest for with the P experimental date. Yet, the N and K experiment had 16 and 26 $\mu g\ g^{-1}$ more lycopene respectively for the early harvest than the later one. These finding can be linked to climatic factors. The rainfall for the two weeks prior to the first harvest was less than 15 mm while for the second harvest, there was approximately 40 mm of rain (Appendix B, Table 3). Also the overall mean temperature of a two week period prior to the first harvest was only 2°C greater than that at the second harvest. The temperature reached a minimum of 1.2°C during the period prior to the second harvest. It was shown that lycopene biosynthesis was reduced at temperatures less than 12°C (Dumas et al., 2003). Low temperature and high rates of precipitation could have inhibited lycopene biosynthesis.

4.2.3 Effect of stage of ripeness at harvest and post-harvest

Tomatoes harvested at breaker stage then ripened post-harvest for 17 days contained significantly less (between 12 vs. 30 $\mu g\ g^{-1}$) lycopene than tomatoes harvested at the light red stage and post-harvest ripened for 10 days for the three nutrient experiments. Giovanelli et al., (1999) found that when a*/b* values, which is the ratio of two color index that distinguish different colors according to numerical standards, of tomatoes that were ripened post-harvest were above 2.0. They reported that lycopene accumulation was much greater in post-harvest ripened than in vine-ripened tomatoes. In the current experiment, tomatoes harvested at light red stage were almost completely vine-ripened yet they had more lycopene than the breaker stage. Differences in results might be due to differences in the post-harvest condition. In the current experiment, the tomatoes were kept in cryovac bags (perforated bags), in a room with varying ventilation conditions and subjected to outside temperatures which ranged between 22.5 and 5.4°C for the first 10 days and between 24.6 to 1.1°C for the total of 17 post-harvest days (Appendix B, Table 4), while Giovanelli described the conditions to be a well-ventilated room at 20°C.

Toor and Savage (2006), observed the effect of different post-harvest temperatures on lycopene levels in tomatoes harvested at a light-red stage. They observed that with temperatures of 15 and 25°C there was 1.8 times more lycopene produced than when the tomatoes were subjected to 7°C. Similarly, Javanmardi and Kubota (2006), observed tomatoes exposed to room temperature (25 - 27°C) had a steady increase in lycopene production over 7 days. While tomatoes exposed to 12°C for 7 days had no significant difference in the lycopene content, following that, the tomatoes were subjected to 5°C for another 7 days. The lycopene content was not affected by this temperature. However, they found that the lycopene content was significantly less when tomatoes were exposed to 5°C than 12°C. The mean of the maximum and mean temperature for the first 10 days after harvest was 18 and 13°C respectively (Appendix B, Table 4). It decreased to 16 and 12°C respectively for the following 7 days. The mean minimum temperature also decreased from 5.4 to 1.1°C. These lower temperatures in the additional week of post-harvest ripening could explain the decrease in lycopene biosynthesis.

It is also important to note that some of the tomatoes harvested at the breaker stage (post-ripened for 17 days) had some green colored tissues within the fruit. Therefore, even though the outer portion of tomatoes was red there was still some lycopene that was not synthesized. Whereas tomatoes harvested at light red stage were completely red.

Table 4.31 The effect of nitrogen, phosphorus and potassium fertilization levels on the lycopene content (µg g^{-1}) of tomatoes harvested at the red stage on two dates in 2009 in Sainte-Anne-de-Bellevue

Nutrient	Fertilization rate	Lycopene content (µg g^{-1})	
		10 September	30 September
N	50	77.74	75.78
	90	99.03	69.46
	130	91.58	72.37
	170	90.80	74.63
Significant linear effect in a regression model		0.0518	n/s
Significant quadratic effect in a regression model		0.0700	n/s
Means lycopene content by day		89.785 a	73.059 b
P	0	87.31	76.99
	20	80.11	64.31
	60	89.50	77.88
	120	82.67	78.79
Significant linear effect in a regression model		n/s	n/s
Significant quadratic effect in a regression model		n/s	n/s
Means lycopene content by day		84.895 a	74.351 a
K	0	79.39	68.38
	20	106.37	65.42
	60	98.22	71.67
	120	92.81	67.19
Significant linear effect in a regression model		n/s	n/s
Significant quadratic effect in a regression model		n/s	n/s
Means lycopene content by day		94.196 a	68.163 b

n/s: not significant
Means followed by different letters are significantly different ($P< 0.05$)
Linear and quadratic regressions were considered significant ($P<0.10$)

Table 4.32 The effect of nitrogen, phosphorus and potassium fertilization levels on the lycopene content (μg g^{-1}) of tomatoes harvested at two ripening stages (breaker and red stage) at one harvest date in 2010 in L'Assomption

Nutrient	Fertilization rate	Lycopene content (μg g^{-1})	
		Breaker stage	Red stage
N	50	33.74	47.50
	90	33.16	43.98
	130	35.55	55.54
	170	34.91	41.54
Significant linear effect in a regression model		n/s	n/s
Significant quadratic effect in a regression model		n/s	n/s
Means lycopene content by maturity stage		34.342 a	47.141 b
P	0	35.83	59.42
	20	34.73	49.10
	60	38.29	59.09
	120	31.23	52.66
Significant linear effect in a regression model		n/s	n/s
Significant quadratic effect in a regression model		n/s	n/s
Means lycopene content by maturity stage		35.020 a	55.068 b
K	40	36.44	51.12
	80	37.38	43.52
	160	36.62	54.48
	280	31.57	45.25
Significant linear effect in a regression model		n/s	n/s
Significant quadratic effect in a regression model		n/s	n/s
Means lycopene content by maturity stage		35.503 a	48.592 b

n/s: not significant

Means followed by different letters are significantly different at $P < 0.05$ according to the LSD test

Linear and quadratic regressions were considered significant at $P<0.10$

5. General conclusions

The first objective of this study was to assess the effect of different fertilization levels of nitrogen, phosphorus and potassium on tomato growth by looking at the yield and quality of the fruits. It was hypothesized that higher levels of each of these nutrients would produce higher yields. Both the total and marketable yield were not affected by increasing levels of nitrogen (N). The lack of response to N fertilization may be due to leaching. In Sainte-Anne-de-Bellevue, leaching was associated to high initial soil N levels, while in L'Assomption it was associated to the high fertilization concentrations and the soil type; loamy sand being more prone to leaching. For soils high in initial P in most cases, no additional P fertilizer was required to have maximum yield. In Sainte-Anne-de-Bellevue and in L'Assomption in 2010, the yield was not affected by increasing levels of P. However, the total, marketable and percentage marketable yield in 2009 in L'Assomption, was affected by increasing phosphorus fertilization levels the response being quadratic with a minimum at 60 kg P_2O_5 ha^{-1}. It was hypothesized that the response might have been associated to mycorrhizae influence. It was observed in Sainte-Anne-de-Bellevue that for soils high in initial K no additional K fertilizer was required to have maximum yield. However, for soils low in initial K, such as L'Assomption, especially in 2009, applying 160 kg K2O ha^{-1} was found to maximize yields. Overall, our results suggest that most tomatoes fields in Quebec are over fertilized.

The second objective was to determine which fertilization level of N, P, and K lead to highest concentration of lycopene. It was hypothesized that higher levels of N, P and K would increase lycopene content in tomatoes. However, P fertilization did not affect lycopene content. Both and N and K fertilization increased lycopene production and it was maximized when applying 90 and 20 kg ha^{-1} of N and K, respectively, but only for early harvests. Tomatoes harvested earlier in the season, at a more advanced ripening stage and with a shorter post-harvest period had significantly more lycopene.

The third objective was to determine optimum time of harvest to have highest production of lycopene. It was hypothesized that the tomatoes harvested later would contain more lycopene that the tomatoes harvested earlier in the season. This was shown to be the opposite. Tomatoes harvested at an early stage had between 16 and 26 µg g^{-1} more lycopene than the ones harvested at a later date. This response was associated with climatic factors.

The final objective was to determine which ripening stage and post-harvest time lead to highest production of lycopene. It was hypothesized that the tomatoes harvested at a light-red stage and ripened post-harvest to a red stage would contain more lycopene than the ones harvested at the breaker stage and post-harvest ripened to the same stage. This hypothesis was confirmed.

6. Future research

1. In the current study, four levels of fertilization were tested for each of the three nutrients. It is suggested to increase the number of rates tested to better determine the exact crop response.
2. In the nitrogen (N) fertilization experiment there was a constant application of 50 kg N ha^{-1} as preplant. Results showed that this pre-plant rate might have been too high. This should be tested with lower preplant fertilization rates. It could also be interesting to include higher rates as there was no decrease in the yield with the rates that were used, and some studies have shown that the fertigation technique requires higher fertilization rates (Zhang et al., 2010 a and b).
3. It could be valuable information to determine the soil mycorrhizae activity; as it was implicated in the yield response to increasing phosphorus rates.
4. A critical step that needs major improvements is the fertigation technique. It was mentioned in section 4.1 that the schedule of irrigation/fertigation plays a major role in the distribution of the N in the soil. Li et al, (2003) showed that the combination that kept the most nitrate in the upper portion of the soil profile was 1:2:1 water-fertigation-water, thus using this combination would be most valuable to reduce the current problem of leaching.
5. Once the fertigation method is perfected, it could be interesting to apply potassium through fertigation. Applying this nutrient through fertigation has done in other regions of North America. Like N, a nutrient that can be readily injected in the fertigation system without much clogging and is mostly required for fruit quality later in the season.
6. For all three nutrients, leaching potential was estimated based on the residual nutrients in the soil; however, better methods to calculate leaching could be used to better understand the effect of the fertilization on the soil nutrient level.
7. It is necessary to have replicates for the foliar and fruit biomass samples in order to perform statistical analyses.

References Cited

Abdul-Baki, A., Spence, C., Hoover, R. 1992. Black p.olyethylene mulch doubled yield of fresh-marketable field tomatoes. HortScience. 27(7): 787-789.

Agarwal, S., and Rao, A.V. 1998a. Bioavailability and in vivo antioxidant properties of lycopene from tomato products and their possible role in the prevention of cancer. Nutrition and Cancer. 31:199–203.

Agarwal, S., and Rao, A.V. 1998b. Tomato lycopene and low density lipoprotein oxidation: a human dietary intervention study. Lipids. 33:981–984.

Agriculture and Agri-Food Canada. 2002. 2002-2003 Canadian Vegetable Situation and Trends (Excluding potatoes). Market and Industry Services Branch. Ottawa. Canada. 16 pages.

Alfaro, M.A., Jarvis, S.C., Gregory, P.J. 2004. Factors affecting potassium leaching in different soils. Soil Use and Management. 20: 182-189.

Alba, R., Cordonnier-Pratt, M.-M., Pratt, L.H. 2000. Fruit-localized phytochromes regulate lycopene accumulation independently of ethylene production in tomato. Plant Physiology. 123:363-370.

Almeselmani, M., Pant, R.C., Singh, B. 2010. Potassium level and physiological response and fruit quality in hydroponically grown tomato. International Journal of Vegetable Science. 16(1): 85- 99.

Alva, A.K., Paramasivam, S., Fares, A., Delgado, J.A., Mattos, Jr, D., Sajwan, K. 2006. Nitrogen and irrigation management practices to improve nitrogen uptake efficiency and minimize leaching losses. Journal of Crop Improvement. 15(2): 369-420.

Amati, M., Dekker, E., Linger, T. V., Pinners, E., Tam, S.C.A. 2002. How to grow tomato and peppers. Agrodok 17: Wageningen, Netherlands. 71 pages.

Ames, B.N., Gold, L.S., Willet, W.C. 1995. Causes and prevention of cancer. Proceedings of the National Academy of Science USA. 92:5258–5265.

Askegaard, M. and Eriksen, J. 2000. Potassium retention and leaching in an organic crop rotation of loamy sand as affected by contrasting potassium budgets. Soil Use and Management. 16: 200-205.

Aziz, A.B. 1968. Seasonal changes in the physical and chemical composition of tomato fruits as affected by nitrogen levels. H. Veenman. Mededelingen Landbouwhogeschool Wageningen. 68(7): 1-6.

Badr, M.A. and El-Yazied, A. 2007. Effect of fertigation frequency from subsurface drip irrigation on tomato yield grown on sandy soil. Australian Journal of Basic and Applied Sciences. 1(3): 279-285.

Badr, M.A., Abou Hussein, S.D., El-Tohamy, W.A., Gruda, N. 2010. Nutrient uptake and yield of tomato under various methods of fertilizer application and levels of fertigation in arid lands. Gesunde Pflanzen. 62(1): 11-19.

Bar-Yosef, B. and Sheikholslami, M.R., 1976. Distribution of water and ions in soils irrigated and fertilized from a trickle source. Soil Science Society American Journal. 40 (4): 575–582.

Bargel, H. and Neinhuis, C. 2005. Tomato (*Lycopersicon esculentum* Mill.) fruit growth and ripening as related to the biomechanical properties of fruit skin and isolated cuticle. Journal of Experimental Botany. 56(413): 1049-1060.

Barreiro, J., Milano, M., Sandoval., A.J. 1997. Kinetics of colour change of double concentrated tomato paste during thermal treatment. Journal of Food Engineering. 33(3-4): 359-371.

Barrett, D.M. and Anthon, G. 2001. Lycopene content of California-grown tomato varieties. Acta Horticulturae. 54: 165-173.

Batheja, K., Sinha, A.K., Seth, S. 2009. Studies on water treatment for removal of nitrate. Asian Journal Experimental Sciences. 23(1): 61-66.

Battilani, A., Plauborg, F.L., Hansen, S. 2008. Nitrogen uptake and nitrogen use efficiency of fertigated potatoes. Acta Horticulturae. 792: 61-68.

Beegle, D.B. and Lingenfelter, D.D. 1995. Soil acidity and aglime. Penn State University Cooperative Extension. Agronomy facts 3. RV5M995ps1508.

Ben-Oliel, G., Kant, S., Naim, M., Rabinowitch, H.D., Takeoka, G.R., Buttery, R.G., Kafkafi, U. 2004.Effects of ammonium to nitrate ratio and salinity on yield and fruit quality of large and small tomato fruit hybrids. Journal of Plant Nutrition. 27(10): 1795-1812.

Benard, C., Gautier, H., Bourgaud, F., Grasselly, D., Navez, B., Caris-Veyrat, C., Weiss, M., Genard, M. 2009. Effect of low nitrogen supply on tomato (*Solanum lycopersicum*) fruit yield and quality with special emphasis on sugars, acids, ascorbate, carotenoids, and phenolic compounds. Journal of Agriculture and Food Chemistry. 57: 4112-4123.

Bergstrom, L. and Brink, N. 1986. Effects of differentiated applications of fertilizer N on leaching losses and distribution of inorganic N in the soil. Plant and Soil. 93: 333-345.

Bieche, B.J. Ed. 1999. Part 2. Proc. Workshop on irrigation and fertigation of processing tomato. Acta Horticulturae. 487:477-178.

Bohm, F., Tinkler, J.H., Truscott, T.G. 1995. Carotenoids protect against cell membrane damage by the nitrogen dioxide radical. Nature Medicine. 1:98–99.

Boileau, T. W. M., Boileau, A. C., Erdman, J. W. 2002. Bioavailability of all-trans and cis-isomers of lycopene. Experimental Biology and Medicine. 227 : 914–919.

Bosland, P.W. and Votava, E. 2000. Peppers: Vegetable and Spice Capsicums. Issue 12 of Crop Production Science in Horticulture. CABI. 204 pages.

Brace Centre for Water Resources Management of McGill University. 2007. Adaptation Measures for the Ontario Fruit Industry Due to Climate Change. Scientific Report. 111pages.

Brandt, S., Pék, Z., Barna, É., Lugasi, A., Helyes, L. 2006, Lycopene content and colour of ripening tomatoes as affected by environmental conditions. Journal of the Science of Food and Agriculture. 86: 568-572.

British Columbia, Ministry of Agriculture and Lands. 2009. Vegetable Production Guide 2008-2009: Beneficial Management Practices for Commercial Growers in British Columbia. Chapter 7 : Crop Recommendations – Tomatoes. 212 pages. URL:" http://www.agf.gov.bc.ca/fieldvegetable/production_guide/2008_2009/tomatoe.pdf ". Page last accessed: 06/29/11.

Brummell, D.A. 2006. Cell wall disassembly in ripening fruit. Functional Plant Biology. 33: 103-119.

Bruulsema, T.W., Fixen, P.E., Snyder, C.S. 2004. Fertilizer nutrient recovery in sustainable cropping systems. Better Crops. 88: 15-17.

Burt, C.M. 1998. Chemicals for fertigation. Proceedings of International Irrigation Show. Irrigation Association Annual Conference. IA's 19th Annual Conference. Nov. 1-3. San Diego, California. Irrigation Training and Research Center. 8 pages.

Buzby, J.C., Wells, H.F., Kumcu, A., Lin, B.-H., Lucier, G., Perez, A. 2010. Canned Fruit and Vegetable Consumption in the United States: An Updated Report to Congress. Administrative Publication No. (AP-050). USDA. Economic Research Service. 34 Pages.

Camelo, A.F. and Gómez, P.A. 2004. Comparison of color indexes for tomato ripening. Horticultura Brasileria. 22(3): 534-537.

Carpenter, S.R. 2008. Phosphorus control is critical to mitigating eutrophication. Proceedings of the National Academy of Sciences. 105(32): 11039-11040.

Carrari, F. and Fernie, A.R. 2006. Metabolic regulation underlying tomato fruit development. Journal of Experimental Botany. 57(9): 1883-1897.

Carrier, A. 2009. La Semaine Verte. Reportage : La fin de la tomate des champs? [Audio on the Internet]. Put online on September 12th, 2009.. 9:06 min. sound. URL: " http://www.radio-canada.ca/audio-video/pop.shtml#urlMedia%3Dhttp://www.radio-canada.ca/Medianet/2009/CBF/LaSemaineVerte200909120607_1.asx&promo%3DZAPmedia_LaSemaineVerte ". Page last accessed: 06/29/11.

Carrillo-Lopez, A. and Yahia, E.M. 2010. Qualitative and quantitative changes in carotenoids and phenolic compounds in tomato fruit during ripening. Acta Horticulturae.877: 1303-1308.

Carter, M.R. and Gregorich, E.G. 2008. Soil Sampling and Methods of Analysis. CRC Press. Boca Raton, Florida. USA. 1224 pages.

Centre d'Expertise en Analyse Environnementale du Québec et Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (CEAEQ and MAPAQ). 2003. Détermination de l'azote ammoniacal et des nitrates dans les sols agricoles : méthode par titrimétrie. MA 1010 – NO 1.0. Ministère de l'Environnent du Québec. 10 pages.

Centre de Référence en Agriculture et Agroalimentaire du Québec (CRAAQ). 2003. Guide de référence en fertilisation. 1st Edition. Centre de référence en agriculture et agroalimentaire du Québec. Ste Foy, QC. 295 pages.

Chasse, G. A., Mak, M. L., Deretey, E., Farkas, I., Torday, L. L., Papp, J. G. 2001. An ab initio computational study on selected lycopene isomers. Journal of Molecular Structure (Theochem). 57: 27-37.

Cheung, A.Y., McNellis, T., Piekos, B. 1993. Maintenance of chloroplast components during chromoplast differentiation in the tomato mutant *Green flesh*. Plant Physiology. 101: 1223-1229.

Collins, J.K., Perkins-Veazie, P., Roberts, W. 2006. Lycopene: from plants to humans. HortScience. 41(5): 1135-1144.

Condron, L. M., Turner, B. L., Cade-Menun, B. J. 2005 Chemistry and Dynamics of Soil Organic Phosphorus, In: Sims, J.T., Sharpley, A. N. Phosphorus: Agriculture and the Environment. Agronomy Monograph 46. ASA, CSSA, and SSSA, Madison, WI, USA, Pp. 87–121.

Cooperband, L. 2002. Building soil organic matter with organic amendments: A resource for urban and rural gardeners, small farms, turf grass managers and large-scale producers. University of Wisconsin-Madison. Centre for Integrated Agricultural Systems. Wisconsin. USA. 13 pages.

Cousineau, P.A. 2009. Personal Communication - Quebec fresh market tomato standards. Les Maraîchers P A Cousineau & fils, Sainte-Clothilde, QC., Canada.

Cutler, K.D. 1997. Tantalizing tomatoes : Smart tips &tasty picks for gardeners everywhere. Brooklyn Botanic Garden. 21st Century Gardening Series. NY, USA. 111 pages.

Dangler, J.M. and Locascio, S.J. 1990. Yield of trickle-irrigated tomatoes as affected by time of N and K application. Journal of American Society of Horticultural Science. 115: 585-589.

Daniel, T.D., Sharpley, A.N., Edwards, D.R., Wedepohl, R., Lemunyon, J.L. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. Journal of Soil Water Conservation. 49: 30-38.

Davies, J.N., Hobson, G.E. 1981. The constituents of tomato fruit - the influence of environment, nutrition, and genotype. Critical Reviews in Food Science and Nutrition. 15: 205-280.

Dekock, P.C., Hall, A., Inkson, R.H.E. 1979. Active iron in plant leaves. Annals of Botany Company. 43: 737-740.

De Pascale, S., Tamburrino, R., Maggio, A., Barbieri, G., Fogliano V. Pernice R. 2008. Effects of nitrogen fertilization on the nutritional value of organically and conventionally grown tomatoes. Acta Horticulturae. 700: 107-110.

Di Cesare, L.E., Migliori, C., Viscardi, D., Parisi, M. 2010. Quality of tomato fertilized with nitrogen and phosphorus. Short communication. Italian Journal of Food Science. 2 (22): 186- 191.

Di Mascio, P., Kaiser, S., Sies, H. 1989. Lycopene as the most efficient biological carotenoid singlet oxygen quencher. Archives Biochemistry and Biophysics. 274:532–538.

Djodjic, F., Borling, K., Bergstrom, L. 2004. Phosphorus leaching in relation to soil type and soil phosphorus content. Journal of Environmental Quality. 33: 678-684.

Djodjic, F., Ulen, B., Bergstrom, L. 2000.Temporal and spatial variations of phosphorus losses and drainage in a structured clay soil. Water Research. 34 (5): 1687-1695.

Dobermann, A. 2005. Nitrogen use efficiency: state of the art. Proc. IFA International Workshop on Enhanced-Efficiency Fertilisers. Frankfurt, Germany. 16 pages.

Doerge, T.A., R.L. Roth, Gardner, B.R. 1991. Nitrogen fertilizer management in Arizona. University of Arizona College Agr. Rpt. 191025. Tucson. Arizona. USA. 93 pages.

Dorais, M., Ehret, D.L., Papadopoulos, A.P. 2008. Tomato (*Solanum lycopersicum*) health components : from the seed to the consumer. Phytochemistry Review. 7: 231-250.

Dumas, Y., Dadomo, M., Lucca, D., Grolier, P. 2003. Review. Effects of environmental factors and agricultural techniques on antioxidant content of tomatoes. Journal of the Science of Food and Agriculture. 83:369-382.

Egea, I., Barsan, C., Bian, W., Purgatto, E., Latché, A., Chervin, C., Bouzayen, M., Pech, J-C. 2010. Chromoplast differentiation: Current status and perspectives. Plant Cell Physiology. 51(10): 1601-1611.

Environment Canada. 2012. National Climate Data and Information Archive. Canadian Climate Data Online. URL: “http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html “. Page last accessed 19/03/12.

Fanasca, S., Colla, G., Maiani, G., Venneria, E., Rouphael, Y., Azzini, E., Saccardo, F. 2006. Changes in antioxidant content of tomato fruits in response to cultivar and nutrient solution composition. Journal of Agricultural and Food Chemistry. 54: 4319-4325.

FAOSTAT (Food and Agriculture Organization of the United Nations). 2012. Food and Agricultural commodities production. URL: "http://faostat.fao.org/site/567/default.aspx ". Page last accessed: 29/06/11.

Feller, C. and Fink, M. 2005. Growth and yield of broccoli as affected by the nitrogen content of transplants and the timing of nitrogen fertilization. HortScience. 40(5): 1320-1325.

Fertilizer Industry Federation of Australia (FIFA). 2006. Australian Soil Fertility Manual. Third Edition. Csiro Publishing. 176 pages.

Fish, W.W., Perkins-Veazie, P., Collins, J.K. 2002. A quantitative assay for lycopene that utilizes reduced volumes of organic solvents. Journal of Food Composition Analysis. 15: 309-317.

Ford, M.C. 1933. The nature of phosphate fixation in soils. Journal of the American Society of Agronomy. 25:134-144.

Fornelli, F., Leone, A., Verdesca, I., Minervini, F., Zacheo, G. 2007. The influence of lycopene on the proliferation of human breast cell line (MCF-7). Toxicology in Vitro. 21(2): 217-223.

Fraser, P.D., Truesdale, M.R., Bird, C.R., Schuch, W., Bramley, P.M. 1994. Carotenoid biosynthesis during tomato fruit development. Plant Physiology. 105: 405-413.

Gabor, B. and Wiebe, W. (Eds) 1997. Tomato Diseases. A practical guide for seedsmen, growers and agricultural advisors. Seminis Vegetable Seeds, Inc., California USA. 62 pages.

Gautier, H., Rocci, A., Buret, M., Grasselly, D., Dumas, Y., Causse, M. 2005. Effect of photoselective filters on the physical and chemical traits of vine-ripened tomato fruits. Canadian Journal of Plant Science.85: 439-446.

Geisseler, D., Linsler, D., Piegholdt, C., Andruschkewitsch, R., Raupp, J., Ludwig, B. 2011. Distribution of phosphorus in size fractions of sandy soils with different fertilization histories. Journal of Plant Nutrition and Soil Science. 174: 891-898.

Ghiri, M.N., Abtahi, A., Karimian, N., Owliaie, H.R., Khormali, F. 2011. Kinetics of non-exchangeable potassium release as a function of clay mineralogy and soil taxonomy in calcareous soils of southern Iran. Archives of Agronomy and Soil Science. 57(4): 343-363.

Gillaspy, G., Ben-David, H., Grulssem, W. 1993. Fruits: A developmental perspective. The Plant Cell. 5: 1439-1451.

Giovanelli, G., Lavelli, V., Peri, C., Nobili, S. 1999. Variation in antioxidant components of tomato during vine and post-harvest ripening. Journal of the Science of Food and Agriculture. 79: 1583-1588.

Gleason, M.L. and Edmunds, B.A. 2006. Tomato diseases and disorders. Iowa State University. University Extension. PM 1266. 12 pages.

Godbout, G. 1957. Étude Pédologique du comte de Berthier. Ministère de L'Agriculture. Bulletin technique No. 5. Divisons des Sols École Supérieure d'Agriculture. Sainte-Anne-de-la-Pocatière, Comte de Kamouraska. 80 pages.

Grierson, D. and Kader, A.A. 1986. Fruit ripening and quality. In: Atherton, J.G. and Rudich, J. (Eds). The Tomato Crop. Chapman and Hall, London, UK. Pp. 241-275.

Griffin, G., Jokela, W., Ross, D., Pettinelli, D., Morris, T., Wolf, A. 2009. Chapter 4 Recommended Soil Nitrate Tests. Recommended Soil Testing Procedures for the Northeastern United States. Cooperative Bulletin. 493. 12 pages.

Gunes, A., Alpaslan, M., Inal, A. 1998. Critical nutrient concentrations and antagonistic and synergistic relationships among the nutrients of NFT-growth young tomato plants, Journal of Plant Nutrition. 21 (10): 2035-2047.

Gunter, C.C. 2010. Potassium application timing and method for the reduction of yellow shoulder in processing tomato. Acta Horticulturae. 852: 291-296.

Halbrooks, M.C.and Wilcox, G.E. 1980. Tomato plant development and elemental accumulation. Journal of American Society of Horticultural Science. 105: 826-828.

Halliday, D.J. and Trenkel, M.E. 1992. IFA World Fertilizer Use Manual. International Fertilizer Industry Association. Paris. France. 632 pages.

Halliwell, B. 1994. Free radicals, antioxidants and human disease: curiosity, cause or consequence? Lancet. 344:721–724.

Hansen, L. and Pedersen, E. F. 1975. Losses of nutrients by leaching in agricultural plant production. Tidsskr. Planteav (Journal of Plant Production). 79: 670- 68.

Hanson, B.R., Hopmans, J., Simunek, J. 2005. Effect of fertigation strategy on nitrogen availability and nitrate leaching using microirrigation. HortScience. 40 (4): 1096- 1147.

Hart, D.J. and Scott, K.J. 1995. Development and evaluation of an HPLC method for the analysis of carotenoids in foods, and the measurement of the carotenoid content of vegetables and fruits commonly consumed in the UK. Food Chemistry. 54: 101–111.

Hartz, T.K. 1991. Potassium fertilization effects on processing tomato yield and fruit quality. Proceedings of the tomato& health seminar, (Ed. Bieche, B.) Pamplona: 3rd Worldwide Congress of the Tomato Processing Industry, pp. 45-49.

Hartz, T.K. and Hochmuth, G.J. 1996. Fertility management of drip-irrigated vegetables. Vegetable Research & Information Center. University of California. 8 pages.

Hartz, T.K, Johnstone, P.R., Francis, D.M. Miyao, E.M. 2005. Processing tomato yield and fruit quality improved with potassium fertigation. HortScience. 40(6): 1862-1867.

Hartz, T.K., Miyao, G., Muller, R.J., Cahn, M.D., Valencia, J., Brittan, K.L. 1999. California, Potassium requirements for maximum yield and fruit quality of processing tomato. Better Crops. 83 (2): 26- 28.

Hebbar, S.S., Ramachandrappa, B.K. Nanjappa, H.V., Prabhakar, M. 2004. Studies on NPK drip fertigation in field grown tomato (*Lycopersicon esculentum* Mill.). European Journal of Agronomy. 21(1): 117-127.

Heeb, A., Lundegardh, B., Ericsson, T., Savage, G.P. 2005. Effects of nitrate-, ammonium-, and organic-nitrogen-based fertilizers on growth and yield of tomatoes. Journal of Plant Nutrition and Soil Science. 168: 123-129.

Helyes, L., Lugasi, A., Pék, A. 2007. Effect of natural light on surface temperature and lycopene content of vine ripened tomato fruit. Canadian Journal of Plant Science. 87: 927-929.

Hemwall. J.B. (Ed). The Fixation of Phosphorus by Soils. In: Norman. A.G. 1957. Advances in Agronomy. Volume 9. Academic Press. N.Y. USA. 308 pages.

Heuvelink, E. 2005. Tomatoes. Crop Production Scicence in Horticulture 13. CABI Publishing. Massachusetts. USA. 339 pages.

Hidetoshi, A. 2007. Changes in nutrient absorption during growth of cherry tomato in hydroponic culture. Bulletin of Fukuoka University of Education. 56(3):9–13.

Ho, L.C. and Hewitt, D.J. 1986. Fruit development. In: Atherton J.G. and Rudich, J. (Eds.). The Tomato Crop: A Scientific Basis for Improvement. Chapman and Hall, London, UK. Pp. 201-240.

Hochmuth, G. and Hanlon, E. 2000. A Summary of N, P, and K Research with Tomato in Florida. University of Florida. IFAS Extension. SL355. 38 pages. URL: "http://edis.ifas.ufl.edu/cv236 ". Page last accessed: 03/25/12.

Howard, R. J., Garland, J.A., Seaman, W.L. (Eds.) 1994. Diseases and Pests of Vegetable Crops in Canada: an Illustrated Compendium. The Canadian Phytopathological Society. Entomological Society of Canada. Canada. 554 pages.

Jakobsen, S.T. 1993. Interaction between plant nutrients: III. Antagonism between potassium, magnesium, calcium. Acta Agriculturae Scandinavica. Section B. Soil and Plant Science. 43(1):1-5.

Javanmardi, J. and Kubota, C. 2006. Variation of lycopene, antioxidant activity, total soluble solids and weight loss of tomato during postharvest storage. Postharvest Biology and Technology. 41(2): 151-155.

Jones, J.B. 1999. Tomato Plant Culture: In the Field, Greenhouse, and Home Garden. CRC Press LLC. Florida. USA. 199 pages.

Jones, J.B. 2008. Tomato Plant Culture: In the Field, Greenhouse, and Home Garden. Second Edition. CRC Press Taylor & Francis Group. Florida. USA. 399 pages.

Jones, B.L. and Porter, J.W. 1999. Biosynthesis of carotenes in higher plants. CRC Critical Reviews in Plant Science. 3:295-324.

Kabu, K.L. and Toop, E.W. 1970. Influence of potassium-magnesium antagonism on tomato plant growth. Canadian Journal of Plant Science. 50: 711-715.

Kafkafi, U. 2005. Global aspects of fertigation usage. In: Imas. P. and Price, M.R. (Eds.). Fertigation: Optimizing the Utilization of Water and Nutrients. IPI Proceedings fertigation symposium China. 20-24 September. Pp.8-22.

Kang, J.-H., Liu, G., Shi, F., Hones, D.A., Beaudry, R.M., Howe, G.A. 2010. The tomato *odourless-2* mutant is defective in trichome-based production of diverse specialized metabolites and broad-spectrum resistance to insect herbivores. Plant Physiology. 154: 262-272.

Kelley, W.T. and Boyhan, G.E. 2010. Commercial Tomato Production Handbook. B 1312. University of Georgia Cooperative Extension. CAES Publications. 48 pages. URL: "http://www.caes.uga.edu/applications/publications/files/pdf/B%201312_3.PDF". Page last accessed: 06/29/11.

Kemble, J.M., Tyson, T.W., Curtis, L.M. 2004. Guide to Commercial Staked Tomato Production in Alabama. Alabama Cooperative Extension System. ANR-1156. 12 pages. URL:" http://www.aces.edu/pubs/docs/A/ANR-1156/ANR-1156.pdf ". Page last accessed: 06/29/11.

Kingery, W.L., Wood, C.W., Delaney, D.P. Williams, J.C., Mullins, G.L. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. Journal of Environmental Quality. 23: 139-147.

Klein, D., Kumar, R., Köpke, U. 2005.Influence of management practices on quality and biodiversity of tomatoes in Germany. Researching Sustainable Systems – International Scientific Conference on Organic Agriculture, Adelaide, Australia, September 21-23. 4 Pages.

Knox, E., and D.W. Moody. 1991. Influence of hydrology, soil properties, and agricultural land use on nitrogen in groundwater. In: Follett, R.F., Keeney, D.R., Cruse, R.M. (Eds.) Managing nitrogen for ground water quality and farm profitability. SSSA, Madison, WI. USA. Pp. 1–7.

Kobryń, J. and Hallmann, E. 2004. The effect of nitrogen fertilization on the three tomato types cultivated on rockwool. Acta Horticulturae. 691: 341-348.

Koide, R.T. and Li, M.1990. On host regulation of vesicular-arbuscular mycorrhizal symbiosis. New Phytologist. 114: 59-74.

Krumbein, A., Schwarz, D., Kläring, H.-P. 2006. Effects of environmental factors on carotenoid content in tomato (*Lycopersicon escolentum* (L.) Mill.) grown in a greenhouse. Journal of Applied Botany and Food Quality. 80(2): 160-164.

Kuti, J.O. and Kouru, H.B. 2005. Effects of genotype and cultivation environment on lycopene content in red-ripe tomatoes. Journal of the Science of Food and Agriculture. 85: 2021-2026.

Lau, T.-C. and Stephenson, A.G. 1994. Effects of soil phosphorus on pollen production, pollen size, pollen phosphorus content, and the ability to sire seeds in Cucurbita pepo (Cucurbitaceae). Sexual Plant Reproduction. 7(4):215-220.

Lerner, B.R. 2001. Tomatoes. Purdue University Cooperative Extension Service. Department of Horticulture. West Laffayette, IN. 5 pages.

Le Strange, M. W. L., Schrader, T., Hartz, K. 2000. Fresh-market tomato production in California University of California, Division of Agriculture and Natural Resources Publication 8017. 3. 8 pages.

Li, J., Zhang, J., Rao, M. 2004. Wetting patterns and nitrogen distribution as affected by fertigation strategies from a surface point source. Agricultural Water Management. 67: 89-104.

Li, J., Zhang, J., Ren, L. 2003. Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. Irrigation Science 22 (1): 19–30.

Locascio, S.J., Hochmuth, G.J., Rhoades, S.M., Olson, S.M., Smajstrla, A.G. Hanlon, E.A. 1997. Nitrogen and potassium application scheduling effects on drip-irrigated tomato yield and leaf tissue analysis. HortScience 32:230-235.

Lu, Y., Etoh, H., Watanabe, N. 1995. A new carotenoid, hydrogen peroxide oxidation products from lycopene. Bioscience, Biotechnology and Biochemistry. 59: 2153–2155.

Magdoff, F.R., Jokela, W.E., Fox, R.H., Griffin, G.F. 1990. A soil test for nitrogen availability in the northeastern United States. Communications in Soil Science and Plant Analysis. 21(13-16): 1103-1115.

Maguire, R.O. and Sims, J.T. 2002. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Mehlich 3.Soil Science Society of America Journal. 66: 2033:2039.

Marim, B.G., da Silva, J.H., Guimaraes, M.A., Belfort, G. 2005. Sistemas de tutoramento e conducao do tomateiro visando producao de frutos para consumo *in natura*. Horticultura Brasileira. 23: 951-955.

Marković, K., Krbavčić, I.P., Krpan, M., Bicanic, D., Vahčić, N. 2010. The lycopene content in pulp and peel of five fresh tomato cultivars. Acta Alimentaria. 39(1): 90-98.

Marschner, H. 1995. Mineral Nutrition of Higher Plants. Second Edition. Academic Press Limited. San Diego. California. USA. 889 pages.

Marschner, P. 2011. Marschner's Mineral Nutrition of Higher Plants. Third Edition. Academic Press. Technology & Engineering. California. USA. 672 page.

Maynard, D.N. and G.J. Hochmuth. 1997. Knott's Handbook for Vegetable Growers. John Wiley & Sons Inc, New York. USA. 582 pages.

Maynard, D.N. and Hochmuth, G.J. 2007. Knott's Handbook for Vegetable Growers. Fifth Edition. John Wiley & Sons, Inc. New Jersey, USA. 621 pages.

McNeal. B.L., Stanley, C.D., Graham, W.D., Gilreath, P.R., Downey, D., Creighton, J.F. 1995. Nutrient loss trends for vegetables and citrus fields in west central Florida. I. Nitrate. Journal of Environmental Quality. 25: 95–100.

McQuaker, N.R., Brown, D.F., Kluckner P.D. 1979. Digestion of environmental materials for analysis by inductively coupled plasma- atomic emission spectrometry. Analytical Chemistry. 51(7):1082-1084.

Menary, R.C. and van Staden, J. 1976. Effect of phosphorus nutrition and cytokinins on flowering in the tomato, *Lycopersion esculentum* Mill. Australian Journal of Plant Physiology. 3(2): 201-205.

Mohammad, M.J. 2004. Squash yield, nutrient content and soil fertility parameters in response to methods of fertilizer application and rates of nitrogen fertigation. Nutrient Cycling in Agrosystems. 68(2): 99-108.

Moigradean, D., Lazureanu, A., Gogoasa, I., Poiana, M.-A., Harmanescu, M., Gergen, I. 2007. Influence of NPK fertilization on nutritional quality of tomatoes. Buletin Universitatea de Ştiinţe Agricole şi Medicină Veterinară Cluj-Napoca. ISSN 1454-2382. 64: 282–286.

Monaghan, J.M. and Wood, M. 2010. Improved efficiency of nutrient and water use for high quality field vegetable production using fertigation. Acta Horticulturae. 852: 145-152.

Montagu, K.D. and Goh, K.M. 1990. Effects of forms and rates of organic and inorganic nitrogen fertilizers on the yield and some quality indices of tomatoes (*Lycopersicon esculentum* Mill.) New Zealand Journal Crop Horticultural Science. 18:31-37.

Morse, A. 2009. Floral scent and pollination of greenhouse tomatoes. Master Thesis. Guelph University. ON. Canada. 139 pages.

Mortensen, A. and Skibsted, L.H. 1997. Relative stability of carotenoid radical cations and homologue tocopheroxyl radicals. A real time kinetic study of antioxidant hierarchy. FEBS Letters. 417:261–266.

Mulvaney, R.L., Khan, S.A., Ellsworth, T.R. 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. Technical Reports: Plant and Environment Interactions. Journal of Environmental Quality. 38: 2295-2341.

Nayak, A. K., Kanwar, R.S., Rekha, P.N., Hoang, C.K., Pederson, C.H. 2009. Phosphorus leaching to subsurface drain water and soil P buildup in a long-term swine manure applied corn-soybean rotation system. International Agricultural Engineering Journal. 18 (3-4): 25-33.

None. 2010. Tomatoes: Fresh Market and Processing. Ohio Vegetable Production Guide. Bulletin 672-10. The Ohio State University. Ohio. USA. Pp. 270-285.

Oded, A., Uzi, K. 2003. Enhanced performance of processing tomatoes by potassium nitrate-based nutrition. Acta Horticulturae. 613: 81-87.

Oke, M., Ahn, T., Schofield, A., Paliyath, G. 2005. Effects of phosphorus fertilizer supplementation on processing quality and functional food ingredients in tomato. Journal of Agricultural and Food Chemistry. 53: 1531-153.

Olson, S.M., Stall, W.M., Vallad, G.E., Webb, S.E., Smith, S.A., Simonne, E.H., McAvoy, E.L., Santos, B.M. 2011. Tomato Production in Florida. Chapter 23. In: University of Florida. 2011. Vegetable Handbook. IFAS Extension 2010-2011. Pp. 295-316.

Ontario Ministry of Agriculture Food & Rural Affaires (OMAFRA) 1990. Irrigation Scheduling for Tomatoes: Water Budget Approach. Fact Sheet. URL:” http://www.omafra.gov.on.ca/english/crops/facts/90-049.htm”. Page last accessed: 02/07/11.

Ontario Ministry of Agriculture Food & Rural Affaires (OMAFRA). 2001. Growing Greenhouse Vegetables. Publication 371. Ontario Ministry of Agriculture, Food, and Rural Affairs. Toronto Canada. 116 pages.

Ontario Ministry of Agriculture Food & Rural Affaires (OMAFRA). 2006. Tomatoes – Fertility. URL: "http://www.omafra.gov.on.ca/english/crops/pub363/9-fert-tomatoes.htm ". Page last accessed: 21/03/11.

Ontario Ministry of Agriculture Food & Rural Affaires (OMAFRA). 2010. Tomatoes Fertility. Vegetable Production Recommendations 2010-2011. Publication 363SE, Supplement. Toronto. ON. Canada.

Ontario Ministry of Agriculture Food & Rural Affaires (OMAFRA). 2011. Field Tomato Grading and Packing Manual. URL:" http://www.omafra.gov.on.ca/english/food/inspection/fruitveg/manuals/field_tomatoes.htm". Page last accessed: 08/21/11.

Peet, M.M. 1996. Tomato. In: Peet, M.M. (Eds.). Sustainable Practices for Vegetable Production in the South. Focus Publishing, R. Pullins Company, Newburyport, MA, Pp. 149-157.

Persson, J.-A. 2008. Handbook for Kjeldahl Digestion: A Recent Review of the Classical Method with Improvements Developed by Foss. Fourth Edition. Foss. Hilleroed Danmark. 84 pages.

Petzoldt, C. (Ed.) 2011. Chapter 27 – Tomatoes Field. Integrated Crop & Pest Management Guidelines for Commercial Vegetable Production. Cornell Cooperative Extension Publication. NYS IPM Program. URL: "http://www.nysaes.cals.cornell.edu/recommends/27frameset.html". Page last accessed: 06/29/11.

Picken, A.J.F., Stewart, K., Klapwijk, D., 1986. Germination and Vegetative Development. In: Atherton, J.G., Rudich, J. (Eds.). The Tomato Crop: A Scientific Basis for Improvement. Chapman and Hall, London, UK. Pp.111-157.

Pincemail, J. 1995. Free radicals and antioxidants in human disease. In: Favier, A.E., Cadet, J., Kalyanaraman, B., Fontecave, M., Pierre, J.-L. (Eds): Analysis of Free Radicals in Biological Systems. Basel, Switzerland: Birkhaüser Verlag, Pp 83–98.

Plummer, C. 1999. Modeling the U.S. Processing Tomato Industry. Special Article. USDA. Economic Research Service. Vegetables and Specialities/ VGS-279. Pp. 21-25

Pool-Zobel, B.L., Bub, A., Muller, H., Wollowski, I., Rechkemmer, G. 1997. Consumption of vegetables reduces genetic damage in humans: first result of a human intervention experiment with carotenoid-rich foods. Carcinogenesis. 18:1847–1850.

Preedy, V.R., Wateson, R.R. 2008. Tomatoes and Tomato Products, Nutritional, Medicinal and Therapeutic Properties. Science Publishers. Enfield, New Hampshire, USA. 643 Pages.

Pretty, J.N., Brett, C., Gee, D., Hine, R.E., Mason, C.F., Morison, J.I.L., Raven, H., Rayment, M.D., van der Bijl, G. 2000. An assessment of the total external costs of UK agriculture. Agricultural Systems. 65(2): 113-136.

Pujos, A. and Morard, P. 1997. Effects of potassium deficiency on tomato growth and mineral nutrition at the early production stage. Plant and Soil. 189:189-196.

Qawasmi, W., Mohammad, M.J., Najim, H., Qubursi, R. 1999. Response of bell pepper grown inside plastic houses to nitrogen fertigation. Communications in Soil Science and Plant Analysis. 30(17-18): 2499-2509.

Ramírez, L.F.S., Muro, J.E., Sànchez, P.G. 2009. Potassium affects the lycopene and β-carotene concentration in greenhouse tomato. Acta Horticulturae. 821: 223-228.

Rao, A.V. and Agarwal, S. 2000. Role of antioxidant lycopene in cancer and heart disease Review. Journal of the American College of Nutrition. 19(5): 563-569.

Raymundo, L.C., Chichester, C.O., Simpson, K.L. 1976. Light-dependent carotenoid synthesis in tomato fruit. Journal of Agriculture and Food Chemistry. 24(1): 59-64.

Reisenauer, H.M. 1979. Soil and Plant-Tissue Testing in California. University of California Division Agriculture Science Bulletin 1897. California USA. 54 pages.

Rubatzky, V.E. and Yamaguchi, M. (Eds.) 1997. World Vegetable: Principles, Production, and Nutritive Values. Chapman and Hall/International Thompson Publishing, New York. 843 pages.

Rutkovienė, V. M., Česonienė, L. Černulienė, S. 2004. Vandens taršos azoto junginiais tyrimai modelinėse nejudinto grunto sistemose. *Žmogaus ir gamtos sauga*: 10 mokslinės konferencijos straipsnių rinkinys. Kaunas, LŽŪU, Pp. 81–83 (in Lithuanian).

Sadler G., Davis J., Dezman D. 1990. Rapid extraction of lycopene and β-carotene from reconstituted tomato paste and pink grapefruit homogenates. Journal of Food Science. 55(5):1460-1461.

Saito, S. and Kano, F.J. 1970. Influence of Nutrients on Growth of Solanaceous Vegetable Plants, Quality and Chemical Composition in their Fruit. (Part 1) On the Effect of Different Phosphate Levels on the Lycopene Content of Tomatoes. Journal Agricultural Science of Tokyo. 14:233-238.

Salo, T., Suojala, T., Kallela, M. 2002. The effect of fertigation on yield and nutrient uptake of cabbage, carrot and onion. Acta Horticulturae.571: 235- 241.

Samaila, A., Amans, E.B. Abubakar, I.U., Babaji, B.A. 2011. Nutritional quality of tomato (*Lycopersicon esculentum* Mill) as influenced by mulching, nitrogen and irrigation interval. Journal of Agricultural Science. 3(1): 266 – 270.

Sanchez, C.A. and Doerge, T.A. 1999. Using nutrient uptake patterns to develop efficient nitrogen management strategies for vegetables. HortTechnology. 9(4): 601-606.

Sanchez-Martin, L., Vallejo, A., Dick, J., Skiba, U.M. 2008. The influence of soluble carbon and fertilizer nitrogen on nitric oxide from two contrasting agricultural soils. Soil Biology and Biochemistry. 40(1): 142-151.

Santos, B. M. and Vallad, G.E. 2010. Cultural practices for vegetable and small fruit crops: Does shoot pruning improve tomato yield and reduce bacterial spot infestation? University of Florida IFAS Extension. Publication # HS1180. URL: “http://edis.ifas.ufl.edu/hs1180”. Page last accessed: 05/04/11.

Sargent, S.A. and Moretti, C.L. 2002. Tomato. 7 pages In: Gross, K.C., Wang, C.Y. and Saltveit, M.E. (Eds). Agricultural Handbook 66 – The Commercial Storage of Fruits, Vegetables and Florist and Nursery Crops. URL: “ http://www.ba.ars.usda.gov/hb66/contents.html “ Page last accessed: 04/16/12 .

Savić, S., Stickić, R., Savić, D., Srdic, M., Zdravkivic, J. 2006. The effect of partial root drying on growth and ions content and distribution on tomato. Acta Horticulturae. 700: 79-82.

Schenk, M.K. 2006. Nutrient efficiency of vegetable crops. Acta Horticulturae. 700: 21-34.

Schröder, J.J., Neeteson, J.J., Oenema, O., Struik, P.C. 2000. Does the crop or the soil indicate how to save nitrogen in maize production?: Reviewing the state of the art. Field Corps Research. 66(2): 151-164.

Schroeder, M.S. and Janos, D.P. 2004. Phosphorus and intraspecific density alter plant responses to arbuscular mycorrhizas. Plant and Soil. 264: 335-348.

Scott, K.J. and Hart, D.J. 1995. Development and evaluation of an HPLC method for the analysis of carotenoids in foods, and the measurement of the carotenoid content of vegetables and fruits commonly consumed in the UK. Food Chemistry. 54: 101-111.

Serio, F., Leo, L., Parente, A., Santamaria, P. 2007. Potassium nutrition increases the lycopene content of tomato fruit. The Journal of Horticultural Science & Biotechnology. 82(6): 941-945.

Sharma, S.K. and Le Maguer, M. 1996. Lycopene in tomato and tomato pulp fractions. Italian Journal of Food Science. 8(2): 107-113.

Sharpley, A.A., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C., Reddy, K.R. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. Journal of Environmental Quality. 23: 437-451.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. Journal of Environmental Quality. 24: 920-926.

Sharpley, A. N. and Rekolainen, S. 1997. Phosphorus in agriculture and its environmental implications. In: Tunney, H., Brookes, O.T., Johnston, A.E. (Eds). Phosphorus Loss from Soil to Water. Center for Agriculture and Biosciences International. New York USA. Pp. 1-53.

Shedeed, S.I., Zaghloul, S.M., Yassen, A.A. 2009. Effect of method and rate of fertilizer application under drip irrigation on yield and nutrient uptake by tomato. Ozean Journal of Applied Science. 2(2): 139-147.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., Zhang, F. 2011. Phosphorus dynamics : form soil to plant. Plant Physiology. 156: 997-1005.

Shi, J. 2000. Lycopene in tomatoes: chemical and physical properties affected by food processing. Critical Reviews in Food Science and Nutrition 40:1-42.

Sibler, A., Xu, G., Levkovitch, I., Soriano, S., Bilu, A., Wallach, R. 2003. Higher fertigation frequency : the effects on uptake of nutrients, water and plant growth. Plant and Soil. 253: 467-477.

Simard, R.R., Beauchemin, S., Haygarth, P.M. 2000. Potential for preferential pathways of phosphorus transport. Journal of Environmental Quality. 29: 97-105.

Simon, K.E., Mandau, U. and Schubach, A. 2002. Beratungs- und Informationssystem Gartenbau – Kennzahlen für den Betriebsvergleich. Publisher Arbeitskreis Betriebswirtschaft im Gartenbau e.V., Hannover, Germany Heft 42.

Sims, J.T., Simard, R.R., Joern, B.C. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality. 27: 277-293.

Singh, U. 2006. Integrated Nitrogen Fertilization for Intensive and Sustainable Agriculture. Journal of Crop Improvement. 15 (2): 259-288

Si-smail, K.G., Bellal, M., Halladj, F. 2007. Effect of potassium supply on the behaviour of two processing tomato cultivars and on the changes of fruit technological characteristics. Acta Horticulturae. 758: 269-274.

Sogbedji, J.M., van Es, H.M., Yang, C.L., Geohring, L.D., Magdoff, F.R. 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. Journal of Environmental Quality. 29: 1812-1820.

Solomon, E.P., Berg, L.R., Matrin, D.W. (Eds). 2004. Biology. Seventh Edition. Cengage Learning. Belmont, CA. USA. 1248 pages.

Stahl, W. and Sies, H. 1992.Uptake of lycopene and its geometrical isomers is greater form heat-processed than from unprocessed tomato juice in humans. American Institute of Nutrition. 122: 2161-2166.

Statistics Canada. 2011. Fruit and Vegetable Production. Catalogue no. 22-003-X. Available online: « http://www.statcan.gc.ca/pub/22-003-x/22-003-x2011001-eng.pdf ». Page last visited: 06/29/11.

Stevenson, F. J. and Cole, M. A. 1999 Cycles of Soil. Second Edition. John Wiley & Sons, New York, USA. 428 pages.

Stout, W.L., Sharpley, A.N., Pionke, H.B. 1998. Reducing soil phosphorus solubility with coal combustion by-products. Journal of Environmental Quality. 27: 111-118.

Suojala, T., Salo, T., Pulkkinen, J. 2006. Drip irrigation and fertigation of pickling cucumber. Acta Horticulturae. 700: 153-156.

Taber, H., Perkins-Veazie, P., Li, S., White, W., Rodermel, S., Xu, Y. 2008. Enhancement of tomato fruit lycopene by potassium is cultivar dependent. HortScience. 43(1): 159-165.

Tan, C.S., Zhang, T.Q., Reynolds, W.D., Warner, J., Drury, C.F. 2009. Farm-scale processing tomato production using surface and subsurface drip irrigation and fertigation. Acta Horticulturae. 823: 77-82.

Tapia, M. L. and Gutierrez, V. 1997. Distribution pattern of dry weight, nitrogen, phosphorus, and potassium through tomato ontogenesis. Journal of Plant Nutrition. 20: 6: 783-791.

Taylor, M.D. and Locascio, S.J. 2004. Blossom-end rot: A calcium deficiency. Journal of Plant Nutrition. 27(1): 123-139.

Tei, F., Benincasa, P., Guiducci, M. 2002. Critical nitrogen concentration in processing tomato. European Journal of Agronomy. 18(1-2): 45-55.

Thomas, R.L. and Jen, J.J. 1975. Phytochrome-mediated carotenoids biosynthesis in ripening tomatoes. Plant Physiology. 56(3): 452-453.

Thompson, R.B., Martinez, C., Gallardo, M., Lopez-Toral, J.R., Fernandez, M.D. 2006. Management factors contributing to nitrate leaching loss from a greenhouse-based intensive vegetable production system. Acta Horticulturae. 700: 179-184.

Thompson, T.L., Doerge, T.A., Godin, R.E. 2002. Subsurface drip irrigation and fertigation of broccoli: 1. Yield, quality and nitrogen uptake. Soil Science Society of America Journal. 66:186-192.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. Science. 292: 281-284.

Toor, R.K., Savage, G.P., Lister, C.E. 2006. Seasonal variations in the antioxidant composition of greenhouse grown tomatoes. Journal of Food Composition and Analysis. 19(1):1-10.

Tremblay, N. and Beaudet, P. 2006. Soil N_{min} content and P_2O_5 export from vegetable crops in Quebec (Canada). Acta Horticulturae. 700: 185- 190 .

Tremblay, N., Scharpf, H.C., Weier, U., Laurence, H., Owen, J. 2001. Régie de l'azote chez les cultures maraîchères – Guide pour une fertilisation raisonnée. Bulletin technique. AAC. Ministère de l'agriculture et de l'agroalimentaire du Canada. Montréal. Canada . 70 pages.

Trudel, M.J. and Ozbun, J.L. 1971. Influence of potassium on carotenoid content of tomato fruit. Journal of American Society of Horticultural Science. 96: 763-765.

Tu, J.C., Liptay, A., Tan, C.S., Drury, C.F., Reynolds, D. 2004. Effects of drip irrigation and drip fertigation on yield of processing tomato in South-Western Ontario. Acta Horticulturae. 653: 195-200.

Ueta, T., Ikeba, T., DongHyuk, A., Kawano, K.K., Matsumoto, E. 2009. Effects of drip fertigation on yield and quality of leaf vegetables, and on efficiency of nitrogen fertigation in outdoor plant culture. Japanese Journal of Soil Science and Plant Nutrition. 80(5): 477-486.

Ulen, B. 1999. Leaching and balances of phosphorus and other nutrients in lysimeters after application of organic manures or fertilizers. Soil Use Manage. 15:56–61.

USDA. 1997. Agricultural Statistics, 1997. USDA National Agriculture Service, United States Government Printing Office, Washington DC.

Virginia Cooperative Extension. 2010. Commercial Vegetable Production Recommendation. VirginiaTech, Virginia State University. Publication no. 456-420. 294 pages. Virginia State, Petersburg. URL:" http://pubs.ext.vt.edu/456/456-420/456-420_pdf.pdf ". Page last accessed: 30/06/11.

Wang, Z. and Li, S. 2004. Effects of nitrogen and phosphorus fertilization on plant growth and nitrate accumulation in vegetables. Journal of Plant Nutrition. 27(3): 539-556.

Wang, K.J., Xu, X.W., Lei, J.Q., Li, S.Y., Wang, Y.D. 2008. The vertical distribution of the root system of the desert highway shelterbelt in the hinterland of the Taklimakan Desert. Chinese Science Bulletin. 53(2): 79-83.

Whalen, J.K, and Sampedro, L. 2010. Soil Ecology and Management. Modular Texts. CABI International Oxfordshire, UK. 296 pages.

Witzlum, J.L. 1994. The oxidation hypothesis of atherosclerosis. Lancet. 344:793–795.

Wu, W.B., Chlang, H.S., Fang, J.Y., Hung, C.F. 2007. Inhibitory effect of lycopene on PDGF-BB-induced signalling and migration in human dermal fibroblasts: a possible target for cancer. Biochemical Society Transactions. 35(5): 1377-1378.

Xiuming, H. and Papadopoulos, A.P. 2004. Effects of calcium and magnesium on plant growth, biomass partitioning, and fruit yield of winter greenhouse tomato. HortScience. 39 (3): 512-515.

Zdravković, J., Marković, Ž., Zdravković, M., Damjanović, M., Pavlović, N. 2007. Relation of mineral nutrition and content of lycopene and β-carotene in tomato (*Lycopersicon esculentum* Mill.) fruits. Acta Horticulturae. 729: 177-181.

Zhang, T., Tan, C., Bruulsema, T. 2006. Fertigation boosts nitrogen for tomatoes and peppers. Better Crops. 90(4): 8-10.

Zhang, T.Q., Tan, C.S., Liu, K. 2009. Phosphorus and potassium application to processing tomatoes grown with drip irrigation. Acta Horticulturae. 823: 97-102.

Zhang, T.Q., Tan, C.S., Liu, K., Drury, C.F., Papadopoulos, A.P., Warner, J. 2010a. Yield and economic assessments of fertilizer nitrogen and phosphorus for processing tomato with drip fertigation. Soil and Crop Management. 102(2): 774- 780.

Zhang, T.Q., Liu, K., Tan, C.S., Hong, J.P., Warner, J. 2010b. Evaluation of agronomic and economic effects of nitrogen and phosphorus additions to green pepper with drip fertigation. Soil and Crop Management. 102(5): 1434-1440.

Zhou, Y.H., Wu, J.X., Zhu, L.J., Shi, K., Yu, J.Q. 2009. Effects of phosphorus and chilling under low irradiance on photosynthesis and growth of tomato plants. Biologia Plantarum. 53(2): 378-382.

Zotarelli, L., Scholberg, J. M., Dukes, M. D., Munoz-Carpena, R. 2007. Monitoring of nitrate leaching in sandy soils: Comparison of three methods. Journal of Environmental Quality. 36. 953-962.

Zotarelli, L., Scholberg, J.M., Dukes, M.D., Munoz-Carpena, R., Icerman, J. 2009. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agricultural Water Management. 96: 23-34.

Appendix A

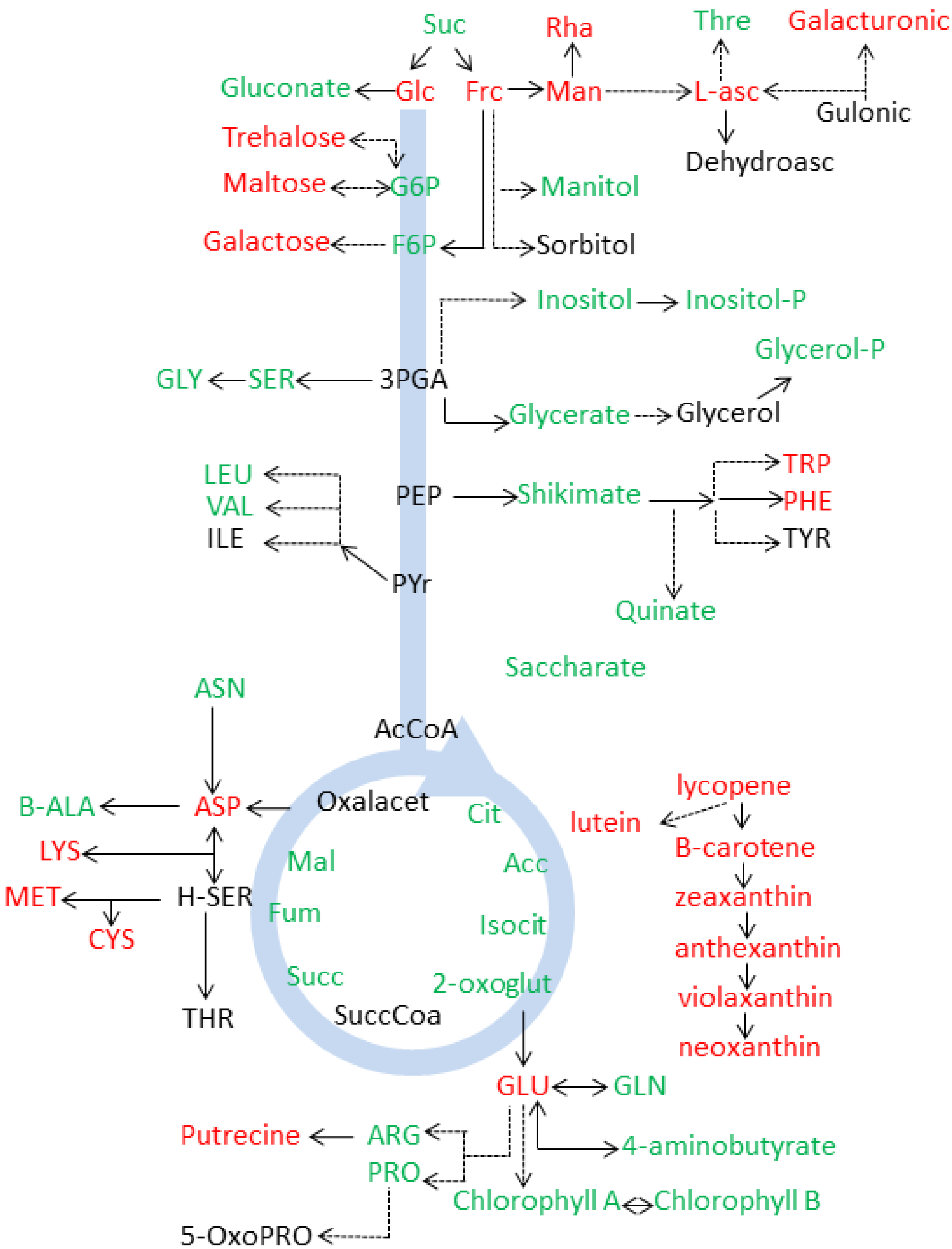

Figure 2.1 Schematic representation of the metabolic changes occurring in the transition from development to ripening processes in tomato fruits. (Sugars, sugar-phosphates, sugar-alcohols, amino and organic acids, pigments, and cell wall components were determined in pericarps of tomato samples taken from 30 days until 60 days after anthesis (DAA). Names of metabolites in red, green, and grey indicate increased, decreased, and no changes, respectively, in the levels of the corresponding metabolite at 60 DAA with respect to 30 DAA. Names in white letters indicate that the corresponding metabolite was not determined, and are included in the graph for explanatory reasons only [Modified from Carrari and Fernie, 2006])

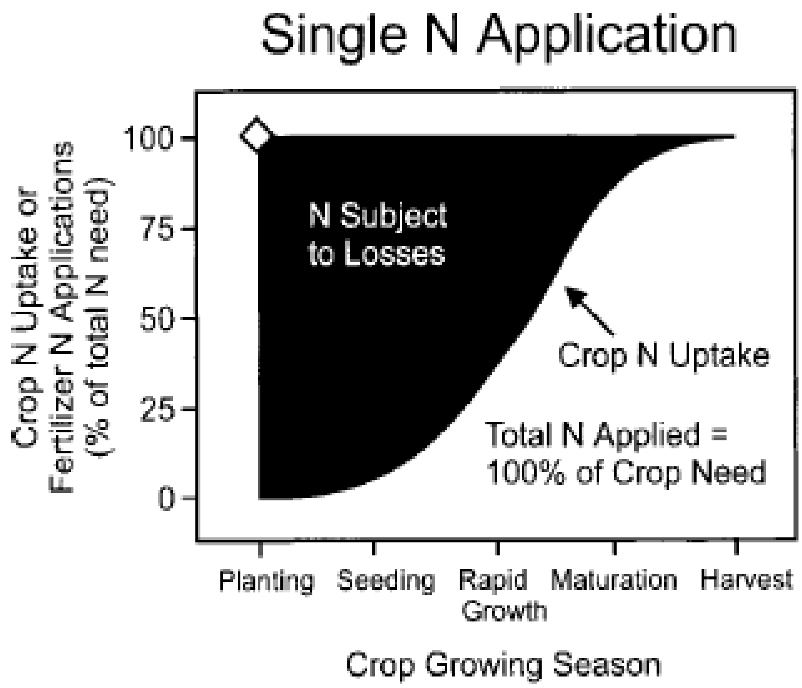

Figure 2.2 Potential losses and crop uptake for nitrogen throughout plant development with a single fertilizer application at planting (found in Sanchez and Doerge, 1999).

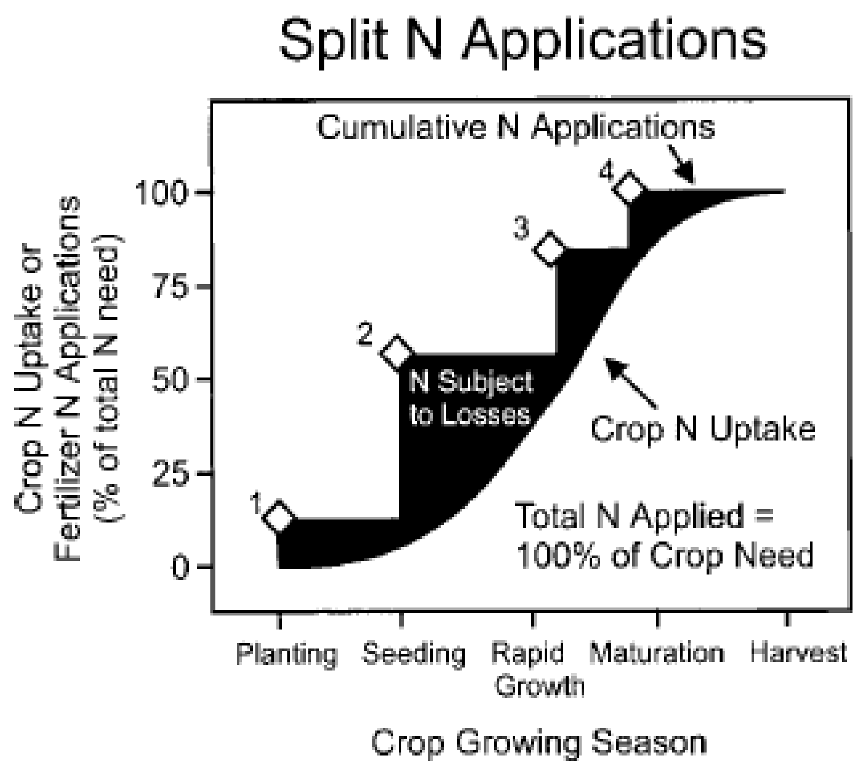

Figure 2.3 Potential loss and crop uptake for nitrogen throughout plant development with multiple smaller fertilizer application at planting that closely match crop N uptake (Found in Sanchez and Doerge, 1999).

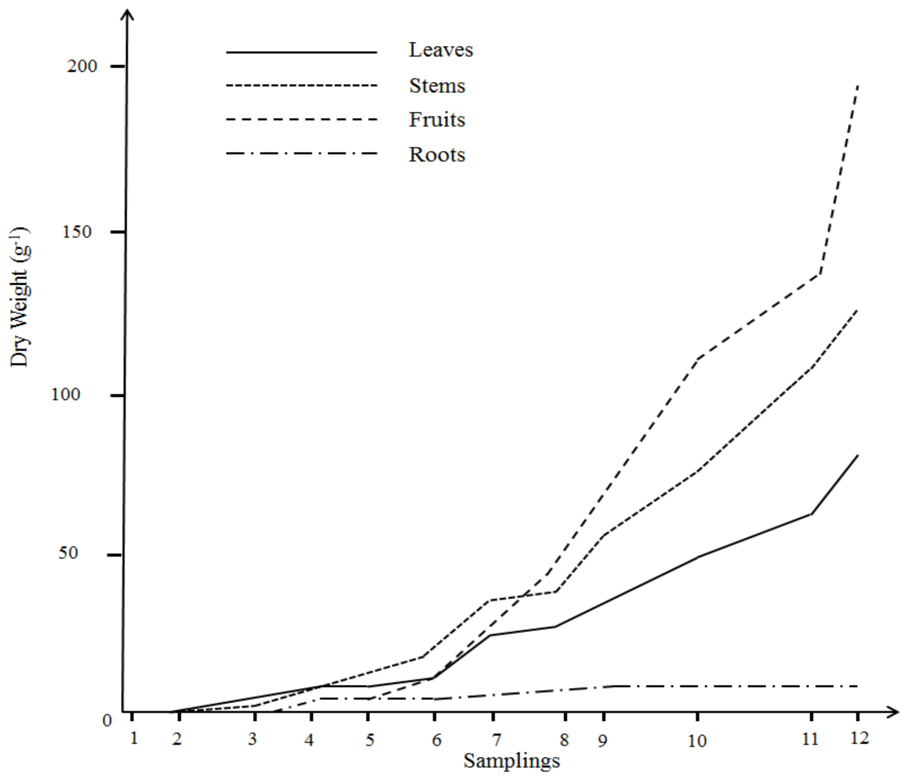

Figure 2.4 Dry weight of leaves, stems, fruits, and roots through tomato plant ontogenesis (Modified from Tapia and Gutierrez, 1997)

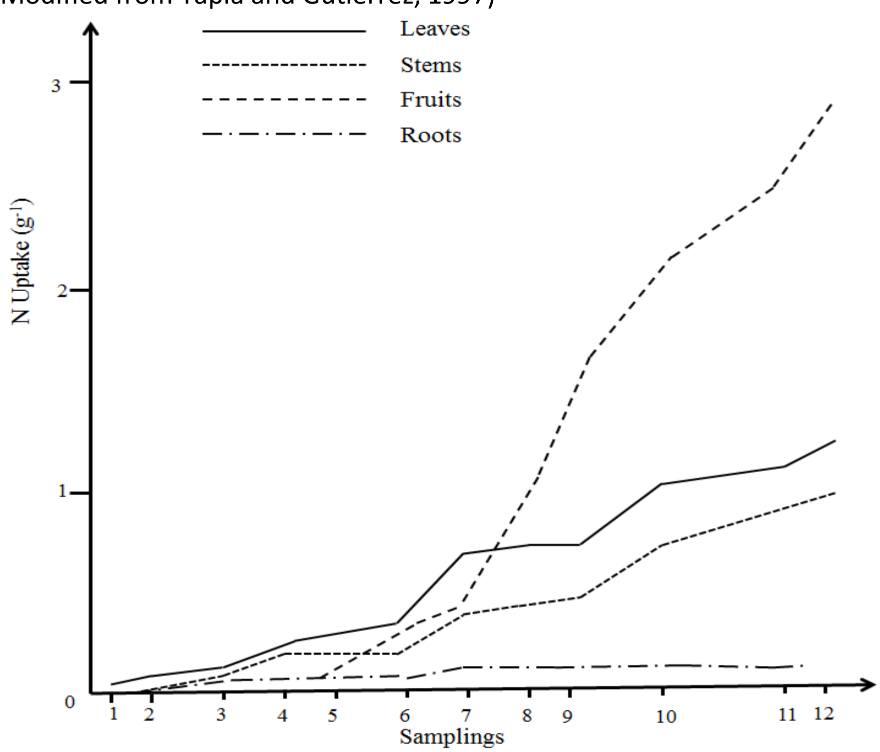

Figure 2.5 Nitrogen uptake throughout tomato plant ontogenesis and allocation in divers plant parts: leaves, stems, roots, and fruits (Modified from Tapia and Gutierrez, 1997)

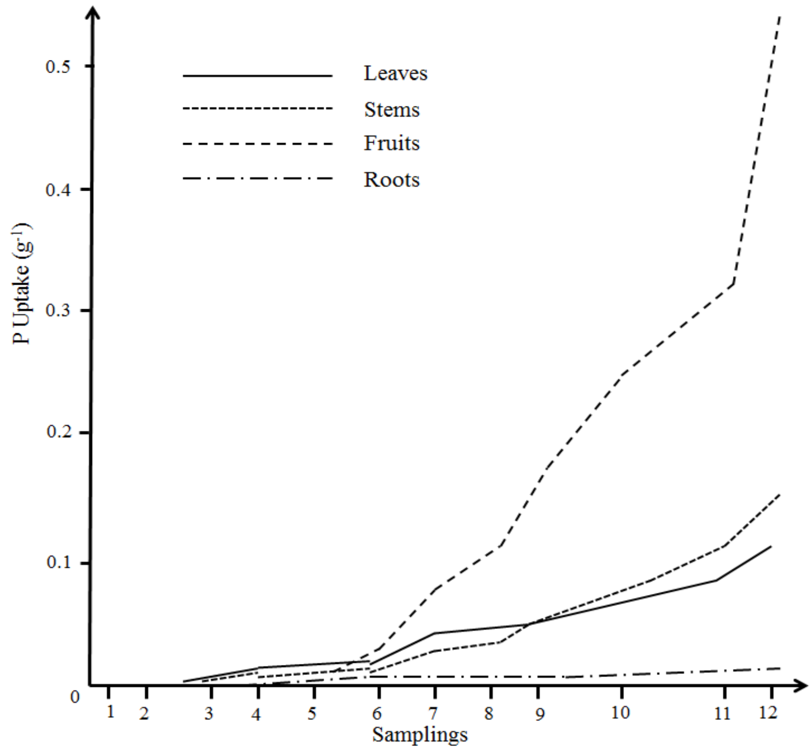

Figure 2.6 Phosphorus uptake throughout tomato plant ontogenesis and allocation in divers plant parts: leaves, stems, roots, and fruits (Modified from Tapia and Gutierrez, 1997)

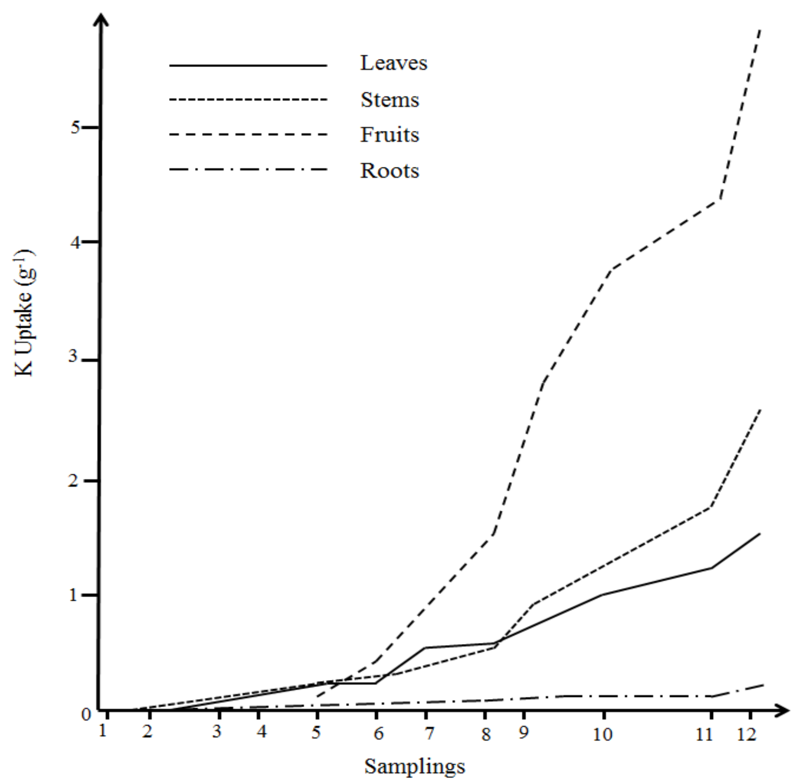

Figure 2.7 Potassium uptake throughout tomato plant ontogenesis and allocation in divers plant parts: leaves, stems, roots, and fruits (Modified from Tapia and Gutierrez, 1997)

Appendix B

Table 1. Daily meteorological data for Lavaltrie, Québec for the 2009 season (data collected on site)

Month	Day	Maximum temperature °C	Minimum temperature °C	Mean temperature °C	Total precipitation mm
May	1	20.9	8.7	16.2	10.6
May	2	14.6	6.1	11.2	0.2
May	3	18.2	6.2	14.4	0.0
May	4	20.1	9.8	15.4	0.0
May	5	19.7	8.8	15.4	0.0
May	6	14.0	10.8	12.7	0.0
May	7	---	---	---	0.0
May	8	21.6	11.9	16.8	0.0
May	9	19.2	11.8	16.3	4.8
May	10	8.9	8.0	8.6	0.0
May	11	16.6	8.1	12.7	0.0
May	12	18.1	7.2	14.7	0.0
May	13	20.8	10.3	17.1	0.0
May	14	17.5	13.1	15.2	4.6
May	15	19.6	9.2	14.2	0.0
May	16	17.6	5.6	12.2	25.8
May	17	16.7	5.7	8.9	0.0
May	18	14.7	2.0	8.3	0.0
May	19	18.6	4.2	12.1	0.0
May	20	13.4	3.9	7.3	0.2
May	21	30.9	2.7	19.4	0.2
May	22	21.4	7.9	17.1	0.4
May	23	21.8	4.2	13.4	0.0
May	24	24.5	9.6	17.3	0.0
May	25	14.8	4.8	9.9	0.0
May	26	17.1	-1.3	8.3	0.0
May	27	11.7	6.7	10.1	15.6
May	28	16.6	9.4	12.4	5.2
May	29	18.7	11.2	14.6	18.2
May	30	18.3	9.6	13.2	6.2
May	31	15.7	5.0	11.3	0.2
June	1	15.3	3.4	9.9	5.0
June	2	19.3	8.7	13.2	0.2
June	3	20.8	5.9	13.7	0.0
June	4	20.2	6.7	13.9	0.0
June	5	24.8	4.6	16.1	0.0
June	6	24.5	7.8	17.3	0.0
June	7	20.8	6.1	13.9	0.0
June	8	19.6	3.8	12.8	0.0
June	9	12.0	6.9	10.3	25.0
June	10	18.1	11.5	14.3	0.8
June	11	24.0	9.7	16.9	0.0
June	12	24.8	14.4	18.8	0.4
June	13	25.1	13.3	18.9	0.0

June	14	27.6	10.0	18.9	0.0
June	15	24.6	12.3	16.2	2.0
June	16	25.0	10.4	17.7	0.0
June	17	27.0	12.0	19.8	0.0
June	18	21.1	12.9	15.7	11.4
June	19	20.1	13.6	16.8	0.8
June	20	21.8	16.0	18.9	0.0
June	21	25.1	18.1	20.7	0.0
June	22	24.3	15.7	21.4	0.0
June	23	29.0	12.6	21.0	0.0
June	24	29.4	15.3	22.8	0.0
June	25	31.9	17.3	24.3	0.0
June	26	27.6	17.8	20.9	8.0
June	27	21.7	16.8	19.2	4.0
June	28	26.4	15.8	20.2	0.0
June	29	19.7	17.3	18.5	44.6
June	30	28.3	14.2	20.7	28.0
July	1	27.2	16.6	21.2	0.4
July	2	23.9	17.0	20.1	0.4
July	3	22.8	17.1	18.8	2.4
July	4	20.4	14.2	17.1	4.0
July	5	25.3	13.3	18.6	0.0
July	6	23.8	11.6	17.5	0.4
July	7	20.0	12.8	16.1	1.2
July	8	20.4	13.8	16.2	1.4
July	9	26.1	11.3	18.5	0.2
July	10	27.1	9.8	19.8	0.0
July	11	25.0	14.7	19.2	48.0
July	12	21.8	13.1	17.6	0.4
July	13	20.8	10.0	14.4	2.0
July	14	19.5	9.9	14.5	0.0
July	15	23.2	9.3	16.2	0.0
July	16	23.2	15.5	18.7	0.6
July	17	26.4	14.3	20.4	1.8
July	18	24.0	16.0	18.5	12.2
July	19	23.4	14.3	18.4	0.0
July	20	25.6	14.4	20.0	0.0
July	21	27.3	12.4	20.6	0.0
July	22	21.8	15.9	18.9	1.6
July	23	25.5	14.7	20.3	0.0
July	24	25.1	17.3	20.1	0.0
July	25	23.5	14.9	19.0	0.0
July	26	18.1	14.8	16.4	21.0
July	27	25.1	16.3	19.4	6.6
July	28	28.2	17.0	22.2	0.0
July	29	28.9	19.1	22.7	14.4
July	30	26.6	19.1	22.6	0.0
July	31	22.9	17.3	20.8	0.0
August	1	-	-	-	0.0
August	2	21.6	18.9	19.9	7.8
August	3	25.1	16.2	22.8	0.0

August	4	28.3	17.8	21.3	1.2
August	5	25.3	15.1	20.3	0.2
August	6	22.3	14.4	17.6	1.8
August	7	21.2	11.2	16.2	8.8
August	8	23.7	7.7	16.1	0.2
August	9	24.7	12.2	18.4	0.0
August	10	29.9	19.6	23.8	0.0
August	11	26.8	17.7	21.1	7.6
August	12	28.8	15.3	21.6	0.2
August	13	29.7	13.8	21.7	0.2
August	14	31.6	17.3	24.4	0.0
August	15	31.2	18.2	24.5	0.0
August	16	31.2	18.0	24.8	0.0
August	17	32.4	20.3	24.9	2.0
August	18	29.4	21.6	24.8	0.6
August	19	26.8	15.4	22.4	0.2
August	20	24.1	12.1	18.9	0.4
August	21	28.3	18.2	22.6	4.2
August	22	29.2	19.9	23.9	0.2
August	23	26.3	19.3	21.8	1.6
August	24	26.5	15.7	20.8	0.8
August	25	26.1	10.8	19.1	0.2
August	26	23.8	11.2	19.4	0.0
August	27	20.7	5.7	11.1	0.0
August	28	19.6	5.7	13.3	0.0
August	29	15.6	11.1	12.7	10.4
August	30	23.4	12.1	15.8	0.6
August	31	21.4	8.3	14.2	0.0
September	1	22.9	5.1	14.8	0.2
September	2	25.5	12.0	18.8	0.0
September	3	26.2	14.3	21.5	0.0
September	4	26.6	11.9	20.2	0.0
September	5	21.8	8.6	16.3	0.0
September	6	20.9	4.2	12.6	0.0
September	7	24.9	3.8	10.9	0.0
September	8	26.3	13.8	20.4	0.0
September	9	22.0	6.9	16.1	0.0
September	10	24.7	7.1	15.2	0.0
September	11	22.8	5.9	13.8	0.0
September	12	25.6	5.1	14.5	0.2
September	13	21.1	11.6	16.3	1.0
September	14	21.2	9.9	15.1	0.0
September	15	19.2	9.9	14.4	0.0
September	16	16.6	5.9	12.7	0.0
September	17	20.9	2.	12.1	0.0
September	18	16.3	8.4	12.8	3.0
September	19	18.5	5.4	11.0	0.0
September	20	21.7	3.8	12.7	0.0
September	21	25.6	6.2	15.2	0.0
September	22	20.2	10.2	16.3	7.8
September	23	22.8	14.0	19.9	1.0

September	24	19.4	7.3	13.4	0.0
September	25	16.1	3.3	10.1	0.0
September	26	18.7	-0.3	9.4	0.2
September	27	14.9	10.	13.2	18.6
September	28	18.5	11.2	14.3	6.6
September	29	14.8	10.2	12.4	1.4
September	30	-	-	-	-

Table 2. Daily meteorological data for Lavaltrie, Québec for the 2010 season (data collected on site)

Month	Day	Maximum temperature °C	Minimum temperature °C	Mean temperature °C	Total precipitation mm
May	1	20.0	5.2	11.9	5.6
May	2	26.8	9.0	18.6	0.2
May	3	23.9	15.6	20.4	7.6
May	4	21.2	8.6	14.6	8.8
May	5	20.5	7.0	14.2	2.2
May	6	17.8	8.7	13.6	4.4
May	7	14.6	4.4	9.4	0.0
May	8	9.6	3.8	5.8	5.8
May	9	6.4	1.4	4.1	0.2
May	10	10.1	-0.9	3.8	0.0
May	11	16.2	-2.0	8.2	0.0
May	12	15.0	1.3	8.8	0.0
May	13	20.8	-1.2	10.	0.0
May	14	15.6	8.6	11.7	0.0
May	15	16.8	8.6	12.3	9.2
May	16	23.2	4.1	14.5	0.0
May	17	24.5	3.8	153.7	0.0
May	18	26.2	6.2	16.9	0.0
May	19	22.7	9.8	16.2	0.0
May	20	27.8	11.1	19.1	0.0
May	21	21.3	4.2	13.7	0.0
May	22	27.3	5.4	16.4	0.0
May	23	28.6	12.3	21.7	0.0
May	24	31.0	14.8	23.7	0.0
May	25	35.1	17.8	26.8	0.0
May	26	35.3	18.3	27.1	0.0
May	27	27.3	13.3	19.6	0.0
May	28	25.9	9.7	18.4	0.0
May	29	26.0	11.0	18.6	0.2
May	30	24.5	13.7	18.3	0.2
May	31	23.1	6.3	15.6	0.0
June	1	23.1	11.2	16.2	29.2
June	2	26.1	12.9	19.8	0.2
June	3	18.3	14.5	15.9	7.8
June	4	24.7	13.9	19.0	0.4
June	5	20.6	11.5	16.6	1.4
June	6	12.3	9.8	11.1	11.8

June	7	19.7	8.5	14.0	0.0
June	8	20.6	8.1	13.8	0.0
June	9	22.4	5.4	15.4	0.0
June	10	17.3	10.1	13.7	0.8
June	11	22.4	7.6	15.9	0.0
June	12	24.7	14.5	18.9	0.2
June	13	27.4	12.5	19.9	0.0
June	14	19.4	13.9	16.1	3.8
June	15	23.6	8.7	16.3	0.0
June	16	21.1	7.4	14.8	11.6
June	17	26.8	14.1	19.9	1.0
June	18	29.6	14.1	22.3	0.0
June	19	28.8	15.8	21.9	9.4
June	20	27.7	17.3	22.9	0.2
June	21	27.5	14.1	20.6	0.0
June	22	28.1	9.9	20.1	0.0
June	23	27.4	18.7	22.6	0.0
June	24	25.9	14.4	20.7	21.0
June	25	23.2	10.2	17.1	0.0
June	26	23.5	15.7	18.8	0.0
June	27	25.8	13.8	19.6	0.0
June	28	22.8	15.0	17.8	9.6
June	29	19.6	12.6	16.1	0.8
June	30	18.8	9.8	13.8	0.6
July	1	21.5	7.6	15.2	0.0
July	2	26.9	10.0	19.7	0.0
July	3	29.9	15.6	23.1	0.0
July	4	30.2	20.4	24.2	0.0
July	5	34.3	18.8	26.9	0.8
July	6	34.2	22.3	28.6	0.0
July	7	35.3	23.9	29.7	0.0
July	8	36.1	21.8	29.4	0.0
July	9	32.2	20.2	23.6	34.6
July	10	30.1	19.6	23.6	0.6
July	11	31.4	16.7	23.8	0.0
July	12	31.6	16.9	24.3	0.0
July	13	26.0	19.1	21.6	0.8
July	14	30.2	18.7	23.9	0.0
July	15	32.3	14.2	24.1	0.0
July	16	28.3	23.1	24.8	5.0
July	17	29.6	17.7	22.7	21.
July	18	25.4	17.5	21.3	0.0
July	19	24.1	16.6	19.0	12.6
July	20	27.8	14.9	21.5	0.0
July	21	26.7	13.9	19.3	46.6
July	22	28.4	15.2	21.4	1.0
July	23	27.9	12.0	19.9	2.4
July	24	26.6	17.0	21.3	2.0
July	25	23.4	16.9	21.2	0.0
July	26	27.1	14.0	20.8	0.0
July	27	31.1	14.3	23.3	0.0

July	28	28.7	19.3	23.8	0.0
July	29	22.8	12.9	19.4	0.0
July	30	19.9	8.8	15.3	0.0
July	31	24.6	8.8	17.3	0.0
August	1	27.7	8.9	19.0	0.0
August	2	29.3	12.9	20.4	37.8
August	3	24.7	19.1	21.3	21.4
August	4	30.2	19.1	23.4	8.8
August	5	29.8	20.4	24.4	0.0
August	6	20.4	10.7	16.9	0.0
August	7	21.3	6.7	14.9	0.0
August	8	23.2	13.3	18.8	20.4
August	9	28.0	18.3	22.3	0.0
August	10	28.6	16.2	20.1	26.4
August	11	26.0	13.8	19.8	0.2
August	12	24.8	12.8	18.7	0.0
August	13	27.5	12.7	20.1	0.0
August	14	27.3	15.6	21.7	0.0
August	15	26.2	18.7	21.9	24.0
August	16	28.2	19.0	22.5	9.2
August	17	25.8	15.7	19.9	6.8
August	18	23.9	12.3	18.2	0.2
August	19	26.3	10.7	18.6	0.0
August	20	23.8	8.2	16.3	0.0
August	21	18.6	9.8	15.0	2.8
August	22	17.9	14.4	16.3	1.6
August	23	24.8	15.5	19.4	0.8
August	24	25.4	13..6	19.1	0.0
August	25	22.3	12.3	17.1	0.0
August	26	24.2	14.7	18.1	6.0
August	27	21.9	9.8	16.4	0.0
August	28	26.6	15.4	20.3	0.0
August	29	30.9	18.0	24.4	0.0
August	30	31.3	16.6	24.3	0.0
August	31	34.3	21.1	27.3	0.0
September	1	32.6	21.6	26.9	0.0
September	2	28.5	20.6	26.3	2.8
September	3	31.9	20.3	25.4	0.2
September	4	23.5	15.0	18.9	0.6
September	5	17.7	10.4	14.2	0.2
September	6	22.9	9.9	15.4	3.2
September	7	24.8	15.4	18.6	22.2
September	8	21.2	14.7	17.9	2.6
September	9	16.3	11.7	14.5	0.8
September	10	22.9	10.6	15.7	0.0
September	11	23.5	6.1	14.8	0.0
September	12	20.3	9.0	14.1	2.0
September	13	19.6	13.4	15.5	2.2
September	14	19.2	10.4	13.9	0.6
September	15	15.8	6.1	11.2	0.2
September	16	12.2	6.5	9.4	8.4

September	17	19.0	6.9	12.1	0.2
September	18	19.8	3.4	12.9	0.2
September	19	20.6	8.1	14.1	0.0
September	20	18.5	4.8	11.2	0.0
September	21	14.7	3.2	9.3	0.4
September	22	23.4	10.9	17.8	0.0
September	23	14.3	5.4	10.6	0.0
September	24	11.7	8.1	9.9	19.2
September	25	19.9	10.4	14.7	0.2
September	26	12.2	8.6	10.4	0.6
September	27	20.7	10.0	14.4	12.4
September	28	23.2	14.2	18.4	10.0
September	29	19.2	12.2	16.1	0.2
September	30	15.8	11.6	13.9	71.6

Table 3. Daily meteorological data for Sainte-Anne-de-Bellevue 1 station (lat. 45°25'38.000" N, long. 73°55'45.000" W), Sainte-Anne-de-Bellevue, Québec for the 2009 season (Environment Canada).

Month	Day	Maximum temperature °C	Minimum temperature °C	Mean temperature °C	Total precipitation mm
May	1	19.7	8.9	14.3	11.4
May	2	14.7	4.1	9.4	0.2
May	3	18.3	3.7	11	0
May	4	18.8	7.9	13.4	0
May	5	20.6	6.7	13.7	0
May	6	15.7	10.1	12.9	0.6
May	7	13.1	9.7	11.4	6.8
May	8	21.2	9.6	15.4	0.6
May	9	17	8.4	12.7	6.8
May	10	9.9	5.8	7.9	3
May	11	15.5	2.7	9.1	0
May	12	17.7	2	9.9	0
May	13	20.5	6	13.3	0
May	14	19.2	11.9	15.6	4.4
May	15	18.5	6.5	12.5	0
May	16	18.2	5.4	11.8	19.8
May	17	10.8	4.6	7.7	0
May	18	14.1	3.9	9	0
May	19	18.4	5.4	11.9	0
May	20	16.2	5.4	10.8	1
May	21	28.8	6.9	17.9	0
May	22	19.3	6.7	13	0
May	23	21.3	3.9	12.6	0
May	24	23	9.3	16.2	0
May	25	14.9	6.2	10.6	0
May	26	16.3	1.4	8.9	0
May	27	14.5	9.1	11.8	6.4
May	28	15.3	10.3	12.8	4.2
May	29	20.7	11.7	16.2	8.4

May	30	16.5	10.4	13.5	2.6
May	31	14	5	9.5	2.8
June	1	14.8	4.4	9.6	5.4
June	2	17.6	8.9	13.3	0.2
June	3	19.9	8.7	14.3	0
June	4	19	7.6	13.3	0
June	5	23.5	6.2	14.9	0
June	6	23.6	10.1	16.9	0
June	7	18.1	7.6	12.9	0
June	8	18.2	5.4	11.8	0
June	9	14.4	10.8	12.6	14.8
June	10	17.9	10.7	14.3	0.2
June	11	22.7	10.6	16.7	0
June	12	23.6	13.3	18.5	1
June	13	24.4	11.4	17.9	0
June	14	26.1	13.6	19.9	0
June	15	22.5	13.6	18.1	0.2
June	16	24.3	11.2	17.8	0
June	17	26	11.9	19	0
June	18	18.8	14.2	16.5	10.4
June	19	19.9	14	17	1
June	20	20.6	16.2	18.4	0
June	21	25.5	18.3	21.9	0
June	22	23.7	15	19.4	0
June	23	28.6	12.7	20.7	0
June	24	29.2	15.5	22.4	0
June	25	31.8	17.6	24.7	0
June	26	27.5	17.3	22.4	1.2
June	27	22.6	16	19.3	14
June	28	26.1	14.6	20.4	0.2
June	29	20.2	16.8	18.5	13.8
June	30	26.2	13.6	19.9	6.4
July	1	25.3	16.9	21.1	4
July	2	24.3	18.1	21.2	1.2
July	3	23.8	18	20.9	15.4
July	4	20	14.7	17.4	0.2
July	5	24.3	15	19.7	0
July	6	22.2	14	18.1	3
July	7	20.3	14.2	17.3	11.4
July	8	20.4	13.2	16.8	0.2
July	9	24.2	12.2	18.2	0
July	10	26.2	11.3	18.8	0
July	11	25.3	16.4	20.9	44
July	12	20.6	13.3	17	0
July	13	19.6	11	15.3	0.6
July	14	18.7	12	15.4	0.2
July	15	23.1	12	17.6	0
July	16	24.9	16.4	20.7	0.2
July	17	25.9	14.8	20.4	0.4
July	18	24.7	16.2	20.5	4.8
July	19	23.1	15.4	19.3	1.6

July	20	24.5	13.9	19.2	0
July	21	26.6	13	19.8	0.4
July	22	21.9	15.3	18.6	8
July	23	24.8	15.3	20.1	0.4
July	24	24.9	17.7	21.3	0.4
July	25	25	17.2	21.1	1.4
July	26	23.3	15.3	19.3	24.6
July	27	25.6	16.7	21.2	0.2
July	28	28.9	17.7	23.3	4.6
July	29	29.3	18.3	23.8	0.2
July	30	25.1	17.9	21.5	0.2
July	31	22.9	16.8	19.9	0
August	1	27.2	17.7	22.5	0.2
August	2	22.7	17.6	20.2	15
August	3	24.4	13.7	19.1	0.2
August	4	28.1	18.3	23.2	3.8
August	5	23.7	16.3	20	0.2
August	6	22.2	15.8	19	3.2
August	7	21.1	11.1	16.1	0.2
August	8	22.4	9.4	15.9	0
August	9	23.8	15.7	19.8	0
August	10	28.6	19.5	24.1	10.2
August	11	26.2	16.5	21.4	8.4
August	12	27.3	15.4	21.4	0
August	13	29	14.6	21.8	0.2
August	14	29.9	17.7	23.8	0
August	15	29.4	19.5	24.5	0
August	16	29.8	19.8	24.8	0
August	17	31.7	20.9	26.3	1
August	18	29.4	19.4	24.4	0.2
August	19	25.3	15.1	20.2	0
August	20	24.5	12.9	18.7	5
August	21	27.6	18.7	23.2	16.6
August	22	28.5	18.5	23.5	0
August	23	26.2	18.9	22.6	2.8
August	24	24.7	13.8	19.3	0
August	25	25.3	13.5	19.4	0
August	26	23.4	10.7	17.1	0
August	27	19.1	6.3	12.7	0
August	28	18.7	6.4	12.6	0
August	29	16.9	11.9	14.4	7.8
August	30	21.2	10.8	16	6.6
August	31	19.4	8.3	13.9	0
September	1	22.1	7.9	15	0
September	2	24.2	11.4	17.8	0
September	3	24.9	14.6	19.8	0
September	4	25.9	14.3	20.1	0
September	5	20.9	9.3	15.1	0
September	6	19.6	6.7	13.2	0
September	7	24.2	6.4	15.3	0
September	8	25.2	12	18.6	0

September	9	22.3	7.7	15	0
September	10	23.2	8.3	15.8	0
September	11	21.5	7.4	14.5	0
September	12	23.8	7.9	15.9	0
September	13	22.1	9.7	15.9	0
September	14	20.1	10.5	15.3	0
September	15	17.6	12.1	14.9	0
September	16	17.4	6.3	11.9	0
September	17	20.1	5.9	13	0
September	18	17	8.6	12.8	4.2
September	19	16.2	6	11.1	0
September	20	21.1	4.9	13	0
September	21	24.3	4.1	14.2	0
September	22	23	13.7	18.4	11.4
September	23	22.5	11.8	17.2	3.6
September	24	18.4	7.7	13.1	0.2
September	25	15	2.9	9	0
September	26	18.2	1.2	9.7	0
September	27	15.4	11.3	13.4	16.8
September	28	18.3	12.5	15.4	1
September	29	14.4	9.3	11.9	4.4
September	30	10	5.7	7.9	1.2
October	1	7.8	4.3	6.1	0.2
October	2	12.9	3.3	8.1	2.6
October	3	15.4	9.9	12.7	11.6
October	4	15.7	9.8	12.8	1
October	5	14.8	8.8	11.8	1.8
October	6	13.6	7.9	10.8	0.2
October	7	15.5	9.6	12.6	17.8
October	8	13.7	7.3	10.5	0.2
October	9	11.5	9	10.3	11.4
October	10	12.1	3.5	7.8	1.4
October	11	10.8	2.3	6.6	0.4
October	12	10.3	0.6	5.5	0.2
October	13	7.8	1.7	4.8	4
October	14	4.6	0.1	2.4	0
October	15	4.7	-2	1.4	0
October	16	6.7	-2.5	2.1	0
October	17	8.6	-1.8	3.4	0
October	18	9.7	-2.8	3.5	0
October	19	11.6	-4.3	3.7	0
October	20	14.6	6.6	10.6	0
October	21	9.8	3.5	6.7	2
October	22	3.6	-0.2	1.7	13.4
October	23	4.8	-2.3	1.3	15.8
October	24	11.9	4.6	8.3	13
October	25	11.7	2.5	7.1	0.2
October	26	8.1	-0.4	3.9	0
October	27	8.1	3.6	5.9	0
October	28	6.5	3.2	4.9	0.6
October	29	8.6	1	4.8	0

October	30	13.2	1.6	7.4	1.8
October	31	15.9	7.6	11.8	7.1

Table 4. Daily meteorological data for Sainte-Anne-de-Bellevue 1 station (lat. 45°25'38.000" N, long. 73°55'45.000" W), Sainte-Anne-de-Bellevue, Québec for the 2010 season (Environment Canada).

Month	Day	Maximum temperature °C	Minimum temperature °C	Mean temperature °C	Total precipitation mm
May	1	19.3	6.9	13.1	1.6
May	2	26.6	8.8	17.7	0.2
May	3	22.7	14.6	18.7	2.8
May	4	20.3	9.4	14.9	1.4
May	5	21.5	7.5	14.5	0.4
May	6	17	8	12.5	5.2
May	7	M	5.9E	M	M
May	8	12.3	3.1	7.7	11.8
May	9	5.3	1.7	3.5	2.8
May	10	10.9	0.1	5.5	0
May	11	16.5	0.1	8.3	0
May	12	15.1	2.1	8.6	0
May	13	17.9	0.3	9.1	0
May	14	14.4	9.2	11.8	6.2
May	15	17.7	9.8	13.8	1.2
May	16	22.3	6.6	14.5	0.2
May	17	23.9	6.7	15.3	0
May	18	25.6	7.5	16.6	0
May	19	21.3	10.6	16	0
May	20	25.9	11.9	18.9	0
May	21	21.4	8.1	14.8	0
May	22	27.5	7.7	17.6	0
May	23	27.9	11.2	19.6	0
May	24	29.8	17.7	23.8	0
May	25	32.5	18.7	25.6	0
May	26	34.2	19.1	26.7	0
May	27	25.4	12.7	19.1	0
May	28	25.5	11.1	18.3	0
May	29	25.9	15.7	20.8	0
May	30	21.5	13.2	17.4	0
May	31	24.2	11	17.6	0
June	1	22.4	12.8	17.6	11.6
June	2	27	16.1	21.6	3
June	3	18.8	15	16.9	19
June	4	24	15.2	19.6	0.2
June	5	21.9	11.8	16.9	4.8
June	6	12.9	10.4	11.7	13.4
June	7	18.9	9.7	14.3	0
June	8	19.7	9.1	14.4	0
June	9	21.6	11	16.3	0.4
June	10	15.3E	12.1E	13.7E	3E

June	11	21.5	10.2	15.9	0
June	12	20.9	12.4	16.7	0.6
June	13	26	11.8	18.9	0
June	14	18.5	13	15.8	1.8
June	15	22	10.9	16.5	0.2
June	16	19	9.4	14.2	34.2
June	17	25.6	14.2	19.9	5.2
June	18	27.5	15.2	21.4	0
June	19	29.4	14.9	22.2	8.8
June	20	26.9	19	23	0.4
June	21	25	13.4	19.2	0
June	22	25.7	13.2	19.5	3
June	23	26.1	18.7	22.4	5.8
June	24	23.8	15.9	19.9	24.2
June	25	22.1	13.9	18	0.2
June	26	20.1	16.6	18.4	0
June	27	24.5	16.3	20.4	0
June	28	27.3	17.5	22.4	19.4
June	29	20.1	14.2	17.2	0.4
June	30	19.1	11.3	15.2	0.8
July	1	20	11.9	16	0.8
July	2	24.5	13.2	18.9	0
July	3	27.9	15.1	21.5	0
July	4	29.6	18.7	24.2	0
July	5	32.5	19.8	26.2	0
July	6	33.2	23.8	28.5	0
July	7	33.7	23.3	28.5	0
July	8	33.9	23.1	28.5	0
July	9	30.6	20.7	25.7	30.2
July	10	28.7	19.3	24	0.4
July	11	30	19.2	24.6	0
July	12	29.5	17.9	23.7	0
July	13	26.8	20.1	23.5	6
July	14	28.3	18.9	23.6	0
July	15	29.8	16.7	23.3	0
July	16	27.6	22.7	25.2	0
July	17	28.8	19.9	24.4	17
July	18	25.4	18.3	21.9	0.2
July	19	23.7	18.3	21	M
July	20	27	16	21.5	M
July	21	26.4	15.7	21.1	5.4
July	22	26.7	15.5	21.1	0.2
July	23	25.4	14.4	19.9	0
July	24	26.9	17.4	22.2	0.4
July	25	23.2	18.5	20.9	0
July	26	25.8	16.2	21	0
July	27	29.3	16	22.7	0
July	28	27.9	18	23	0
July	29	23.1	13.5	18.3	0
July	30	20.6	10	15.3	0
July	31	22.8	8.9	15.9	0

August	1	26.2	10	18.1	0
August	2	27.6	14.3	21	6.2
August	3	25.9	19.9	22.9	71.8
August	4	28.4	20	24.2	19
August	5	28.6	17.9	23.3	16.6
August	6	20	10.8	15.4	0.4
August	7	20.5	10.8	15.7	0
August	8	23.7	14.4	19.1	16.4
August	9	26.4	18.5	22.5	0.4
August	10	28.1	16	22.1	0.2
August	11	26.2	14.8	20.5	0.2
August	12	24.8	14.1	19.5	0
August	13	26	13.2	19.6	0
August	14	27.2	16.9	22.1	0
August	15	25.6	20	22.8	14.8
August	16	27.6	19.6	23.6	6.2
August	17	25.7	16.1	20.9	0
August	18	22.7	13.8	18.3	0
August	19	26.5	11.1	18.8	0
August	20	22.2	10.1	16.2	0
August	21	20.3	11	15.7	1.6
August	22	18.4	15.1	16.8	7
August	23	24.2	14.7	19.5	1.6
August	24	24.6	13.7	19.2	0
August	25	22.1	12.9	17.5	0
August	26	23.2	14.2	18.7	0.2
August	27	21.8	12.3	17.1	0
August	28	25.8	15	20.4	0
August	29	29.4	18.5	24	0
August	30	29.8	17.2	23.5	0
August	31	31.5	21.2	26.4	0
September	1	31.6	22	26.8	0
September	2	27.6	22.3	25	0
September	3	33.1	18.5	25.8	0
September	4	21.4	13.9	17.7	2.4
September	5	18	10.7	14.4	0
September	6	22.5	9.1	15.8	1.4
September	7	26.2	15.9	21.1	15.2
September	8	20.3	15.2	17.8	2.8
September	9	16.5	12.4	14.5	4.2
September	10	21.4	9.2	15.3	0.2
September	11	22.2	7.8	15	0
September	12	20.9	11.4	16.2	0
September	13	20	11.1	15.6	3.2
September	14	17.9	10	14	1
September	15	15.5	8.2	11.9	0
September	16	14.1	6.6	10.4	15
September	17	17.5	7.2	12.4	0.2
September	18	20.3	5.4	12.9	0
September	19	18.6	9.1	13.9	0
September	20	17.9	5.5	11.7	0

September	21	19.1	5.7	12.4	0.6
September	22	22.2	9.6	15.9	1.4
September	23	14.2	5.6	9.9	3.8
September	24	22.5	9	15.8	12.2
September	25	21.7	10.9	16.3	1.2
September	26	12.8	8.4	10.6	0
September	27	19.7	10.8	15.3	11.6
September	28	24.6	15.6	20.1	6.2
September	29	17.8	11.2	14.5	0
September	30	16.3	11.9	14.1	75.0
October	1	16.9	8.4	12.7	4.0
October	2	12.7	4.5	8.6	0.2
October	3	12.3	1.1	6.7	0.0
October	4	14.8	4.2	9.5	0.0

E= Estimated
M= Missing