ECOPHYSIOLOGY OF SEEDLING EMERGENCE AND DEVELOPMENT OF SEEDLING EMERGENCE MODELS (SEM) FOR CUT AND PEEL CARROTS (*Daucus carota* var Sativus L.)

by

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DEDICATION

I dedicate my MSc. Thesis to my beloved parents Mr. and Mrs. Vithanage and Fiancé Sampath Suriyabandara. Their advices, encouragement and continuous financial assistance laid the foundation to face all challenges confidently and achieve my goals

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ABSTRACT

Effect of soil moisture potential (Ψ), temperature (T), genotype, seeding depth (SD) and rate (SR) on seedling emergence (SE), emergence velocity (EV), root yield and grades of cut and peel carrots were studied.

SE was reduced at –120 kPa and totally inhibited at -156 kPa. EV was the lowest at – 5 kPa and – 90 kPa. SE was delayed by 33 d at 5°C, reduced at 30°C and totally inhibited at 35 and 40 °C. Heat units 99.75 and 159.60°Cd were the lowest to initiate and complete SE respectively while the optimum was 300 – 350 °Cd. There was no interaction effect between Ψ and T on SE. Honey snax at 85 seeds/ 30 cm showed the best SE whereas, Triton recorded the highest total yield at 2.54 cm SD and Fancy yield at 85 seeds/ 30 cm implying certain crop ecological and management factors can influence SE, root yield and quality.

LIST OF ABBREVIATIONS AND SYMBOLS USED

Abbreviations / Chemical Formulas:

SEM	Seedling emergence model	O_2	Oxygen
TT	Thermal time	CO_2	Carbon Dioxide
SE	Seedling emergence	^{o}Cd	Degree days
EV	Emergence velocity	GV	Germination velocity
SAS	Statistical analysis systems	IQF	Individually quick frozen
NS	Nova Scotia	FC	Field capacity
PEG	Poly ethylene glycol	RH	Relative humidity
VOP	Virtual osmotic potential	HTT	Hydrothermal time
ISE	Initiation of seedling emergence	DAS	Days after seeding
CSE	Completion of seedling emergence		

Symbols:

Ψ	Water potential	Ψ_m	Matric potential
T	Temperature	$\Psi\pi$	Osmotic potential
G_d	Number of seeds germinated	t_g	Seed population
Ψ_p	Turgor pressure	Ψ_{cell}	Water potential of the cell
d	Number of days since the beginning of test		
G_t	Total no. of seeds germinated at the end	T_b	Base Temperature
Ψ_e	Potential of the environment	Ψ_s	Water potential of the seed
Q_T	Thermal time constant	g	Fraction of seed germination
Q_{HT}	Hydrothermal-time constant	Q_H	Hydrotime
Ψ_b	Base water potential		
F	Rate of water flow from the environment to seed		

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Chapter 1

Introduction

1.1 General Introduction

Vegetable production, in many countries of the world, has become a major component of economy, being a good source of nutrients and income. Carrots and beets are the most widely grown root vegetables for its enlarged fleshy roots (Swiader and Ware, 2002). Total carrot production around the world in 1983, has been recorded as 11 million MT (Hartmann et al., 1988) and in 2005 world production approached 24 million MT on 1.1 million hectares (FAOSTAT data from www.top5ofanything, 2007). Although, carrots were used as a food crop in 16th century, it has been primarily used for medicinal purposes in European countries (Swiader and Ware, 2002). Carrots were first introduced to North and South America in early 1600s (Hartmann et al., 1988). Carrot is one of the largest crops in Nova Scotia (NS), contributing nearly 12 million dollars per year to the NS economy directly or indirectly (Briscoe, 2006). As per statistics Canada 2010 (www.statcan.gc.ca), the recorded total area under carrot production was 2636 acres and total carrot production was 55754 t while representing the highest farm gate value of commercial vegetables in Nova Scotia, $ 6 143 000; the data includes both baby carrots and regular carrots (www.gov.ns.ca) .

Carrots are commercially grown for both the fresh market and processing and at the same time they are extensively grown in home gardens too. Carrot cultivars are being grouped according to their shape, length of root or the intended market use. According to the length and shape, carrots fall in to four types, or categories: Danvers, Chantenay, Nantes, and Imperator. Chantenay, Nantes and Danvers are commonly use as processing cultivars and due to more cylindrical shape Nantes are best to develop varieties for baby carrots (Swiader and Ware, 2002).

The largest Individually Quick Frozen (IQF) carrot processor in North America, the Oxford Frozen Foods Limited in Nova Scotia, process approximately 65 million pounds of IQF carrots per year (Rajasekaran et al., 2004). Targeting, changing food habits and increasing demand of consumers, Oxford Frozen Foods Ltd. introduced IQF baby (cut and peel) carrots to the industry as a high value crop.

The critical issue with the cut and peel carrot processing is lower percentage of recovery of Fancy grade and root uniformity. Currently, only about 30-33 % of the total roots constitute the preferred Baby grade (1.3 – 1.95 cm in diameter). The industry's major focus is to increase the percentage of preferred baby grade from 30-33% up to 60%.

Root grade is a consequence of genetic interaction with various management and environmental factors. For Example, poorly or sporadically emerged seedlings can give rise to a poor crop stand altering root grades (Bewley and Black, 1982; Rajasekaran et al., 1992, 2002; Finch-Savage, 1995; Corbineau et al., 1994; Hartmann et al., 1997; Rowse and Finch-Savage, 2003; Briscoe et al., 2006). Understanding interrelationships between management (irrigation, fertilizers) and agro-ecological factors such as soil temperature, soil moisture and rain fall, soil nutrients would enable us to determine the link between seedling emergence and eco-physiological factors on carrot yield and quality. The success of a crop in an agro-ecosystem to a certain extent depends on extent of seed's ability to respond to soil and environmental stimuli (Baskin and Baskin, 1998). In fact, seeds are considered to be bio-sensors (Briscoe et al., 2006). Seeds start germination only when environmental conditions are favourable for their establishment, reproduction and survival, otherwise they will remain dormant until favorable weather. They do not respond to adverse environmental conditions since that would deprive the seeds' ability to germinate, grow and successfully complete their life cycle (Briscoe et al., 2006; Bewley and Black, 1982; Rajasekaran et al., 1992, 2002; Hartmann et al., 1997). Carrot stand establishment has become a significant challenge in Nova Scotia due frequently to weather changes and adverse environmental conditions: temperature, soil moisture, poor soil physical properties and low light intensities, affecting yield and root grades while reducing product quality and profit.

Carrots in NS are grown, to a large extent, under rain-fed conditions; low irradiance due to many cloudy days, heavy or poor distribution of precipitation and/or mineral soils with little organic matter content (1-3%), which are the common issues throughout the growing period. Generally, carrot seeds are sown during late April- May in NS, when seasonal soil temperature normally range from 2- 5 ^{o}C (Rajasekaran et al., 2002). If soil forms crust or dry at the time of seeding, seed germination and emergence will be affected. Quick and uniform seedling emergence enables a good crop stand, which can produce quality and uniform roots.

Previous studies under the Processing Carrot Research Programme (PCRP), Nova Scotia Agricultural College (NSAC), was able to develop techniques to promote seed germination and seedling emergence including seed priming, fluid drill technique, and Integrated Gel Seeding Technique (IGST), germination and emergence promoters (Briscoe et al., 2006). During previous work under PCRP, anti-crusting compounds or soil conditioning agents, which facilitate seedling emergence, were also identified (Rajasekaran et al., 2004). There is still a knowledge gap in our understanding on the influence of certain agro-ecological factors and seedling emergence. Factors considered in this study were variety, seed size, seeding rate and seeding depth. The influence of certain agro-ecological factors including soil moisture, soil temperature was also considered. Experimental data collected on seedling emergence based on soil moisture and temperature were used to develop Seedling Emergence Models (SEM). These models will be useful in predicting seedling emergence based on environmental and soil moisture variables under different crop management situations.

1.2 Hypothesis and Objectives

Hypothesis

The overall hypothesis of this study, is that seedling emergence of cut and peel baby carrots is influenced by genotype, certain crop management (seed size, seeding depth and seeding rate) and environmental (soil moisture, soil temperature, rainfall and heat units) factors, independently or interactively and seedling density determines yield and grades.

Objectives

The overall objective of this study is to understand the relationship between various environmental, soil and input variables, and seedling emergence to develop seedling emergence models (SEM) for predicting seedling emergence and to understand the extent of influence of these factors on cut and peel root grades.

Thus, the primary objectives are to:

- understand the relationship between soil temperature and seedling emergence,
- understand the relationship between soil moisture and seedling emergence,
- understand the interactive effects of soil moisture and soil temperature on seedling emergence,
- develop hydrothermal models for seedling emergence; and to
- determine the effect of seed size, seed variety, seeding depth, seeding rate, soil moisture, rainfall and soil temperature on seedling emergence, yield and root grades.

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Chapter 2

Literature Review

2.1 General Introduction to Carrot

Carrots are basically a temperate type root vegetable which is grown for its enlarged fleshy tap root. Carrot growth performances are best at temperatures ranging from 15 ^{o}C to 20 ^{o}C (McMahon et al., 2007). Warm temperatures make roots shorter and less tapered giving an undesirable strong flavour and coarse root texture (Hartmann et al., 1988). Best colour development occurs at 15^{o}C and below 10^{o}C causes longer, more slender and paler roots due to reduction in carotene production (Matthews and Powell, 1986; Herner, 1986; Hartmann et al., 1988; Swiader and Ware, 2002). Carrots can be found in different shapes such as short and stumpy or long and tapering, like a cone, ranging from 2 to 6 cm in diameter (Yamaguchi, 1983). Fleshy roots are slender and vary in length from 5-25cm and they are divided in to types according to shape and length of roots whereas each type is represented by different cultivars (McMahon et al., 2007).

Both the enlarged hypocotyl and prominent tap root together are form so called carrot (Nonnecke, 1989; Swiader and Ware, 2002). Deep, loose, well drained sandy loams or loams with a slightly acidic reaction are ideal for carrot seed germination when soil pH is at 6.5 (Swiader et al., 1992). Cultivated carrot varieties are biennials whereas the wild type is an annual. Carrot seeds prefer well prepared seed beds with a fine soil structure and free from obstructions such as clods, stones and un-crusted soil (Finch-Savage, 1995) because in heavy soils carrots are likely to produce lots of leaves and forked roots (Swiader and Ware, 2002). Application of fully decomposed manure is important since liquid portion of un-decomposed manure can induce root branching too (Swiader and Ware, 2002).

Carrot has become an important vegetable crop due to its taste and nutritive value; it's a good source of vitamins A, B1, C and B2 (Swiader and Ware, 2002). Quality of commonly used carrots is determined by its level of sugar, mild taste and orange colour.

The best quality is mainly associated with high sugar levels, mild taste and deep orange colour (Swiader and Ware., 2002).

2.2 Classification and Botany of Carrots

Carrot (*Daucus carota* var. *sativus* L.) belongs to family Umbelliferae and it is the only dicot belongs to this family. There are about 60 species of *Daucus* where many of them were described as wild types (Swiader and Ware, 2002). Cultivated types belong to subspecies *sativus* and are biennials, grown as annuals (McMahon et al., 2007). Carrot seed is a schizocarp which is a very small, dry, non-dehiscent fruit with two ripe ovules (Gardner et al., 1985) and it is epigeal in seed germination (Swiader and Ware, 2002).

2.3 Growth and Development of Carrots

The enlarged tap root consists of stem, hypocotyl, and root tissues. Stem and leaves of the carrot plant arise from the upper part of the root, whereas lower part of the root gives rise to absorbing roots (Swiader and Ware, 2002). It produces large number of absorbing lateral roots deep down to 76 to 91 cm when edible taproot begins to enlarge (Swiader and Ware, 2002). Roots can be rough or smooth in texture, with a variety of colors including bright red, yellow, purple or orange. The plant (top) is an erect biennial reaching a maximum height of about 30 cm before flowering and about 100 cm after flowering in the second year. Leaves are green and lobed, having long petioles. The stem has a small plate-like crown developed from the plumule. Elongation of internodes cannot be observed as it occurs in the second year (Swiader and Ware, 2002). First year of growth is in vegetative stage and during second year, plate- like crown starts to elongate and gives rise to branches of 60 to 120 cm high. These branches bear flowers in compound umbels (Swiader and Ware, 2002).

2.4 Definitions

2.4.1 Seed Germination

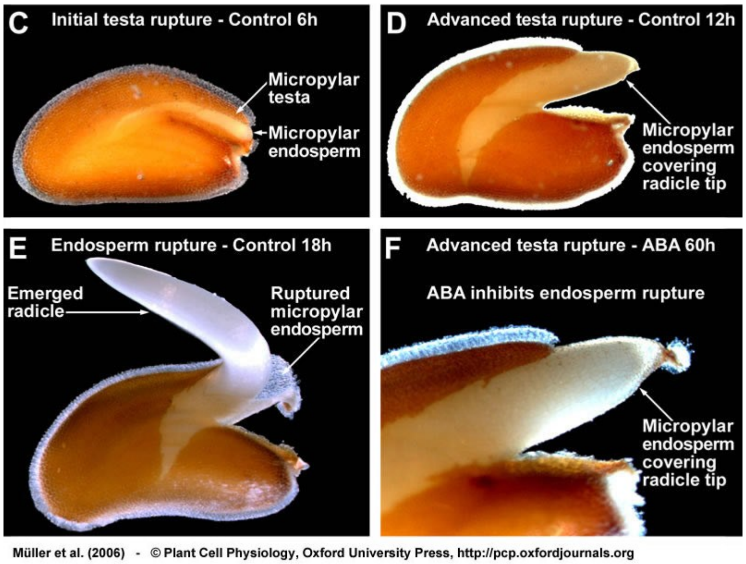

Figure 1: Emergence of Radicle through Ruptured Seed Coat (Source: Plant cell physiology, Oxford university press)

Germination is defined as the emergence of radicle through the ruptured seed coat due to resumption of active growth (Bewley and Black, 1982). Germination starts with the seed water uptake (imbibition) and ends with the beginning of elongation (figure 1) of the radicle (Bewley and Black, 1985). To a grower, germination is the emergence of seedlings (Gardner et al., 1985).

2.4.2 Seedling Emergence

Seedling emergence is defined as the stage at which the first leaf is fully expanded for *Sorghum halepense* (Bewley and Black, 1982). Equally, it is defined as the first appearance of a seedling at the soil surface (Arnold et al., 1990). Seedling emergence of carrots for this study is defined as the emergence of hypocotyl through soil up to fully unfurled two cotyledon leaves.

2.4.3 Epigeal Germination

When two cotyledons rise above the ground and continue to provide nutritive support to the growing point, it is called epigeal germination (McMahon et al., 2007). Hypocotyl elongating in an arch breaks through the soil pulling cotyledon and enclosed plumule through the ground to project them into the air (McMahon et al., 2007).

2.5 Impact of Environmental factors on Seed Germination and Emergence

Variability in seedling emergence within the same population of vegetable crops, directly influence the yield, quality and monetary value of the final product (Finch-Savage et al., 1998). Variations in seedling emergence can occur due to various environmental factors; soil temperature, soil moisture, soil air composition and quality of light (Forcella et al., 2000). Further, soil factors such as soil fertility, salinity, compaction, tillage and surface residue all can influence seedling emergence through their ability to change physical and chemical properties of the soil. However, all these factors can be manipulated directly or indirectly through crop management (Forcella et al., 2000).

Even though, seed germination and vigour of seedlings is gene controlled, seed size, viability, sowing depth, soil moisture, soil oxygen concentration and soil temperature can all affect seed germination, seedling emergence and vigour (Bewley and Black, 1982; Rajasekaran et al., 1992; Hartmann et al., 1997; Rajasekaran et al., 2002). All these factors are known to contribute to poor and sporadic germination and emergence under unfavourable conditions (Bewley and Black 1982; Rajasekaran et al., 1992, Corbineau et al., 1994; Hartmann et al., 1997; Briscoe et al., 2006). Carrots are known to be very sensitive to poor seed bed conditions and it can be very hard to expect fast and uniform seedling emergence as well as crop establishment with a poor seed bed preparation (Salter et al., 1981; Benjamin, 1984). In areas, that have short growing periods, uniform seedling emergence is critical to obtain a uniform crop stand and thereby, uniform root grades (Mathews and Powel, 1986; Herner, 1986).

2.5.1 Temperature

2.5.1.1 Impact of Temperature on Seedling Emergence

Vegetable crops are of different geographical origins, so they have varying growth responses to temperatures. For instance, carrot seeds have germination features similar to species of continental origin. Accordingly, germination variations can be observed depending on temperature variations (Bewley and Black, 1982).

Among all factors affecting seed germination, temperature plays a major role on the time of seed germination, germination percentage, seedling emergence and vigor (Bewley and Black, 1982; Rajasekaran et al., 1992; Corbineau et al., 1994; Hartmann et al., 1997). The importance of temperature in seed germination is similar to an importance of temperature to a chemical reaction because germination will increase due to induced enzyme activity and water balance within the seed with warm temperatures and *vice-versa* (Hegarty, 1973; Rajasekaran et al., 1992).

2.5.1.2 Effect of Temperature on Carrot Seed Germination and Emergence

One of the major constraints of direct seeded vegetable crops in Nova Scotia, being an area having a short growing period, is low soil temperature at the time of seed sowing (Hartmann et al., 1977; Herner, 1986; Rajasekaran et al., 2004, 2005). In Nova Scotia, carrots are directly seeded during late April to May when, soil temperature generally ranges from 2-5 ^{o}C (Rajasekaran et al., 2002). Low temperatures can negatively affect on both germination percentage as well as the germination rate (Kotowski, 1926; Rajasekaran et al., 2002, 2004, 2005). The three cardinal temperatures for seed germination are minimum, optimum and maximum, where optimum cardinal temperature gives the highest percentage of seed germination within the shortest period of time

(Bewley and Black, 1982). The optimum temperature for carrot seed germination is 25 ^{o}C which gives the highest cumulative germination percentage and vigorous seedlings (Finch-Savage et al., 1998). The critical temperature (minimum) for carrot seed germination is 5 ^{o}C (Rajasekaran et al., 2002, 2005) and below the critical temperature, seed germination may not occur. Soil temperatures below 20 ^{o}C can reduce or delay carrot seed germination (Rajasekaran et al., 2002, 2005).

Seeds exposed to temperatures below 20 ^{o}C can be subjected to cold stress and seedlings produced from such seeds will grow poorly, showing abnormalities in root development with other morphological deformities. Further, low soil temperature can limit water flow and reduce water activity or change its configuration due to lack of energy. It reduces the rate of thermo-chemical reactions occurring within the seed to break down stored food, resulting in poor seed germination and emergence (Bewley and Black, 1982). Lack of available water due to limited water flow indicates poor seed germination and a low vigor of emerging seedlings (Simon, 1984). Further, protein synthesis within the seed during germination can also be affected by very low temperatures (2-5 ^{o}C) creating denatured proteins, possibly making them ineffective (Webb et al., 1973; Bewley and Black, 1982). Under low soil temperature, conformational changes that are required for proteins to promote germination may also be affected by inhibiting key metabolic processes that is needed for germinating seeds (Galston and Davis 1970; Rajasekaran et al., 2002) resulting in sporadic seedling emergence and poor crop stands (Hartmann et al., 1997).

2.5.2 Moisture and Seedling Emergence

Seed imbibition, germination, seedling emergence, establishment, subsequent growth and root development all require continuous and sustained supply of water throughout (Bewley and Black, 1982). Seeds must uptake water to initiate seed germination as the first step of emergence, which is called seed imbibition (Bewley and Black, 1982; Baskin & Baskin, 1988). Generally, imbibition of seeds can be completed within less than a day when temperature is between 20 – 25 ^{o}C (Baskin and Baskin, 1988). Low soil moisture limits carrot seed germination and emergence (Rajasekaran et al., 2004). A constant supply of good quality water is essential for carrot seed germination, emergence, good quality carrots with high yields and also to avoid decreased size of roots and rough skins (Hartmann et al., 1988).

2.5.2.1 Physiology of Seed Water Uptake

Amount of seed water uptake depends upon two main factors; i) ability of seeds to uptake water and ii) degree of seed-soil contact. The relationship between soil, moisture and seed can be expressed by using following equation:

$$\Psi cell = \Psi\pi + \Psi m + \Psi p$$

Where $\Psi cell$ is the water potential of the cell of the seed, $\Psi\pi$ is the osmotic or solute concentration effect of cells, Ψm is the matric or hydrational potential of the seeds, *e.g. cell walls; protein bodies,* Ψp is the turgor or hydrostatic potential of cells in an imbibed seed (Bewley and Black., 1982).

Soil-seed system can be represented schematically using analog circuit diagrams, as the movement of water from soil to seed is governed by the rules analogous to flow of electricity described by the Ohm's law (Larcher, 1995).

To visualize flow of water through the soil into the seed, Ohm's law can be used as follow;

$$F = \frac{\varphi e - \varphi s}{i_1 + I + i_2}$$

Where, F is the rate of water flow from the environment to the seed; φe is the water potential of the environment; φs is the water potential of the seed; i_1 is the internal impedance of the soil matrix or other matrix on which a seed is imbibing; I is the external impedance (degree of contact of seed with water supply$^{)-1}$; i_2 is the internal impedance of seeds (including seed coat and air spaces) (Bewley and Black, 1994).

Imbibing seeds uptake only readily available moisture in the soil and soil moisture is therefore, important for seed germination, emergence and vigour (Rajasekaran et al., 2004). Soil moisture between 35% and 40% Field Capacity (FC) is considered as the optimum soil moisture in sandy loam soils for carrot seedling emergence (Rajasekaran et al., 2004). Moisture at 20% FC significantly inhibited carrot seedling emergence (Rajasekaran et. al., 2002). Generally, seed germination of carrot is favoured when soil moisture is maintained at field capacity, whereas high (above 80%) and low soil moistures can inhibit seedling emergence.

2.5.3 Disease Pressure and Seedling Emergence

Seed decay due to soil borne pathogens and reduced growth after emergence can occur in mature plants due to delayed seedling emergence (Bennet and Luther, 1987). Exposure of seeds to low temperature at their early stages of imbibition results in chilling injury (Bewley and Black, 1978). Low temperature at the early phase of water entry induces leakage of solutes from the seeds, due to possible dysfunction of the membrane. This is irreversible as it is a result of chilling injury. This initiates leakage of amino acids, nucleotides or organic acids and sugars. These exudates will provide substrates for the development of fungal pathogens which are present in the soil (Bewley and Black, 1978).

Aster Yellows or carrot yellows occur due to a mycoplasma disease spread by the six spotted leaf hopper. Disease symptoms would be having a pale yellow caste and concentration of very fine rootlets on the tap root (Swiader and Ware, 2002).

Leaf blights are caused by *Alternaria carotae* and *Cercospora dauci,* which are soil born fungal diseases. Infections occur during wet leaf surfaces causing dead leaf spots and also problems of *Alternaria* are severe when experiencing warm days followed by cooler nights (Swiader and Ware, 2002). Most common fungal pathogens identified in Nova Scotia are *Alternaria* and *Cercospora* causing carrot blight and *Rhizoctonia, Phytophthora* and *Pythium* that can cause damping off (PCRP, 2000).

2.5.4 Edaphic (Soil) Factors and Seedling Emergence

Soil crusting can be considered as one of the major constraints for seedling emergence due to poor soil physical properties (mineral soil) and low soil temperature in maritime regions (Briscoe et al., 2006). Crusting is the formation of hard pan on the surface of soil which will act as a physical barrier to the emerging small carrot seedlings. Soil crusts can limit the diffusion of oxygen between the seed embryo and the germinating environment. As a result, it will give rise to sporadically emerged seedlings which will not achieve concentrated crop maturity or potential crop yield (Orzolek, 1987).

Once seeds are planted in the soil, their rate of imbibition (assuming no inherent dormancy mechanism) and germination will be ultimately determined by the impedance of the soil matrix (surface and colloidal forces) and the degree of seed contact with the soil moisture (Bewley and Black, 1982). The nature of seed contact with soil moisture and the uptake of water will be determined by pore geometry, surface tension, evaporative surface of the seed and ambient RH (Bewley and Black, 1982). However, the maximum distance from which a seed can absorb moisture from the soil is 10 mm (Bewley and Black, 1982). Therefore, seed water uptake is influenced by the soil water content of the seed's immediate surrounding (Bewley and Black, 1982). Seedling emergence can also reduce when experiencing higher temperature, due to rapid declining of hydraulic conductivity in surface layer of soil (Lascano and van Bavel, 1986; Finch-Savage et al., 2001).

2.5.5 Importance of Soil Air on Seedling Emergence

Carrot seeds prefer to germinate under higher oxygen concentration than that found in normal air (Bewley and Black, 1982). Increasing seed burial depth, will present reduced O_2 and elevated CO_2 concentrations for the seeds and seedlings emerge. However, it is hard to find soil O_2 lower than 19% and CO_2 concentration above 1% but it is possible to vary these proportions within the immediate surroundings of the seed. Modified gas environment combined with darkness under deep soil burial might be sufficient to suppress seed germination since seeds buried under deep soil can produce volatile inhibitors which cannot readily escape (Bewley and Black, 1982), thereby affecting seedling emergence. Excess of moisture can also reduce carrot seedling emergence, due to lack of available O_2 (Rowse and Finch-Savage, 2003).

2.5.6 Seed Size and Seedling Emergence

Once seed germination is completed, seedlings needed to be pulled through soil to reach the atmosphere called “Emergence”. The success of emergence depends on mechanical obstacles in addition to environmental factors such as temperature and moisture. Seedling emergence can be inhibited or obstructed by the soil clods, compacted and soil crust formed at the surface of soil (Durr et al., 2001). Heavy seeds have the ability to produce longer hypocotyls and emerge despite of deep sowing in soils with hard pans (Tamet et al., 1996). There is a knowledge gap between the optimal size of carrot seeds and its relationship to seeding depth with respect to seedling emergence.

2.6 Seedling Emergence Models

Crop growth models are used to predict seed dormancy, germination and emergence, since common approaches used to document crop growth are imprecise. Crop models display crop phenology or development processes and timing of specific crops (Hodges, 1991). When it comes to crop models, reliability and accuracy of them are very important features as they are used in estimating potential crop yield or predicting germination, emergence or risk management. Models can also be used in assessing risks related to unpredictable weather, to evaluate new cultivars and their adaptability to a given region, and also to analyse sensitivity of crop production to anticipated climatic changes. Moreover, they provide information about how to make best management decisions in cropping practices such as seeding date, plant population, cultivar selection, irrigation, fertilization and rotation to achieve a sustainable production system in agriculture (Jame and Cutforth, 2009). Previous studies on processing carrots, slicer and dicer varieties, under Processing Carrot Research Programme; have developed models for crop competition, yield and quality including resource optimization (Rajasekaran et al., 2006).

2.6.1 Seedling Emergence Modelling

Seedling emergence is considered as the single most important phenological event that has an influence on the success or failure of an annual plant (Forcella et al., 2000). Use of mechanistic model, to simulate seedling emergence as a function of measured or estimated environmental variables is the most promising approach for predicting seedling emergence. Environmental and/or management variables that can be integrated within the model are soil water potential, soil temperature (hydrothermal time), diurnal soil temperature fluctuations, oxygen deficiency, light quality and seed burial depth.

Earlier, plant scientists used initiation of seedling emergence or point in time at 50% emergence (E_{50}) is reached for predicting or estimating seedling emergence which can create errors in their applications (Forcella et al., 2000). Representation of the full emergence cycle with timing is necessary in the dynamic model approach in order to identify important features of seedling emergence, as seedling emergence is not normally distributed around E_{50} value, especially in weeds (Forcella et al., 2000). Seedling emergence models are developed all over the world for both crops and weeds due to this asymmetry of seedling emergence for better representation of important features of emergence, full cycle and timing (Forcella et al., 2000). Among all, species specific models have drawn attention due to their accurate predictions. Thus, cut and peel carrot seedling emergence needs specific models for accurate predictions as a newly introduced high value crop to the industry.

Among all the abiotic factors affecting the time of seedling emergence, the effect of temperature is considered to be the most distinct and recognizable (Forcella et al., 2000; Wang et al., 2009). Nonetheless, ecologists and modellers are debating about the relative importance of temperature and soil moisture on seedling emergence and other plant responses, but most important point to keep in mind is both of these variables are critical (Forcella et al., 2000).

Cumulative thermal time with units of degree days calculated in successive days, by subtracting base temperature (T_b) from daily mean temperature and adding each value to the subtotal until completion of a particular phenological event. This can be used to predict total heat units and growing degree days required from seeding to crop emergence or germination to emergence etc. (Ney and Turc, 1993; Forcella et al., 2000). The linear equation for the cumulative thermal time can be defined as follow (Gallagher, 1979),

$$\mathrm{TT} = \sum_{i=1}^{n}(T - Tb)$$

Where, T is the daily mean temperature, Tb is the base temperature and n is the number of days of temperature observations used in the summation. Thermal time was successful in using emergence models and there are two categories of them: mechanistic and empirical. Mechanistic models have the greatest success in long term because they are developed based on known and experimentally quantified environmental effects on seed germination or seedling emergence (Forcella et al., 2000). Nevertheless, models for soil water potential were not easy to construct due to difficulties in taking related measurements and its cumulative effects on germination and emergence. The "Hydrotime" concept was introduced, with the integration of the cumulative effects of water deficits by Gummerson, (1986). This concept was examined, expanded and well explained by Bradford, (1995).

2.6.1.1 Linear Mathematical Models Developed to Describe Seed Responses for Critical Factors

Germination rate of a given seed fraction (GR_g) was defined as a linear function of temperature between T_b (base temperature) and T_o (optimum temperature) (Bierhuizen and Wagenvoort, 1974).

This can be formulated in Heat Sums or thermal time model as follow:

$Q_T (g) = (T - T_b) t_g$

$Q_T(g)$ is the thermal time to germination of fraction or percentage g, T is the germination temperature, Tb is the base temperature and tg is the seed population. This is a threshold type of model and rate of seedling emergence can be derived using this model.

Analogous to the thermal time model, Hydro-time was defined (Gummerson, 1986; Bradford, 1995) as:

$Q_H = (\psi - \psi_b(g)) t_g$

Where, Q_H is the hydro-time constant, ψ is the soil water potential, $\psi_b(g)$ is the base water potential for a specific germination fraction g and t_g is same as the above.

Effects of sub-optimal temperatures on seedling emergence with respect to different moisture potentials can be explained more elaborately, using hydrothermal time (Bradford, 2002). Combining, heat sums model with hydrotime model, the hydrothermal-time model can be derived. The hydrothermal-time constant (Q_{HT}) for suboptimal temperature T can be defined as (Gummerson 1986; Bradford 1995):

$Q_{HT} = (\psi - \psi_b (g)) (T - Tb) t_g$

Assumptions for this equation are ψ_b is constant and Q_T is independent of temperature and T_b is independent of ψ (Dahal and Bradford 1994; Bradford and Samasco 1994; Kebread and Murdoch, 1999).

There are few models developed for carrots; i) Germination and post-germination growth to carrot seedling emergence: predictive threshold models and sources of variation between sowing occasions (Finch-Savage et al., 1988) ii) Hydrothermal threshold models can describe the germination response of carrot (*Daucus carota*) and onion (*Allium cepa*) seed populations across both sub- and supra-optimal temperatures (Rowse and Finch-Savage, 2003) iii) Seeding rate and seed spacing modulate root yield and recovery of slicer and dicer carrots differently (Rajasekaran et al., 2006). This study was conducted to develop hydrothermal model for cut and peel baby carrots using different soil moisture potentials and temperatures under controlled environmental conditions. Relevance of this model developed for baby carrots to field conditions in maritime regions will also be evaluated, using the field experiment.

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Chapter 3

Relationship between Soil Moisture, Soil Temperature and Seedling Emergence

3.1 Abstract

Individually Quick Frozen (IQF) baby carrots (cut and peel) are the recently introduced high value carrot product by the processing carrot industry. There are four baby grades according to the diameter and fancy is the most preferable grade among all IQF baby carrots. One of major challenges this industry faces is a lack of uniform roots and thus, low percentage of recovery of Fancy grade. Objectives of these experiments were to understand the relationship between soil moisture, soil temperature and their interaction effect on seedling emergence. All 3 experiments were conducted under controlled environmental growth chamber conditions. Soil moisture experiment involved 8 different soil moisture regimes (-5, -10, -20, -30, -40, -50, -60, -90 kPa) whereas the temperature experiment was conducted under 8 different temperature regimes 5, 10, 15, 20, 25, 30, 35, 40 °C and these two experiments were set to a completely randomized design. The third experiment was conducted to identify any interaction effects of soil moisture and temperature, which involved a 2x5 factorial design with 2 levels of temperatures (19 ± 3 and 29 ± 3 °C) and 5 levels of moisture potentials (-5, - 20, - 30, -40, -60 kPa). There was a significant reduction in seedling emergence < -120 kPa and seedling emergence was totally inhibited at – 156 kPa. Seedling emergence velocity was significantly low at -5 and -90 kPa ($P = 0.001$) and significantly high at 20°C and at 30 °C ($P = <0.001$). Decline in soil moisture potentials within containers over time were significant ($P = <0.001$). Seedling emergence was initiated within the shortest (6-8 days) time at 20, 25 or 30 °C ($P = < 0.001$). The seedling emergence was significantly reduced at 30 °C and totally inhibited at 35 and 40 °C, however. The repeated measures analysis showed the effect of temperature on seedling emergence ($P = <0.001$) over time. The third experiment showed there was no significant interaction ($P=0.2378$) effect between soil moisture and temperature on baby carrot seedling emergence. Out of main effects of temperature and soil moisture, the effect of temperature showed a significant influence (P

= <0.0001) on seedling emergence while the effect of soil moisture on seedling emergence was not significant (P = 0.2307). Overall, the effect of temperature on carrot seedling emergence plays a major role compared to soil moil moisture potential. Seedling emergence is negatively influenced at temperatures below 10 °C and above 20 °C. However, moisture potentials <-120 kPa can be a limiting factor for seedling emergence.

3.2 Introduction

Seed germination and emergence is highly influenced both by temperature (Roberts, 1988; Probert, 2000) and soil water potential (Bradford, 1990, 1995; Rowse and Finch-Savage, 2003) and these two factors largely determine the timing of carrot seedling emergence under field conditions (Finch-Savage and Phelps, 1993; Finch-Savage *et al.*, 1998; Rowse and Finch-Savage, 2003). In carrots, timing and spread of time to emergence within the population has a significant impact on the quality of grades obtained, yield and monetary value (Finch-Savage, 1995; Rowse and Finch-Savage, 2003). For example, plant density, determines total yield and mean root size in carrots (Bleasdale, 1967), while timing of seedling emergence within a population influences uniformity of crop stand and thereby, graded yields (Benjamin, 1982).

Seed advancement studies such as osmotic priming which limits moisture availability to seed, have shown development of metabolic advancements within seeds that occur at levels of water stress, preventing them from radicle emergence from seeds (Khan, 1992; Bradford and Haigh, 1994). As in most species, radicle extension growth is less sensitive to moisture stress than radicle emergence from the seed (Ross and Hegarty, 1979). Considering all above factors, Finch-Savage et al., (1998) suggested that the initiation of radicle growth is moisture sensitive and also can act as a rate-limiting factor for seedling emergence from soil. Further, experiments under controlled environmental conditions suggested that post germination growth or seedling emergence can also be quantified using threshold models (Fyfields and Gregory, 1989; Wheeler and Ellis, 1991).

Previous studies on seed germination have showed that percentage seed germination progressively reduced below -670 kPa at 15 °C and below in Poly Ethylene Glycol (PEG). Further, when temperature increased above 15 °C, percentage seed germination has been found to reduce progressively with increasing soil moisture potentials (Rowse and Finch-Savage, 2003). Percentage carrot seed germination also reduced at a water potential of -2800 kPa at 30 °C when, water potentials were maintained using PEG (Rowse and Finch-Savage, 2003). These findings suggest the interactions between soil temperature and moisture on both seed germination and emergence. Emergence Velocity (EV) can be derived using slopes of emergence curves developed with respect to different moisture potentials. Germination Velocity (GV) can be defined (Mugnisjah and Nakambura, 1986; Desplaned and Houle, 1997) as follows,

$$GV = (\sum(G_d / d) / G_t) X 100$$

Where, G_d - Number of seeds germinated on day "*d*", G_t – Total number of seeds germinated at the end of the test, *d* – Number of days since the beginning of the test.

The overall hypothesis relating to the experiments below is, soil moisture and, soil temperature independently or in combination can influence seedling emergence. The specific objectives for three experiments were to: i) understand the relationship between soil moisture potential and seedling emergence, ii) determine the relationship between temperature and seedling emergence, iii) identify whether there is any interaction effect of soil moisture and temperature on baby carrot seedling emergence.

3.3 General Methods

Three experiments were designed to understand the effects of soil moisture, temperature and interaction effect of moisture and temperature on cut and peel baby carrot seedling emergence. All three experiments were conducted under controlled environmental conditions. *Daucus Carota* var sativus L. cultivar Triton was used in all experiments conducted under controlled environments, which was seeded at the rate of 85 seeds per 30 cm, at a seeding depth of 2.5 cm.

3.3.1 Description of Experimental Units

Each experimental unit was a transparent plastic box with the dimensions of 30 cm length, 20 cm width and 25 cm deep with an observation hole at the centre of the lid (figure 5). Top soil, developed from Truro series sandy loam parent material ((sandy loam soils developed on red sandy loam till, derived from medium grained red sandstones (Soil survey of Colchester County, 1948)), was used as the medium to grow carrot seedlings. Sieved soil, using 4 mm and 1.4 mm sieves were used to maintain uniformity of the medium. Total weight of one experimental unit was set to be 3 Kg and all the experimental units were prepared equally for all tree experiments mentioned above. About 3 liters of water were added to each experimental unit and all the containers with excess water left open on greenhouse benches (figure 2), allowing them to dry down until it reached field capacity (0 kPa). Pre-calibrated watermark soil moisture sensors (Spectrum technologies Inc., USA) were installed at 2.5 cm depth which was the seeding depth, to monitor soil moisture potentials at the seeding depth.

Figure 2: Monitoring soil moisture potentials using soil moisture sensor and sensor reader

Then, each of the experimental unit after reaching field capacity at the room temperature (21°C) was transferred to the growth chambers which were set at appropriate temperatures and allowed them to dry down until it reached required level of moisture potentials, which constituted treatments. Upon reaching their required moisture potential, seeding was done at the rate of 85 seeds per 30 cm in three rows. In total, 85 seeds were sown in each experimental unit with spacing of 1 cm (plant to plant) x 2.5 cm (row to row) and at the depth of 2.5 cm.

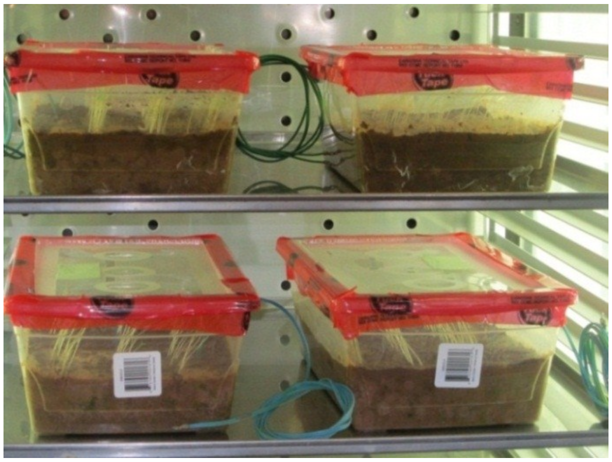

Figure 3: Experimental units with fully emerged seedlings, placed in germination chamber at set temperature.

All the seeded containers were closed with the lids and sealed using a Duct tape (Thermoflo Technologies Ltd., British Colombia, Canada) and small holes on the container walls and lids were also sealed using a gummy substance to eliminate moisture loss. All containers were located in randomly assigned spots within the growth chamber or germination chamber (figure 3) and soil moisture potential within each experimental unit was continuously monitored and recorded, using soil moisture sensors (figure 4c) installed permanently at seeding depth throughout the experiment and digital soil sensor reader (figure 4a).

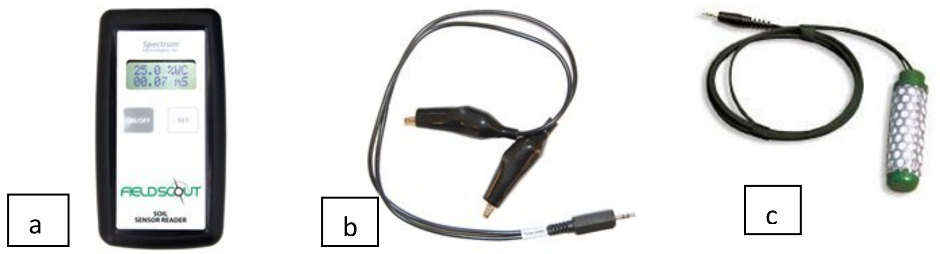

Figure 4: Instruments used to measure soil moisture potential; a – soil sensor reader,

b – Watermark adapter for FieldScout soil sensor reader, c – Watermark soil moisture sensor (Source of Images: www.specmeters.com)

3.3.1.1 Parameters Measured

Soil moisture potentials were monitored throughout the experiment using pre-installed, pre-calibrated water mark soil moisture sensors at the seeding depth of 2.5 cm and digital soil sensor reader (Spectrum Technologies, Inc., USA). Seedling emergence was recorded daily until completion of seedling emergence up to 20 to 25 days from seeding.

Average seedling emergence per day was calculated using 4 replicates, of moisture and temperature experiments and 3 replicates set for the moisture and temperature interaction experiment.

Cumulative seedling emergence was calculated as follows:

Cumulative seedling emergence (%) = (No. of seedlings emerged on day d / 85)*100

Seedling emergence velocities at different temperature regimes and moisture potentials were calculated using following equation ((Mugnisjah and Nakambura, 1986; Desplaned and Houle, 1997),

$$GV = (\sum(G_d / d) / G_t)X100$$

Where GV is the Germination Velocity, G_d - Number of seeds germinated on day "*d*", G_t – Total number of seeds germinated at the end of the test, *d* – Number of days since the beginning of the test.

3.4 Relationship between Soil Moisture and Seedling Emergence in Carrots

3.4.1 Hypothesis and Objectives

Hypothesis: Lower (more negative) soil moisture potential (Ψ) delays seedling emergence of cut and peel baby carrots

Objective: To define the relationship between soil moisture potential and seedling emergence

3.4.2 Materials and Methods

Moisture experiment was conducted with eight different soil moisture potentials (-5, -10, -20, -30, -40, -50, -60 and -90 kPa) and 4 replicates. Growth chamber was adjusted to provide 16 h light per day with the intensity of 180 μ mol cm^{-2} s^{-1}, and the source of light was a combination of florescent (440-460 nm) and incandescent (440-660 nm). Growth chamber was set at 21 °C throughout this experiment and 32 containers or experimental units were prepared as explained under general methods (3.3.1) and located within growth chamber (figure 5), in randomly assigned spots.

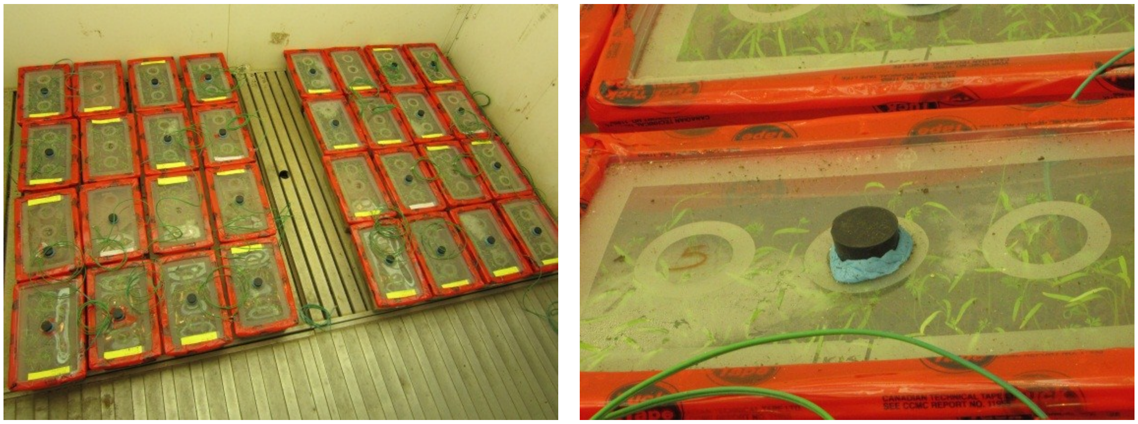

Figure 5: Tightly sealed experimental units with Duct tape and green colour cables from water mark soil moisture sensors, showing final set up within growth chamber.

3.4.2.1 Experimental Design and Statistical Analysis

Moisture experiment was designed as a Completely Randomized Design (CRD) with 4 replicates. Treatments were 8 different soil moisture potentials (in section 3.4.1) and response was seedling emergence. Data collected on both seedling emergence and measured moisture potentials violated normality assumptions (normality, constant variance and independence of error terms). Box-cox method in Minitab16 (Minitab Inc. State college, PA) was used to find the power (λ) of transformation suitable for data transform. Data collected on seedling emergence were square transformed to achieve normality requirements ($SE = SE^2$) since $\lambda = 2$. Data collected on actual moisture potential ($AMP = AMP^{1/2}$) were also violated normality assumptions and they were square root transformed to achieve normality requirements since $\lambda = 0.5$.

Emergence velocities (EV) were calculated separately for treated moisture potentials and emergence velocities met the requirements of three normality assumptions.

Analysis of variance (ANOVA) followed by Tukey's multiple mean comparison was carried out to test the significance of mean seedling emergence under different soil moisture potentials. Tukey's multiple mean comparison was used in this analysis to control type 1 experiment-wise error rate.

Regression analysis was conducted between seedling emergence and soil moisture potential to fit a model. The model adequacy was checked using R^2 ($R^2 > 60\%$) and P value ($P = < 0.05$). Further, regression analysis between emergence velocity and soil moisture potential and measured soil moisture potential and set soil moisture potential were also carried out at $\alpha = 0.05$ to fit models.

3.4.3 Results

3.4.3.1 Effect of Soil Moisture Potential on Baby Carrot Seedling Emergence

Emergence of carrot seedlings progressed more rapidly as long as availability of moisture was not a limiting factor. Cumulative seedling emergence (%) was plotted against days after seeding to visualise trends of seedling emergence over time (figure 6) with respect to different soil moisture potentials. In contrast, percentage seedling emergence was delayed and total seedling emergence was reduced down to 46.5% when soil moisture potential was - 90 kPa.

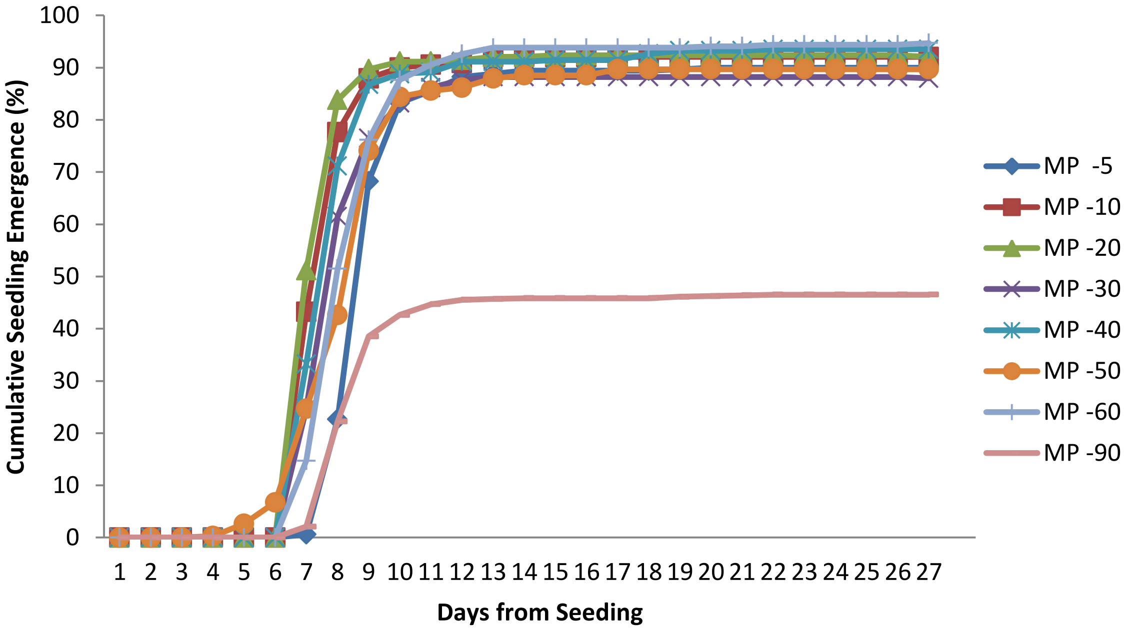

Figure 6: Cumulative seedling emergence (SE) as influenced by set moisture potential (kPa).

Carrots seeds took 5-7 days to emerge through the soil (figure 6) after seeding depending on soil moisture potential at 21 °C. Once seedlings started emerging on day 5, 50% seedling emergence completed by day 8 and reached 90% by 11th day, under all soil moisture potentials, except at – 90 kpa (47%). Carrot seeds completed seedling emergence by 11th day under all different moisture potentials whilst 53% of seeds did not emerge at - 90 kPa. ANOVA followed by Tukey's mean comparisons carried out at the 5% level of significant in Minitab-16, showed a highly significant influence of moisture potential on seedling emergence (P = <0.001). Seedling emergence at – 90 kPa was significantly low (table 1) compared to other seven treated moisture potentials.

Table 1: Mean seedling emergence (%) of variety Triton together with letter groupings.

Soil Moisture Potential (-kpa)	Mean (SE^2) seedling Emergence (transformed)	Back Transformed means of seedling emergence with Letter Groups (-kPa)
-90	2573	51^b
-60	9080	95^a
-50	8156	90^a
-40	8837	94^a
-30	7876	89^a
-20	8514	92^a
-10	8521	92^a
-5	8195	90^a

Means followed by the same letter are not significantly different at α = 0.05 with Tukey's adjustments.

3.4.3.2 Soil Moisture Potential Dynamics

Continuous monitoring of soil moisture potentials within experimental units following seeding showed progressive declining in soil moisture potentials over time. Preliminary experiment conducted showed, spraying water to maintain moisture level at required level gave drastic differences in water potentials within each experimental unit (open system) hence this approach was not adopted. Therefore, recorded moisture potentials within sealed experimental units with respect to set moisture potentials were plotted to understand the trends of moisture reduction over time (figure 7). Reduction in available moisture potential was low at -5, -10, -20 and -30 kPa overtime, whereas rapid decline in moisture potential showed at -40, -50, -60 and -90 kPa (figure 7). These low moisture potentials showed a sudden drop on day 5 which continued to decline (figure 7) until 11th day.

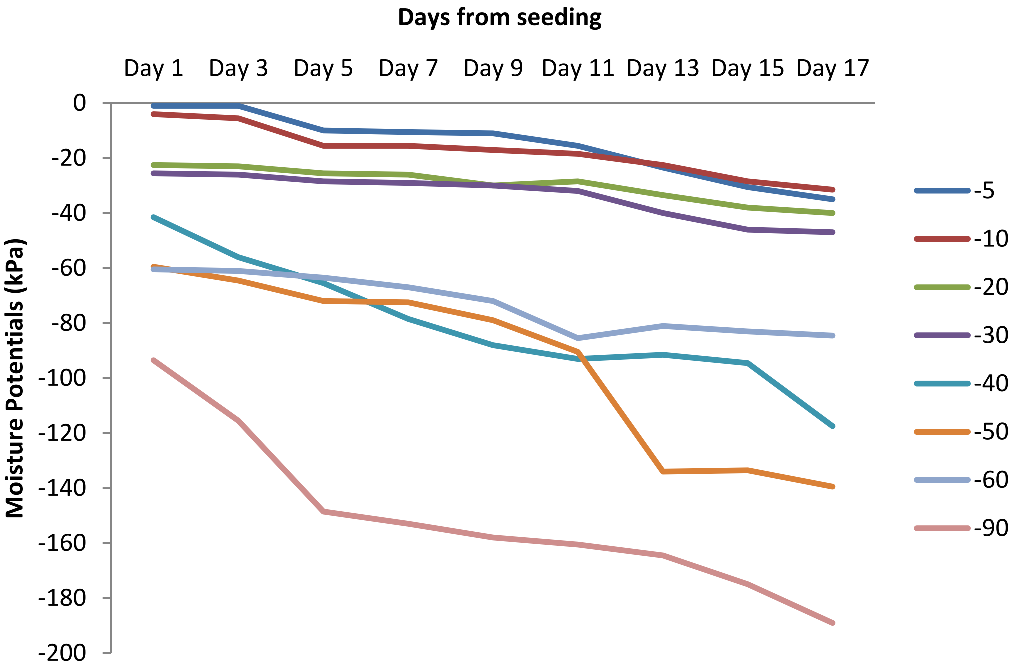

Figure 7: Dynamics of soil moisture potential (kPa) declining overtime.

Significance of mean moisture reduction over time with respect to set moisture potential were tested using ANOVA followed by Tukey's mean comparison at 5% level of significant. The moisture reduction over time was highly significant (P = <0.001) and the highest available moisture reduction was observed at -90 kPa (table 2).

Table 2: Means of recorded moisture potentials from seedling emergence up to completion, together with letter groupings in response to set moisture potentials.

Set Moisture Potential (–kPa)	Recorded Mean Moisture Potential - Transformed	Recorded Mean Moisture Potential (-kPa) Back transformed
90	12.00	144.00^{a}
60	8.90	79.20^{b}
50	9.30	86.50^{b}
40	8.00	64.00^{b}
30	5.70	32.50^{c}
20	5.20	27.00^{c}
10	3.70	13.70^{cd}
5	2.70	7.30^{d}

Means followed by the same letters are not significantly different at $\alpha = 0.05$ level of significance with Tukey's mean comparisons, P= <0.001.

In contrast, available moisture reduction was comparatively low at the set soil moisture potentials of -5, -10, -20 and -30 kPa.

3.4.3.3 Regression Model for Measured and Set Moisture Potentials

Regression analysis between recorded moisture potential and set or treated moisture potential showed a significant (($R^2 = 97.3$ %, P = <0.001 at $\alpha = 0.05$) positive linear relationship suggesting; although the decline in soil moisture potential is parallel, the decline in soil moisture potential for a set moisture potential may be greater in more negative soil moisture potentials.

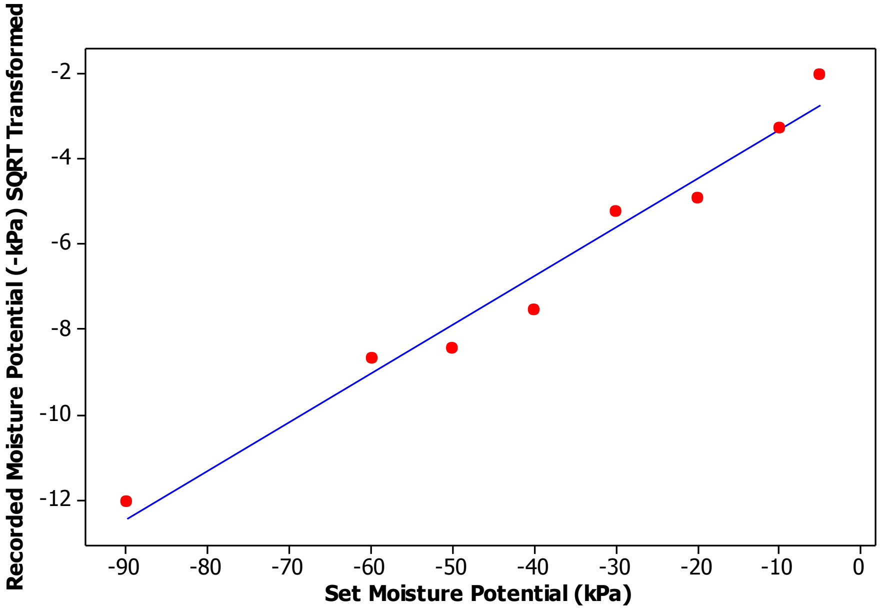

Figure 8: Linear regression between measured soil moisture potential and set moisture potential (-kPa), the regression model fitted was, Rec. MP = -4.83 + 0.012 Set. MP.

When set moisture potential (Ψ) was more negative (-90 kPa), the recorded Ψ was very low (-144 kPa) while set Ψ was -5 kPa, recorded Ψ soil was not very low (7.3 kPa). This suggests, increasing Ψ (figure 8) increases recorded Ψ proportionately. Since, recorded moisture potential was the available moisture for emerging seedlings; recorded Ψ was used in regression analysis below instead of set Ψ.

3.4.3.4 Regression Analysis of Seedling Emergence and Measured Soil Moisture Potential

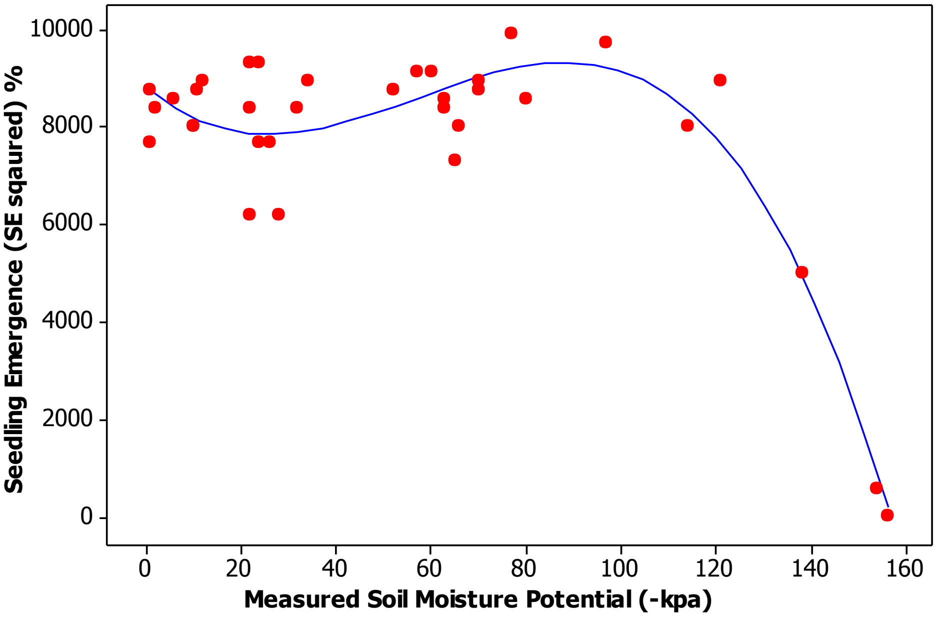

Figure 9: Third-order polynomial regression of percentage seedling emergence of variety Triton. The regression model fitted was, $SE = 93.95 - 9.17MP + 1.45MP^2 - 0.11MP^3$, seedling emergence data on Y-axis are square transformed (SE^2).

The regression analysis between mean seedling emergence (%) and moisture potentials (-kPa) showed a significant positive cubic relationship ($R^2 = 86.3\%$, $P = 0.001$) at 5% level, implying that increasing available moisture (> -120 kPa) can increase seedling emergence up to -97 kPa. However, moisture potentials below -120 kPa reduced seedling emergence significantly (figure 9)

3.4.3.5 Emergence Velocity

Emergence velocities for each of the moisture potential were calculated using the equation mentioned in section 3.3.1.1. ANOVA followed by Tukey's multiple mean comparison (which control type-I experiment wise error rate) for emergence velocities was conducted to test the significance of means at different soil moisture potentials. Analysis of variance showed a significant difference between mean seedling emergence velocities (P = 0.001 at 5% level of significance) at observed soil moisture potentials. The highest seedling emergence velocity was recorded at -20 kPa and the lowest velocity was recorded at -5 kPa (table 3). Seedling emergence velocity at – 20 was significantly higher compared to -5, -60 and – 90 kPa.

Table 3: Means of emergence velocities together with letter groupings in response to different moisture potentials.

Moisture Potentials	Mean Emergence Velocity with Letter Grouping (Percentage seedling emerged /day)
-90	12.88^{cd}
-60	13.39^{bcd}
-50	14.01^{abcd}
-40	14.42^{abc}
-30	14.13^{abcd}
-20	15.40^{a}
-10	15.01^{ab}
-5	12.46^{d}

(Means sharing same letter group are not significantly different at α = 0.05 with Tukey's adjustments)

3.4.3.6 Regression Analysis of Emergence Velocity

The regression analysis between emergence velocity and moisture potential (figure 10) showed a significant positive quadratic relationship ($R^2 = 84.4\%$, $P = 0.01$) at 5% level. Increasing soil moisture potential above -10 kPa showed a decrease in seedling emergence velocity, suggesting moisture potentials above -10 kPa and below -40 kPa can reduce emergence velocities of carrot seedlings.

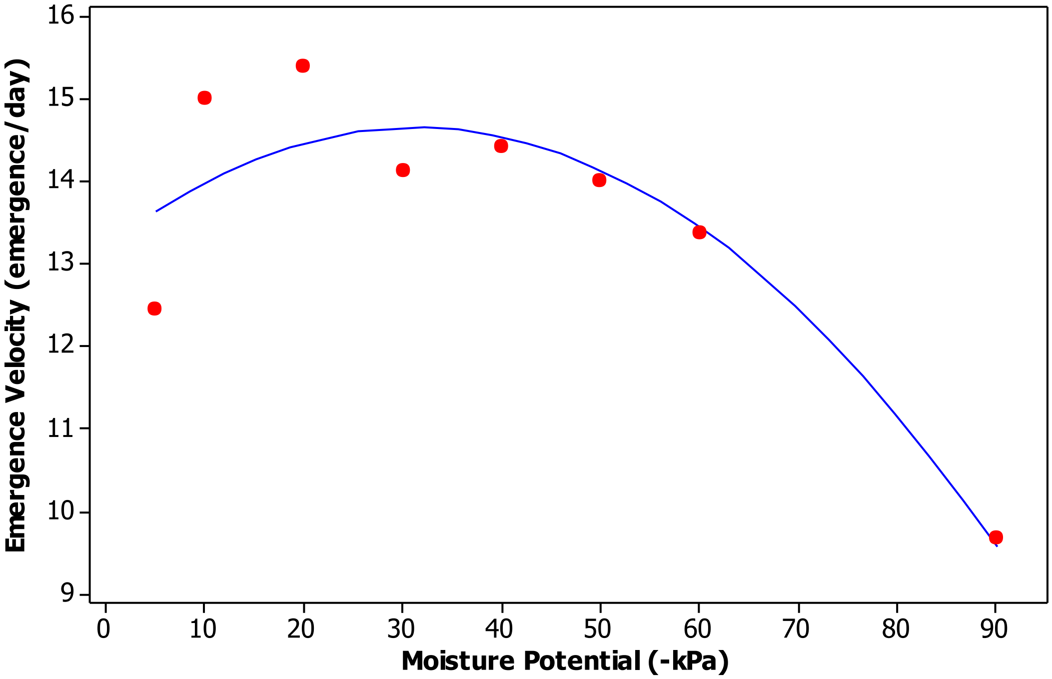

Figure 10: Second order polynomial fitted for emergence velocities, the model fitted for emergence velocities is, $EV = 13.21 + 0.09284\ MP - 0.00148MP^2$.

Containers with seedlings which completed emergence (figure 11) showed different responses depending on moisture availability. Starting from drier moisture potential -90kPa up to -5 kPa, carrot seeds received enough soil moisture to emerge but moisture potential below – 90 kPa (measured moisture potential <- 120 kPa) was unable to provide sufficient moisture for plant survival after emerging.

3.4.3.7 Seedling Response to Soil Moisture Potentials at Completed Emergence

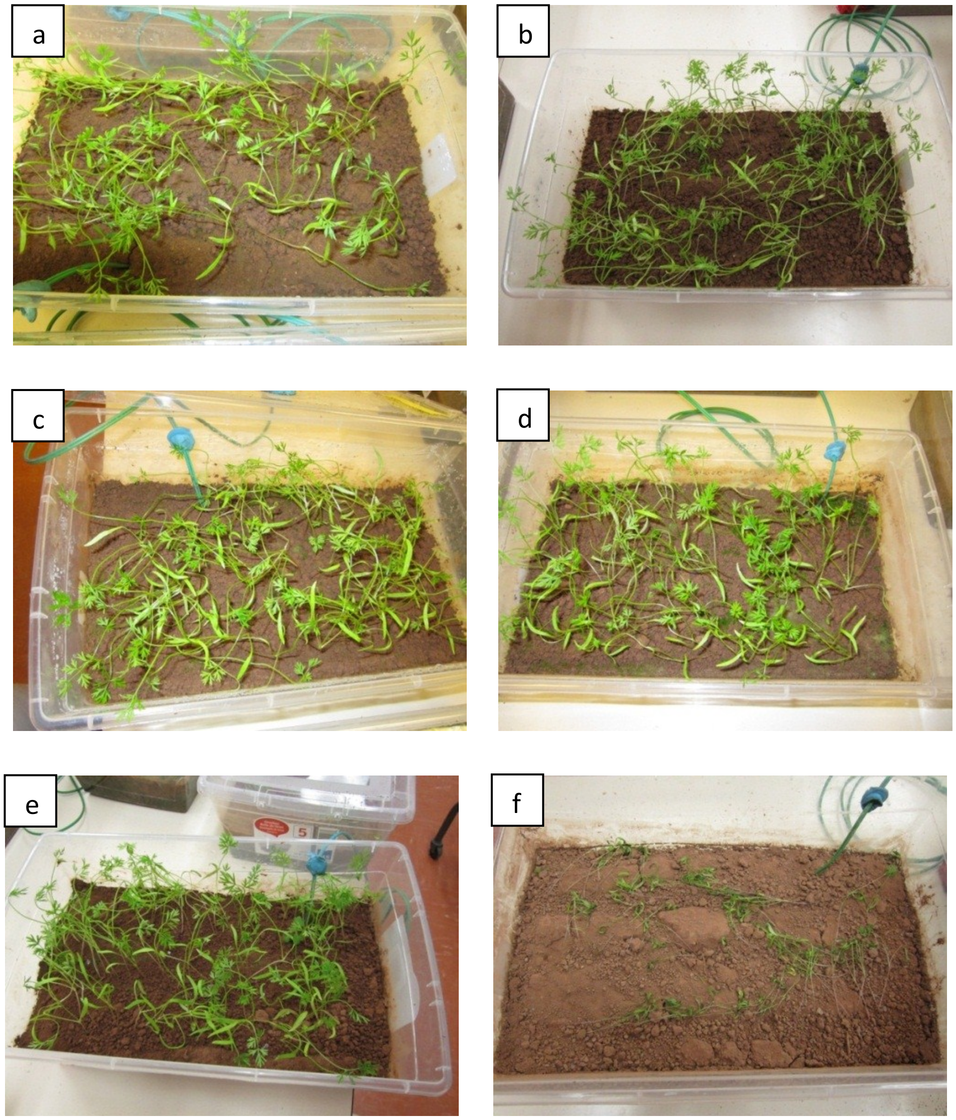

Figure 11: Seedling Emergence at; a. moisture potential/MP (-5 kPa), b. MP -10 kPa, c. MP (-20 kPa), d. MP (-30 kPa), e. MP (-40 kPa), f. MP (-90 kPa)

3.4.4 Discussion

Soil moisture potential plays a major role in seedling emergence as found in literature (Bewly and Black, 1982; Baskin and Baskin, 1988). Influence of moisture stress on seedling emergence was better explained by the results of this experiment. In this study variety Triton was used at the seeding rate of 85 seeds/ 30 cm and 2.5 cm seeding depth at 21 °C to obtain above discussed results. As shown in Figure 6, significantly low seedling emergence ($P = <0.001$) was recorded at moisture potential -90 kPa. The effect of soil moisture potentials on seedling emergence was not significant starting from -5, -10, -20, -30, -40, -50 up to -60 kPa but moisture potential at or below -90 kPa (at set moisture potential) did not provide sufficient moisture, for seedling emergence and or to complete seedling emergence. The Regression model fitted for seedling emergence (figure 9) also showed, seedling emergence started to decline at -120 kPa and totally inhibited at – 156 kPa.

Since, more negative soil moisture potentials showed a rapid decline in soil moisture potentials which was non-uniform among all 4 replicates, 8 replicates set at -90 kPa were used in this experiment to confirm seedling response to declining moisture. Seeds sown within 8 replicates with set moisture potential -90 kPa, showed different responses in seedling emergence depending on available soil moisture such as, 3 experimental units showed zero emergence (when soil moisture potential <-150 kPa) and rest of the replicates showed a good total seedling emergence. In certain cases, emerged seedlings under -90 kPa (figure 11f) showed plant wilting and death over time, implying moisture potentials < -90 kPa may provide sufficient moisture for seedlings to emergence but not the survival after emergence.

In contrast, the emergence velocities were significantly higher at moisture potentials -10, -20 and -40 kPa whereas the lowest was recorded at -5 kPa, implying excess availability of moisture may also reduce carrot seedling emergence, possibly due to lack of available O_2 (Rowse and Finch-Savage, 2003).

Moisture reduction within experimental units over time was significant at -50, -60 and -90 kPa compared to other moisture potentials. Total seedling emergence at moisture potential -90 kPa reduced to 47%, may be due to seed competition for limited available water and rest of 53% of seeds may not be able to get sufficient moisture to initiate seedling emergence. As Ross and Hegarty, (1979), explained in most species, radicle extension growth is less sensitive to moisture stress than radicle emergence from the seed suggesting, moisture potential up to -120 kPa may be sufficient to initiate radicle emergence from the carrot seeds.

Moisture losses or reduction in available moisture within experimental units were observed when monitoring soil moisture throughout the experiment as explained in Figure 7. All the set moisture potentials showed this trend and it could be due to many reasons. It is possible that moisture can escape as vapour even from a very tiny hole in container, although they were sealed carefully. In this close system, some of the moisture as vapour can also be utilized to become equilibrium with air space. Further, most of the condensed moisture observed on container walls did not released back to the soil since there was no day and night temperature difference. Moreover, a sudden drop in soil moisture potentials was observed under more negative soil moisture potentials on day 5 as demonstrated in Figure 7. It may possibly be due to utilization of available limited water by germinating seeds and emerging seedlings. Further, this experiment was conducted in a closed system, which can possibly limit available O_2 to emerging seedlings, but microorganisms developed within top soil system might be able to release some O_2 to the growing environment (e.g. Algae grown on top soil).

Regression models fitted between seedling emergence and measured soil moisture potential, actual soil moisture potential and set moisture potential, emergence velocity and soil moisture potential under controlled environmental conditions can be utilized to predict carrot seedling emergence as influenced by moisture potentials but there is a chance to change these predictions with temperature or abiotic and biotic influences under the field conditions. Main purpose of developing a model between seedling emergence and soil moisture potential was to identify the effect of moisture stress on baby carrot seedling emergence and to predict the timing of seeding and suitable other management practices for quick, uniform and vigorous seedling emergence. Studies similar to this work were carried out before to understand the effects of soil moisture and temperature stress on carrot seedling emergence and to find suitable techniques to overcome effect of those stresses (Briscoe et al., 2006). Gels and seed germination and emergence promoters (GEP's) were used to overcome cold stress and drought in Briscoe et al., (2006) and thereby, to obtain a uniform and vigorous seedling emergence for carrots, using cultivar Oranza, a slicer carrot. In comparison to Briscoe et al., 2006, this experiment was mainly focused on to identify the moisture potentials that can reduce cumulative seedling emergence under constant environmental conditions. Moreover, Finch-Savage et al., 1998, conducted a study to understand the germination and post-germination growth of carrot, cv. Nantura and Nandor in response to different temperatures and moisture potentials. *D. carota* cv. Nandor was used to record germination in laboratory conditions and moisture potentials were established using moist absorbent paper (Whatman, grade 181) with polyethylene glycol solution. At the same time they used field soil in trays to mimic field conditions with soils brought up to the field capacity (0.005 MPa or 5 kPa), the nominal field capacity to avoid moisture stress. The results of Finch-Savage et al., showed germination was unaffected by soil moisture potential (Ψ) as long as Ψ remained above the base water potential (Ψ_b) which is similar to the results discussed under 3.4.3.1 in this study. Finch-Savage et al., (1998), was found initiation of radicle growth up to penetration of seed coat operates as a moisture sensitive function and that determines timing of seedling emergence under variable soil moisture conditions. Further, they observed a distribution of base water potential depending on temperatures and recorded a decline in percentage germination at – 0.8 MPa (-800 kPa) and a lack of germination at -1.2 MPa (-1200 kPa). Ross and Hegarty, (1979), were also stated Ψ_b carrots as -0.81 MPa and they also stated these variations in Ψ_b for carrots are not vary large. However, in the current study – 156 kPa was recorded as the Ψ_b, which measured using watermark soil moisture sensors permanently installed at the seeding depth in top soil (Truro series).

3.4.5 Conclusion

Lower or more negative soil moisture potentials (<-120 kPa) reduced carrot seedling emergence significantly, accepting the hypothesis of this experiment. However, soil moisture potentials closer to field capacity (moisture potentials closer to 0 kPa) may also reduce (table 3) velocity of carrot seedling emergence significantly. Seedling emergence was totally inhibited at -156 kPa.

3.5 Relationship between Temperature and Seedling Emergence

3.5.1 Hypothesis and Objective

Hypothesis: Increasing temperatures influence seedling emergence differentially on baby carrots

Objective: To understand the relationship between temperature and seedling emergence

3.5.2 Materials and Methods

This experiment was carried out in a germination chamber (Conviron-controlled environments Ltd., Winnipeg) to facilitate more accurate control of wide range of temperatures from 5 °C to 40 °C. This experiment was set to a completely randomized design with eight different temperature regimes; 5, 10, 15, 20, 25, 30, 35 and 40 °C with 4 replications (figure 12) for each treatment. The germination chamber was adjusted to provide 16 h light per day for all the treatment temperatures regimes and the light intensity within the germination chamber was 20µ mol cm^{-2} s^{-1} throughout whereas the source of light was florescent tubes. Experimental units were prepared as explained under general methods (3.3.1) and transferred to the germination chamber set at the particular temperature to be tested.

Figure 12: Experimental set-up inside the Germination Chamber with 4 replicates.

3.5.2.1 Experimental Design and Statistical Analysis

This experiment was designed as a completely randomized design and data collected on seedling emergence was checked for normality assumptions. Analysis of Variance followed by Tukey's mean comparison was carried out to identify the significance of treatment means using statistical package, Minitab 16 (State College, PA.USA). Tukey's multiple mean comparison was used to control type I experiment-wise error rate. Data collected on total seedling emergence, emergence velocity and date of initiation of seedling emergence were met with requirements of normality assumptions but data collected on measured soil moisture potential violated normality assumption. Box-cox transformation was used to find the power of transformation (λ) and according to λ value data were log transformed (SE = log base_{10} SE) to use in ANOVA (Minitab 16, State college, PA, 2010).

3.5.3 Results

3.5.3.1 Effect of Temperature on Baby Carrot Seedling Emergence

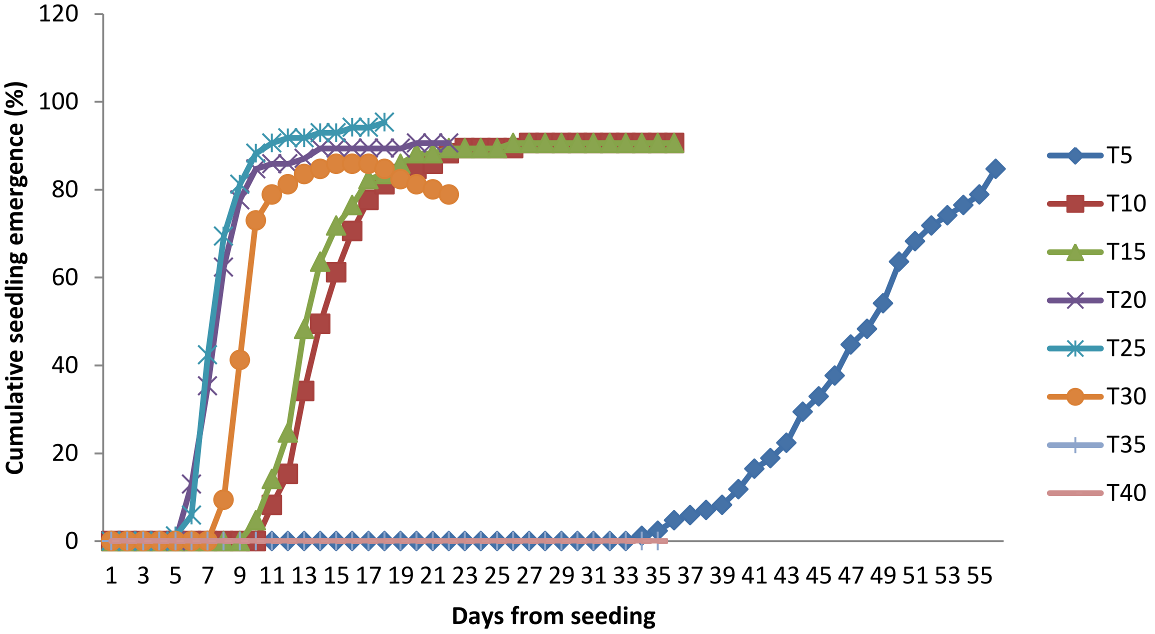

Figure 13: Cumulative seedling emergence (%) over time as influenced by different temperature regimes.

Temperature significantly influenced seedling emergence. Quick seedling emergence (within 4-5 days after seeding) and emergence completion was observed at 20 and 25 °C (figure 13), whilst seedling emergence was delayed by 33 days at 5 °C. Cumulative seedling emergence reached 91% on 11th day under 25 °C and 20th day under 20 °C whereas cumulative seedling emergence reached 85% on 56th day (figure 13) at 5 °C. Seedling emergence at 10 and 15 °C showed similar trends as to that of those at 20 or 25 °C, but it took 9 days to initiate seedling emergence at 15 °C and 10 days at 10 °C. Further, total number of days required to reach 91% seedling emergence was 25 days at 10 and 15°C. Seedling emergence under 30 °C however, showed a different trend compared to other treatments since, seedling emergence started on 7th day after seeding and reached a maximum of 85% on the 15th day but from 17th day after seeding, percentage seedling emergence started to decrease. Interestingly, there was no seedling emergence at all when temperatures were 35 and 40 °C even after 33 days.

Analysis of variance followed by Tukey's mean comparison was carried out in Minitab - 16 , to test the statistical significance of these variations occurred in means due to the influence of temperature (Tukey's mean comparison was used to control type – I experiment wise error rate).

Table 4: Significance of mean seedling emergence (%) of variety Triton at different temperatures.

Temperature (°C)	Mean Seedling Emergence (%)	Number of Days Required for maximum SE
5	85.25^{ab}	56
10	91.25^{a}	27
15	94.75^{a}	26
20	86.33^{ab}	22
25	90^{ab}	18
30	78.67^{b}	17
35	0.00^{c}	-
40	0.00^{c}	-

Means do not share the same letter are significantly different at $\alpha = 0.05$ with Tukey's adjustments, $P = <0.001$

Mean seedling emergence showed a significant difference ($P = < 0.001$ at $\alpha = 0.05$ level of significant) due to the influence of temperature. The highest total mean seedling emergence was observed at 5, 10, 15, 20 and 25 °C (table 4) whereas seedling emergence at 30 °C, was significantly low and emerged seedlings were pale in colour and some of them died after sometime (Figure 14) . There was no seedling emergence above 30 °C.

Figure 14: Seedlings emerged at 30 °C were pale in colour and died back after sometime

3.5.3.2 Effect of Temperature on Seedling Emergence over Time

Table 5: ANOVA table of repeated measures analysis to see the effect of temperature on seedling emergence evolves as progressing with days.

Effect	DF	F Value	P Value
Temp	5	1627.73	<.0001
Day	9	806.32	<.0001
Temp*Day	45	74.12	<.0001

Using Autoregressive covariance structure at 5% level of significant.

Repeated measures ANOVA with least square (LS) mean comparison in SAS 9.3 (SAS institute Inc., NC, USA) was conducted to see whether the effect of temperature evolves over a period of time. Based on ANOVA, the effect of temperature on seedling emergence over a period of time or temperature and day interaction ($P = < 0.001$) was highly significant (table 5).

The highest significant mean seedling emergence was observed at 25 °C and the lowest significant mean seedling emergence was recorded at 30 °C on day 8 (table 6). As an example, day 18th showed the highest significant mean seedling emergence out of all days and this particular mean seedling emergence at 25 °C remained significant at days

21, 24, 27, 30 and 33 out of all other significant days showed in table 6. Moreover, there was no significant difference in mean seedling emergence on day 15th, when temperatures were 25 and 10 °C. All the other significances at different time points are displayed in table 6 as follows,

Table 6: Repeated Measures ANOVA for five different temperature regimes to examine the significance of evolutionary effect of temperature on seedling emergence over time.

Temperature (°C)	Days after seeding	Mean seedling emergence with letter grouping
25	18	80.75^{a}
25	21	80.75^{a}
25	24	80.75^{a}
25	27	80.75^{a}
25	30	80.75^{a}
25	33	80.75^{a}
25	15	79.5^{ab}
10	15	77.75^{ab}
10	21	77.75^{ab}
10	24	77.75^{ab}
10	27	77.75^{ab}
10	30	77.75^{ab}
10	33	77.75^{ab}
15	15	77.75^{ab}
25	11	77.25^{ab}
15	21	76.75^{ab}
15	24	76.75^{ab}
15	27	76.75^{ab}
15	30	76.75^{ab}
15	33	76.75^{ab}
10	18	76.75^{ab}
15	18	76.75^{ab}
15	15	75.50^{ab}
20	15	75.00^{b}
20	18	75.00^{b}
20	21	75.00^{b}
20	24	75.00^{b}
20	27	75.00^{b}
20	30	75.00^{b}
20	33	75.00^{b}
30	15	73.00^{bc}
30	18	72.00^{bc}
20	11	71.50^{bc}
30	21	69.00^{bc}
30	24	68.00^{c}
30	11	67.00^{c}
30	30	66.70^{c}

30	33	66.70^{c}
25	8	64.00^{c}
30	27	62.50^{c}
20	8	19.00^{d}
15	11	9.50^{e}
30	8	7.70^{e}

Least square means together with letter groupings at 5% level of significance and means sharing same letter group are not significantly different.

Since least square mean comparison in table 6, conducted up to 33 days, effect of 5 °C on seedling emergence overtime was not estimated properly. Thus, the following repeated measures analysis was conducted to see whether effect of temperature at 5 °C on SE evolves over time. Proc-mixed glm in SAS 9.3 was used to analyse data collected on seedling emergence at 5 °C.

Table 7: ANOVA table of repeated measures analysis to see the effect of 5 °C on carrot seedling emergence over time.

Type III tests of fixed effects				
Effect	DF	Den DF	F Value	P Value
Day	11	36	36.89	<0.0001

Using Compound Symmetry covariance structure and Proc- Mixed Glm procedure at 5% level of significant.

There was a significant difference between days 42 and 46 in terms of seedling emergence and also between 46 and 48 in least square means of seedling emergence (table 6). The day 42 after seeding is the 8th day after initiation of seedling emergence and showed 19% of emergence and day 46 is the 12th day after initiation of seedling emergence which showed 46% emergence and it was significantly different from day 42 as in table 8. In comparison, when temperature was 10 °C, 18th day after seeding or 8th day after initiation of seedling emergence, recorded 81% seedling emergence and 12 days after initiation emergence showed 84% of seedling emergence implying, even after initiation of seedling emergence, the percentage seedling emergence overtime was low at 5 °C, it may be due to slow emergence rate at 5 °C (table 6, 8).

Table 8: Least Square means of seedling emergence together with letter groupings to observe effect of temperature on seedling emergence over time at 5 °C.

Days after seeding (at 5 °C)	Mean seedling emergence with letter grouping
56	72.50^{a}
54	65.00^{ab}
52	61.50^{ab}
50	58.25^{b}
48	53.75^{b}
46	35.50^{c}
44	25.25^{cd}
42	15.75^{d}
40	10.25^{d}

Means sharing same letter are not significantly different at 5% level of significance.

Effect of 5 °C, over time on carrot seedling emergence was highly significant (P= <0.0001) as shown in ANOVA (table 7) and repeated measures analysis was conducted to separate significant means as shown in table 8.

3.5.3.3 Regression Analysis between Seedling Emergence (%) and Temperature

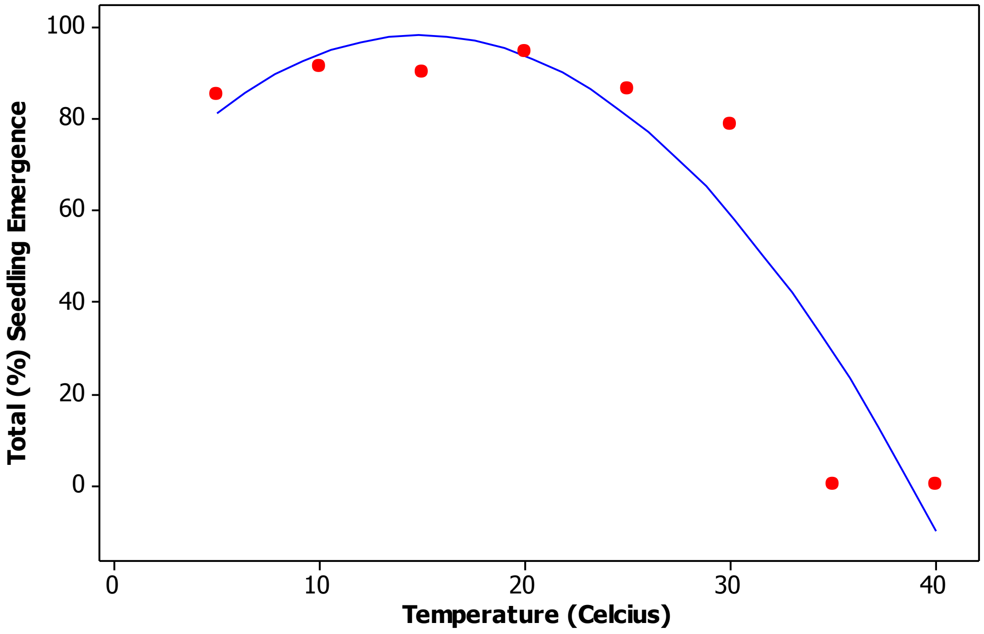

Figure 15: Second order polynomial regression of seedling emergence and Temperature, the regression equation is SE = 59.87 + 5.143 Temp – 0.1722 $Temp^2$.

The regression analysis between total seedling emergence and temperature showed a significant (R^2 = 87.7%, P = 0.005 quadratic relationship (figure 15) at 5 level, implying that increasing temperature beyond 20 °C can reduce carrot seedling emergence. Temperatures between 15 – 20 °C showed the highest percentage of seedling emergence.

3.5.3.4 Significance of Seedling Emergence Initiation Day

Initiation of seedling emergence did not occur on the same day and it was highly varied depending on treated temperature. Analysis of variance followed by Tukey's mean comparison carried out to test the significance of mean day of seedling emergence in Minitab-16 at 5% level of significance.

Table 9: Days for initiation of seedling emergence at different temperatures.

Temperature	Mean seedling emergence (initiation day with letter groupings)
5	35^{a}
10	12^{b}
15	11^{b}
20	8^{c}
25	6^{c}
30	8^{c}

Means sharing same letter group are not significantly different at 5% level of significant, with Tukey's adjustments.

There was a significant difference (P = <0.001) between starting days of seedling emergence (table 9) and seedling emergence initiated within the shortest time at temperatures 20, 25 and 30 °C whereas the days for initiation of emergence delayed significantly beyond 20 °C as temperature declined to 5 °C, which recorded the highest number of days for initiation of seedling emergence. There was no emergence however at the temperatures of 35 and 40 °C.

3.5.3.5 Changes in Emergence Velocities with Respect to Different Temperature

Effect of temperature on emergence velocities were estimated using emergence velocities calculated separately for each temperature. The significance of mean emergence velocities were tested using ANOVA followed by Tukey's mean comparison (controls experiment-wise type – I error) in Minitab-16. The effect of temperature on emergence velocity was highly significant (P= <0.001) at 5% level of significant. The highest emergence velocities were recorded at 20, 25 and 30 °C (table 10) whereas the lowest emergence velocity (0.02) was recorded at 5 °C (except which recorded zero emergence at 35 and 40 °C).

Table 10: Mean seedling emergence velocities together with letter groupings as influenced by different temperatures

Temperature °C	Seedling Emergence Velocities with letter groupings (Percentage SE/ day)
40	0.00^{d}
35	0.00^{d}
30	87.43^{a}
25	100.86^{a}
20	92.12^{a}
15	43.05^{b}
10	37.85^{b}
5	0.02^{c}

The Means share the same letters are not significantly different at 5% level of significance with Tukey's adjustment.

Regression analysis was carried out between emergence velocity and temperature, showed a significant (R^2 = 82.8%, P = 0.005) quadratic relationship (figure 16) at 5% level, suggesting that increasing temperature may enhance emergence velocities up to 20 °C and start to decline the emergence velocity with further increasing temperature.

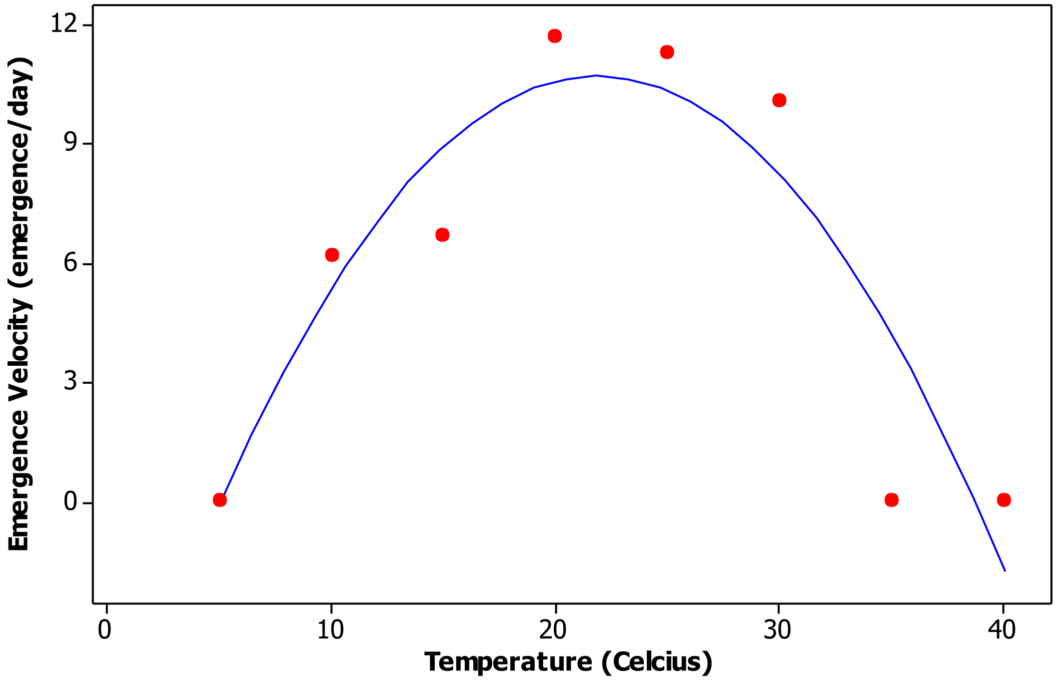

Figure 16: Second order polynomial regression between Seedling emergence velocities and temperature, the regression equation is EV = - 7.319 + 16.50 T – 0.03778 T^2.

3.5.3.6 Soil Moisture Potential Dynamics within Experimental Units over Time

The figure below (figure 17) demonstrates soil moisture dynamics over time with respect to different temperatures. As explained under moisture experiment (under the section 3.4.1.4) recorded moisture potential was different from set moisture potential (-30 to -33 kPa) but the changing patterns of moisture over time were not similar to moisture experiment.

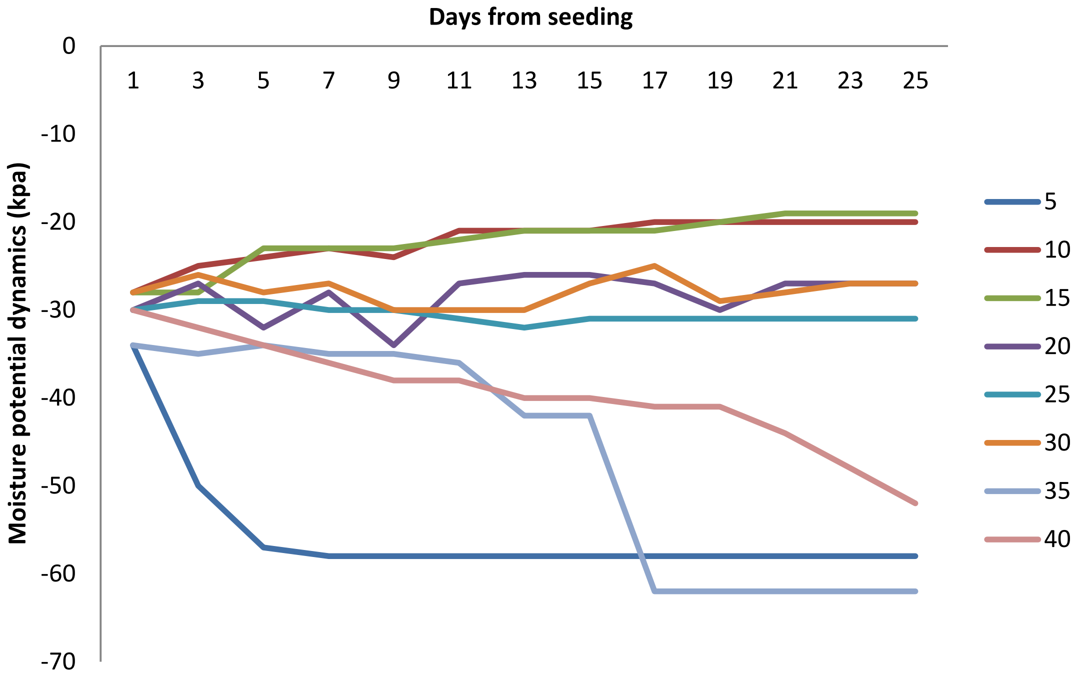

Figure 17: Soil moisture fluctuations over time as influenced by temperature.

Soil moisture potential changes within experimental units over time showed changes depending on the temperature. Basically, soil moisture potential fluctuations within experimental units were less prominent at 20, 25 and 30 °C, but soil moisture potentials at 5, 35 and 40 °C showed a considerable reduction of moisture over time. Soil moisture was progressively reduced at 35 °C, with a gradual reduction up to 15th day followed by a sudden drop (from -35 kPa to -57 kPa) from 15th to 17th day. At 40 °C however, moisture reduction was more gradual over the period (from -32 kPa to -52 kPa) of experiment. Moreover, soil moisture reduction at 5 °C showed a unique trend, which showed a sudden drop within first 5 days after seeding, from -35 kPa to -58 kPa and then moisture level remained constant at -58 kPa throughout the experiment.

Table 11: Mean soil moisture changes overtime with respect to different moisture potentials together with letter groupings.

Temperatures at which moisture potentials recorded	Mean Moisture Potentials (Log transformed)	Back transformed means with letter groups (-kPa)
5	1.76^{a}	58^{a}
10	1.29^{c}	20^{c}
15	1.27^{c}	19^{c}
20	1.42^{c}	27^{c}
25	1.49^{bc}	31^{bc}
30	1.42^{c}	27^{c}
35	1.78^{a}	62^{a}
40	1.70^{ab}	52^{ab}

Means share the same letter are not significantly different at 5% level of significant with Tukey's adjustments, $P = <0.001$.

Soil moisture changes due to influence of temperature was highly significant ($P = <0.001$) at $\alpha = 0.05$ level of significance. Moisture potentials showed a significant reduction in available soil moisture at 5, 35 and 40°C (table 11).

Regression analysis between recorded moisture potential and temperature showed a marginally non-significant ($R^2 = 60.7\%$, $P \geq 0.053$) quadratic relationship, implying temperatures below 10 °C and above 30 °C (figure 18) may reduce available soil moisture within soil.

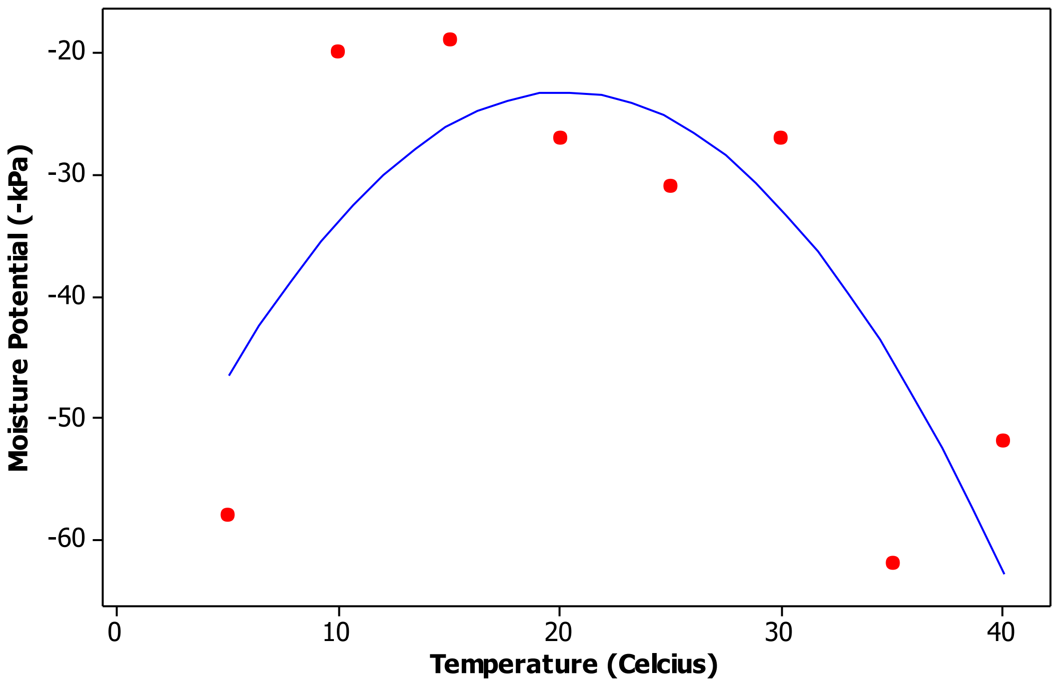

Figure 18: Second order polynomial regression of recorded soil moisture potential and temperature, the regression equation is MP = -64.36 + 4.076T – 0.101T^2.

3.5.4 Discussion

When temperature was 5°C, seedling emergence was delayed by 33 days. Seeds may be accumulating required amount of metabolic energy for emergence up to 33 days (figure 13) and seedling emergence had initiated and acquired usual trend of emergence as of other temperatures. This finding is similar to Rajasekaran et al., (2002, 2004, 2005) and Kotowski (1926), who stated that low temperatures can negatively affect on both germination percentage and rate of germination, however this study results suggest, there is no negative impact on percentage seedling emergence at 5 °C even though emergence delayed significantly. This can be true until temperature reach the base temperature 2.15 °C (Finch-Savage et al., 1998) which inhibits the seedling emergence totally.

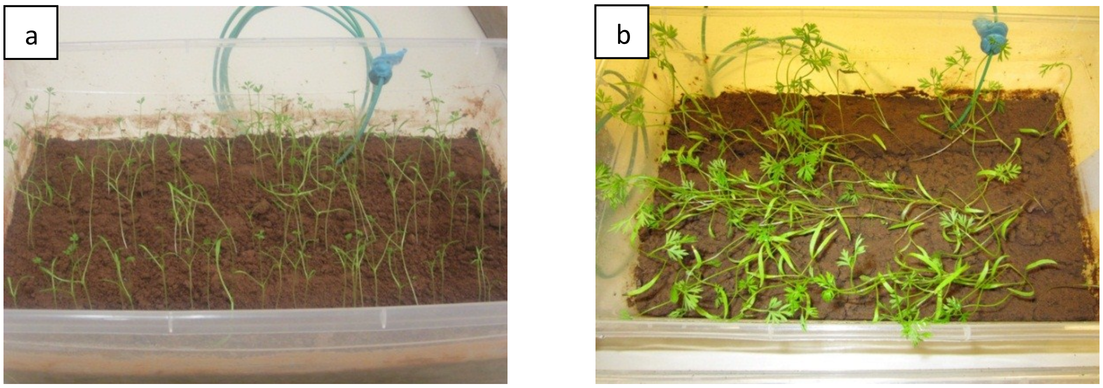

Figure 19: a -Seedling emergence at 10 °C, showing stunted growth at low temperature in unit “a”, b- seedling emergence at 20 °C,

However, there was a significant influence on rate of emergence at low temperatures. Rajasekaram et al., (2002, 2005) stated that soil temperature below 20°C can reduce or delay seedling emergence, confirming above result on delayed seedling emergence at 5 °C for cut and peel baby carrots. Nonetheless, high temperatures, 35 and 40 °C totally inhibited seedling emergence, implying carrot highly sensitive to warmer temperatures, especially when > 30 °C.

Even though, there is no significant difference in cumulative seedling emergence at 10 and 20 °C, phenology of emerged seedlings (figure 19a and 19b) was different, which may be due to cold stress . Plants emerged at 30 °C (figure14) were also showed a poor growth with a pale yellow colour with dyeing back of seedlings. Total seedling emergence was not statistically significant when temperatures were 5, 10, 15, 20 and 25 °C but was significantly (P = <0.001) low at 30 °C. Majority of seedlings emerged at 30°C did not survive very long which can be due to seedling’s sensitivity to high heat. Rowse and Finch-Savage, (2003) estimated temperature for carrot seed germination as 46 °C from HTT (hydrothermal time) model and 36 °C from VOP (virtual osmotic potential) model. Again, Corbineau et al., (1995) estimated between 42-47 °C for three different cultivars and this study conducted under laboratory conditions using polyethylene glycol to maintain soil moisture potential, may be the reason to emerge at higher temperatures. Rowse and Finch-Savage, (2003) recorded same higher temperatures of 38.5 °C from HTT and 33 °C from VOP for seedling emergence of onion and also they have stated germination of onion seeds did not reach 50% at 30 °C during their recording period and also mentioning these estimations can possibly be over estimations.

The estimated highest emergence velocity was recorded at 20, 25 and 30°C (table 10). The minimum moisture reduction within experimental units could also be observed at 20 and 25 °C (figure 18), implying optimum temperature for baby carrot seedling emergence (variety Triton) may be 20 °C. However, moisture reduction within containers was not significantly different when temperatures were 10, 15 and 20 °C. This information is useful for farmers to predict the timing of seed sowing to obtain the highest emergence percentage with the highest emergence velocity and also to initiate seedling emergence within a short period to obtain vigorous seedlings, thereby to achieve a vigorous crop stands. Further, results of repeated measures analysis (table 6 and table 8) with repeated time showed significant effect of temperature on seedling emergence in tested time intervals over time, suggesting effect of temperature has a significant influence on each day of carrot seedling emergence until completion of emergence.

All the regression models fitted above showed increasing temperature above 25 °C and decreasing below 20 °C may reduce emergence velocities and available soil moisture to seeds, implying extreme temperatures of 5 and 35-40 °C may have negative influence on available moisture for seedling emergence. Physiology behind this is seed germination is higher when temperatures are warmer due to induced enzyme activity and water balance within the seed (Hegarty, 1973; Rajasekaran et al., 1992). Low temperatures limit water flow and reduce water activity or change its configuration due to lack of free energy, reducing thermochemical reactions within seed, which need to breakdown stored food (Bewley & Black, 1982). Even though seedling emergence or growth rate increased as sub-optimal temperature increased, higher temperature is associated with more rapid drying of the surface layer, reducing hydraulic conductivity (Lascano and van Bavel, 1986; Finch-Savage et al., 2001). Therefore, 15 - 20 °C (figure 15) can be suggested as the optimum temperature for carrot seedling emergence whereas ceiling or maximum temperature (upper threshold) for carrot seedling emergence can be suggested as 30 °C.

The main purpose of developing temperature and seedling emergence model was to develop hydro-time or hydrothermal time model to facilitate predictions of seedling emergence, which can be useful for carrot producers or scientists

3.5.5 Conclusion

Temperature had a significant influence on timing of seedling emergence, seedling emergence velocity and total seedling emergence. Seedling emergence was significantly low at 30 °C, delayed significantly at 5 °C and totally inhibited at 35 and 40 °C, accepting hypothesis of this experiment. Seeds at 35 °C did not germinate even after transferring to the favorable environmental conditions may be due to loss of seed viability.

3.6 Interaction between Soil Moisture, Temperature and Seedling Emergence

3.6.1 Hypothesis and Objectives

Hypothesis: Soil moisture can affect carrot seedling emergence interactively and differentially depending on the temperature regime.

Objectives: To identify whether there is an interaction effect of soil moisture and temperature on baby carrot seedling emergence

3.6.2 Materials and Methods

This experiment was designed to test the combined effect of soil moisture and temperature on baby carrot seedling emergence. It was designed as a 2x5 factor factorial design with two levels of temperatures, 19 ± 3 and 29 ± 3 °C and five levels of moisture potentials, -5, -20, -30, -40 and -60 kPa with 3 replicates for each treatment combination. Growth chamber conditions were set similar to moisture experiment in section 3.3.1(day length 16 h and light intensity 180 μ mol cm^{-2} s^{-1}). It was conducted in two steps within one growth chamber; the first step was to test the effect of temperature 19 ± 3 °C at five different moisture levels, on seedling emergence and the second stage was to test the effect of temperature 29 ± 3 °C at five different moisture potentials (-5, -20, -30, -40, -60 kPa) on carrot seedling emergence. In total 15 experimental units were used at a time.

Experimental units were prepared as explained in general methods (section 3.3.1) and they were transferred to the growth chamber set at 19 ±3 and 29 ±3 °C separately in two consecutive times until they reach required moisture potentials.

3.6.2.1 Experimental Design and Statistical Analysis

This experiment was designed as a 2x5 factorial with 3 replicates and ANOVA in Minitab 16 was carried out for data collected on seedling emergence to check normality assumptions. Since the data met with the criteria of normality assumptions, ANOVA followed by Tukey's multiple mean comparison in SAS 9.3 with Proc-glm (SAS Institute Inc., NC, USA) was carried out to test the significance of means and interaction effects.

3.6.3 Results

3.6.3.1 Effect of Soil Moisture and Temperature Interaction on Seedling Emergence

Significance of the mean seedling emergence were tested using ANOVA followed by Tukey's mean comparison in SAS 9.3 (SAS institute Inc., NC, USA) using Proc-Glm, at 5% level of significant.

Table 12: 2x5 factorial ANOVA to test the significance of moisture and temperature interaction effect

Source	DF	Type I Sum of Squares	Mean Square	F Value	P value
MP	4	795	198.75	1.53	0.2307
Temp	1	3499.2	3499.2	26.99	<.0001
MP*Temp	4	781.8	195.45	1.52	0.2378
Error	20	2592.67	129.63		

Main effect of soil moisture (P = 0.2307) and interaction effect of soil moisture* temperature (P = 0.2378) were not statistically significant at 5% level of significant. Only the effect of temperature showed a highly significant (P = < 0. 0001) influence (table 12) on baby carrot seedling emergence (variety Triton).

Table 13: Significance of effect of temperature on carrots seedling emergence at two different temperatures together with letter grouping.

Temperature (°C)	N	Mean Seedling Emergence with Letter Grouping
19±3	15	92.13^{a}
29±3	15	70.53^{b}

Means sharing same letter are not significantly different at 5% level of significant with Tukey's adjustments.

Mean seedling emergence at 19±3 °C was significantly higher (table 13) compared to mean seedling emergence at 29±3 °C.

According to figure 20, there can be a little interaction between soil moisture and ambient temperature at 30 °C which is not significant statistically. As explained in Finch-Savage et al., 2001 and section 3.5.4, with increasing temperature, it is possible for rapid drying of surface soil layer reducing hydraulic conductivity.

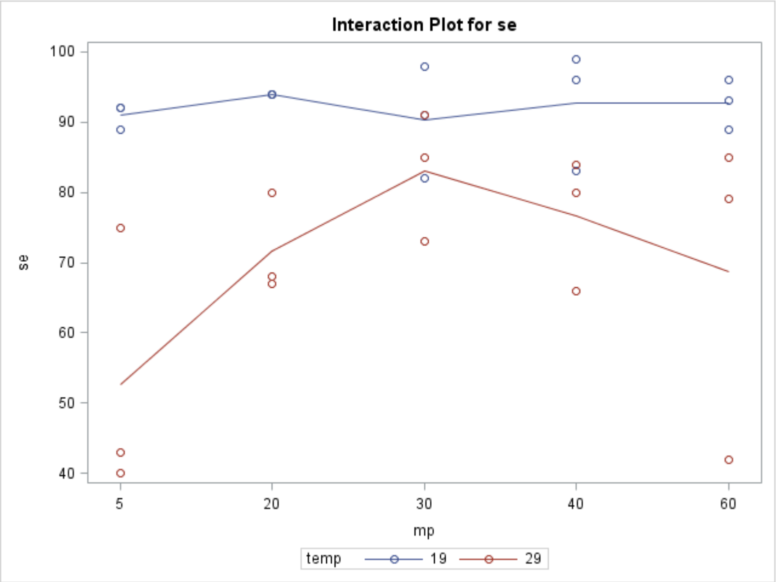

Figure 20: Interaction plot of temperature and moisture potential (kPa) on seedling emergence (a SAS 9.3 output).

3.6.4 Seedling Emergence Trends at Tested Temperatures

Seedling emergence trends (figure 21a and 21b) over time changed depending on temperature and soil moisture treatments.

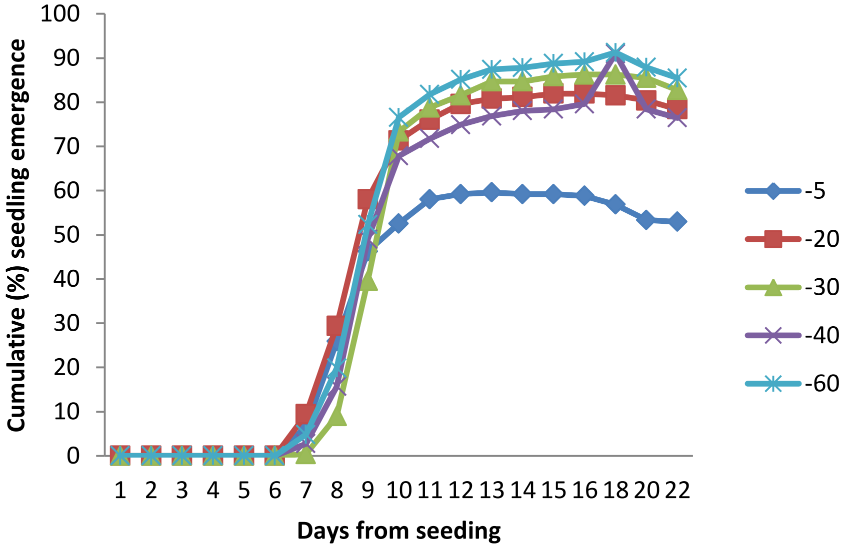

Figure 21a: Seedling emergence trends of carrots (variety Triton) at 29 ± 3 °C under various moisture potentials (-kPa).

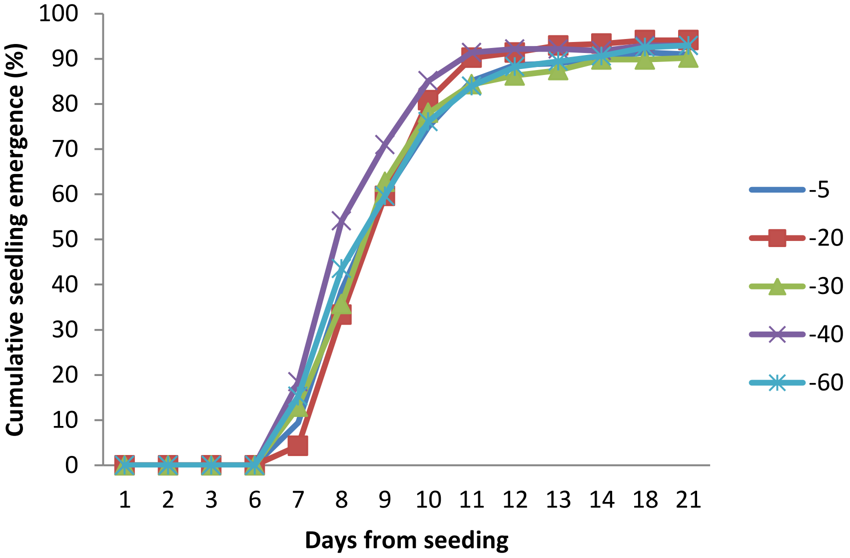

Figure 21b: Cumulative seedling emergence trends of variety Triton over time at 19 ± 3 °C under various moisture potentials

3.6.5 Discussion

The effect of temperature on carrot seedling emergence is highly significant (P = <0.0001) compared to effect of soil moisture (P = 0.2307). There is no significant interaction effect of soil moisture and temperature on carrot seedling emergence (P = 0.2378) at the range of selected two temperatures and five moisture potentials suggesting effect of temperature plays a major role in carrot seedling emergence compared to soil moisture as long as soil moisture potential is remained above the base water potential. Further, studies with wide range of temperatures regimes and soil moisture potentials closer to base water potential (between -120 and -156 kPa)will be needed to see whether there is any interaction effect of these two factors on carrot seedling emergence with meteorological measurements of moisture and temperature in soils. However, Rowse and Finch-Savage, (2003) conducted an experiment to understand the effect of temperature on the minimum or base water potential of carrot seed germination and used hydrothermal threshold (HTT) models to describe it. In that they observed progressive decline in percentage seed germination by moisture potentials below – 0.67 MPa at 15 °C and temperatures below that. Rowse and Finch-Savage, 2003 were also stated; Percentage seed germination was reduced by moisture potential -2.8 MPa at 30°C suggesting there may be an influence of temperature on changes in base water potential of carrots.

In overall, carrot seedling emergence was more sensitive to ambient temperature than soil moisture and also to warmer temperatures than cooler temperatures. As discussed under the section 3.4.3.1 seedling emergence was not significantly influenced by moisture potentials above -120 kPa and as found in literature, there is no significant influence above base water potential (Finch-Savage et al., 1998). However, Finch-Savage et al., 1998, observed initiation of radicle growth (hypocotyl up to penetration of seed coat) as a moisture sensitive step which determines the timing of carrot seed germination and emergence. Further, seedling emergence was not favored by excess availability of moisture (such as soil moisture in field capacity) when temperature was 29 ± 3 °C (figure 21a) and there may be an interaction effect of moisture and temperature on seedling emergence (figure 21) and also this was described by Rowse and Finch-Savage, 2003 using threshold models for changes in base water potential. In carrots, base water potential and temperature do not change greatly depending on cultivar and variations can be occurred within a small range, since Ψ_b was recorded as -0.81 MPa by Ross and Hegarty, 1979 and $\Psi_b(50)$ as 0.84 MPa using HTT (hydrothermal time) and -0.86 MPa using VOP (virtual osmotic potential) showing a very small changes between all estimates.

Finally, as discussed above the effect of moisture potentials on seedling emergence was not significant as long as soil moisture potential remained above base water potential (in section 3.4.3.1 and table 1). The concept of hydrothermal model is used to describe effect of soil moisture and temperature in combination on seedling emergence but based on above results; effect of temperature can better describe variations in carrot seedling emergence as well as for predictions on seedling emergence. Development of independent models using thermal-time may be useful in all predictions of carrot seedling emergence.

3.6.6 Conclusion

There was no significant interaction effect of soil moisture and temperature on baby carrot seedling emergence, rejecting the hypothesis of this experiment. Nonetheless, effect of temperature showed a significant influence on timing of carrot seedling emergence, emergence velocity, percentage seedling emergence and moisture availability, as discussed under the section of 3.5 in detail. However, the effect of soil moisture potential, above base water potential on seedling emergence was not significant (table 1). This was proved by the experiment conducted under the field conditions as well which will discuss under chapter 5. According to Finch-Savage, (2003), there may be an interaction effect between temperature and minimum or base water potential of carrot seedling emergence.

Overall, carrot as a temperate type crop may have adaptations or genetically evolved to response extremely warm and cold temperatures, reducing or delaying seedling emergence and post emergence growth. Further, they may be having threshold temperatures for enzyme activities which are necessary for all biochemical reactions occur in germinating and emerging seeds. This study showed the effect of temperature as the most influential compared to soil moisture within the studied range suggesting, that carrot as a root crop can grow down-ward deep into the soil where soil moisture available and less sensitive for effect of soil surface drying.

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Chapter 4

Thermal Time (TT) Modelling for Predicating Baby Carrot Seedling Emergence

4.1 Abstract

The effect of temperature on carrot seedling emergence was highly significant as presented in chapter 3, section 3.5, compared to effect of soil moisture potential suggesting that carrot seedling emergence is more sensitive to temperature than moisture potential. Thus, thermal time (TT) models were developed to understand the heat units required for initiating and completing seedling emergence. ANOVA conducted to test the TT over different temperature showed a significant ($P = <0.001$) influence on SEI. The minimal thermal (TT) time required to initiate seedling emergence was 92.24 °Cd whereas the maximum TT needed to initiate seedling emergence was 213.52 °Cd. Linear regression between TT-ISE and set temeprature was marginally significant ($P \leq 0.05$, $R^2 = 67.3\%$). Minimum TT required to complete emergence however was 159.6 °Cd at 5 °C. It took 33 days to initiate seedling emergence and 56 days to complete seedling emergence at 5 °C which is a very long time compared to other warmer temperatures used in experiment suggesting seedling emergence may delay until they acquire minimum requirement of TT to ISE. Regression analysis between TT for completion of seedling emergence and temperature showed a significant positive linear relationship ($P = 0.001$, $R^2 = 95.3\%$). Regression analysis between seedling emergence (%) and TT showed a quadratic relationship which was not statistically significant at 5% level but with a $R^2 = 47.4\ \%$ which is closer to 60%, suggested TT beyond 300 °Cd can reduce SE. Regression analysis between TT and emergence velocity showed a significant positive quadratic relationship ($P = 0.013$, $R^2 = 94.4\ \%$), suggesting TT has a significant role to play in completion of seedling emergence and emergence velocity.

4.2 Introduction

Seedling emergence models are useful for farmers to predict timing of seeding and to plan the season, for researchers as information to conduct further studies and policy makers to estimate total cost, yield and income out of growing carrots and spending money on carrot research. As explained in chapter 3, the effect of ambient temperature on seedling emergence was highly significant (section 3.5.3.1) whereas the interaction between effect of soil moisture and ambient temperature on seedling emergence was not significant (section 3.6.4). Therefore, this study focused on models describing effect of temperature. The concept of thermal time (TT) was used to elaborate significant differences occurred in timing of seedling emergence, percentage seedling emergence and emergence velocities. Use of mechanistic models to simulate seedling emergence, as a function of measured environmental variables is known as the most promising approach to predict seedling emergence (Forcella et al., 2000). Cumulative thermal time with units of degree days (°Cd) calculated in successive days can be used to predict total heat units and growing degree days required from seeding to crop emergence or else from germination to emergence (Garcia-Huidobro et al., 1982; Ney and Turc, 1993; Forcella et al., 2000). The linear equation developed to calculate cumulative thermal time can be defined as follows (Tamet et al., 1996),

$$TT = \sum_{i=1}^{n} \left(T - T_b\right)$$

Where, T is the daily mean temperature, T_b is the base temperature and n is number of days of emergence observations at particular temperature.

Previous studies were also conducted on carrots to develop different models and describe germination and emergence patterns using threshold models. Some of studies explain germination and post-germination growth of carrot seedling emergence using predictive threshold models as influenced by sources of variation between sowing occasions (Finch-Savage et al., 1988), hydrothermal threshold models that can describe the germination response of carrot (*Daucus carota* var *Sativus* L.) and onion (*Allium cepa* L.) seed populations across both sub- and supra-optimal temperatures (Rowse and Finch-Savage, 2003) and use of seeding rate and seed spacing to modulate root yield and recovery of slicer and dicer carrots (Rajasekaran et al., 2006). This study was mainly focused on the understanding of the impact of thermal time (TT) on initiation and completion seedling emergence. Seedling emergence models with hydrothermal time were not used in this chapter since soil moisture and temperature interaction (basis for hydrothermal concept) was not significant

4.3 Methods and Statistical Analysis of Data

Results of data collected on seedling emergence at different temperatures were discussed under chapter 3 – II and TT was calculated using same set of data collected in temperature experiment and following equation,

$$TT = \sum_{i=1}^{n} \left(T - T_b\right)$$

Where, T is the daily mean temperature, T_b is the temperature for carrot seedling emergence ($T_b = 2.15$ for carrots according to Finch-Savage et. al., (1998)).

First, TT required to initiate seedling emergence at each temperature was calculated (that is starting from germination up to hypocotyl penetration of soil). These data sets were tested for normality assumptions and conducted analysis of variance followed by Tukey's means comparison, to test the significance of mean TT. The experimental design was a completely randomized design with 4 replicates. At the same time TT needed to complete seedling emergence at different temperatures was also calculated and tested for normality assumptions. ANOVA followed by Tukey's means comparison was carried out to see the significance of TT time required to complete seedling emergence.

Regression analysis between TT to Initiation of Seedling Emergence (ISE) and temperature, TT to Complete Seedling Emergence (CSE) and temperature, Emergence Velocity and TT to CSE and Seedling emergence (%) and TT to CSE were conducted in Minitab- 16 (USA) at 5% level of significant. Field experiment data (Chapter 5) were used to validate these fitted models. Temperature was measured using spectrum thermocouple attached to data logger of the weather station, installed at the seeding depth.

4.4 Results

4.4.1 Thermal Time (TT) for Initiation of Seedling Emergence (ISE)

Table 14: TT required for initiation of seedling emergence (ISE) of carrot together with letter groupings.

Temperature (°C)	Mean TT (°Cd) for initiate seedling emergence (ISE)
30	213.52^{a}
25	144.72^{b}
15	144.56^{b}
20	124.95^{bc}
5	99.75^{cd}
10	92.24^{d}

(Means sharing same letter group are not significantly different at 5% level of significant with Tukey's adjustments).

The ANOVA conducted to test significance of mean TT required for ISE, showed a significant difference in means of TT (P = <0.001) at different temperature regimes tested. Emerging seedlings at 30 °C had accumulated the highest TT time, 213.52 °Cd for ISE (table 14) whereas the lowest TT, 92.24 °Cd for ISE was observed at 10 °C. However TT for ISE at 5 and 10 °C did not differ significantly.

Regression analysis between TT for ISE and set temperatures showed a marginally significant positive ($P \leq 0.05$, $R^2 = 67.3\%$) linear relationship (figure 22) at 5% level suggesting, increasing temperature may increase TT for ISE.

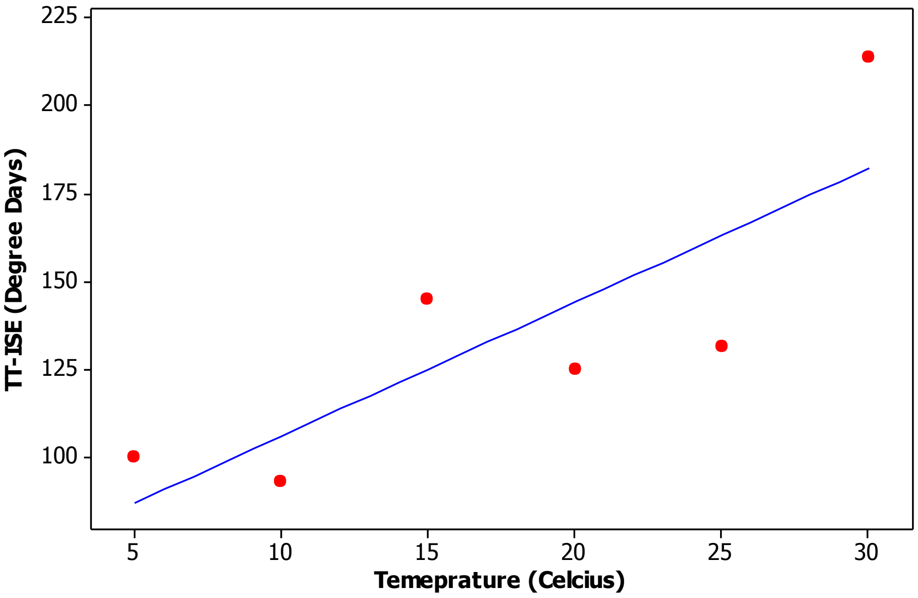

Figure 22: Thermal time required up to penetration of hypocotyl through soil, model fitted was TT -ISE = 67.96 + 3.8 T.

4.4.2 Thermal Time (TT) Required for Completion of Seedling Emergence (CSE)

Table 15: Means of TT for completion of seedling emergence (CSE) of carrot with respect to set temperatures

Set Temperature (°C)	Mean TT (°Cd) required for CSE
30	408.47^{a}
25	377.03^{a}
20	303.45^{ab}
15	247.36^{bc}
10	208.02^{bc}
5	159.60^{c}

(Means sharing same letter group are not significantly different at 5% level of significant with Tukey's adjustments)

The TT for completion of seedling emergence varied significantly (P = < 0.001) with increasing (table 15) set temperatures. The highest TT to CSE was recorded at 25 and 30

°C while the lowest TT to CSE was recorded at 5 °C. However, there was no significant difference between TT-CSE at 5, 10, 15 °C.

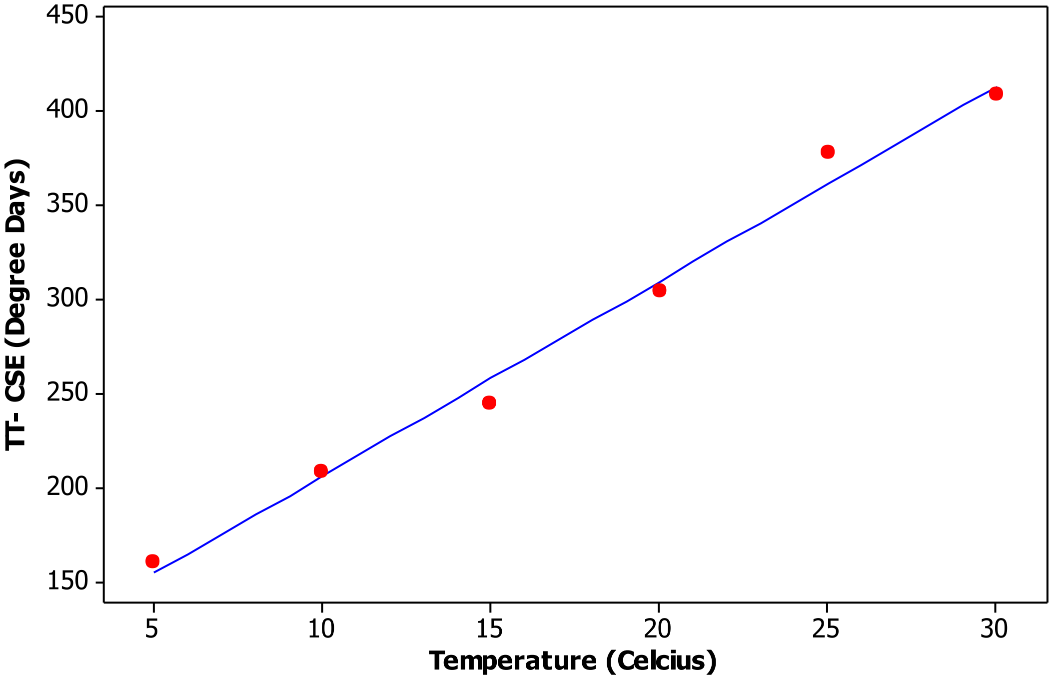

Figure 23: Linear regression between TT to complete seedling emergence and set temperature, model fitted was TT-CSE = 102.4 + 10.35T

Regression analysis between TT to CSE and set temperatures exhibited a significant ($P = <0.001$, $R^2 = 98.9$ %) positive linear relationship suggesting, TT-CSE increased with increasing temperature (figure 23).

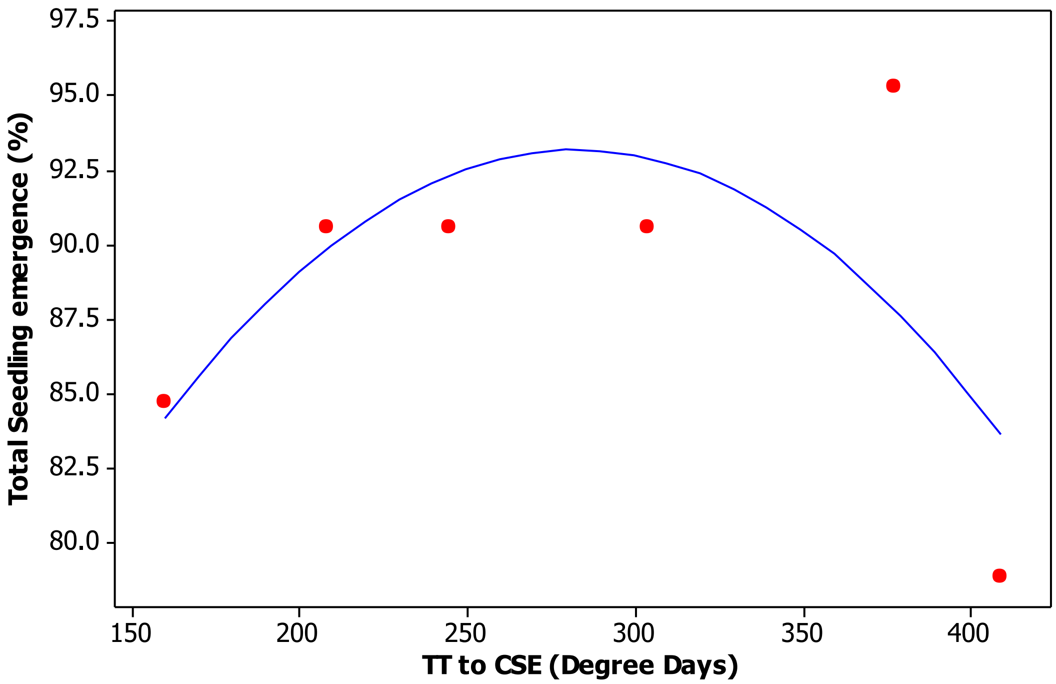

Figure 24: Quadratic regression of average total seedling emergence (%) vs. TT to complete seedling emergence, model fitted was Total SE = 45.43 + 0.34 TT – 0.0006 TT^2.

Regression analysis between percentage seedling emergence and TT- CSE showed quadratic relationship which was not significant statistically ($P = 0.38$, $R^2 = 47.1\%$) at 5% level (figure 24) but R^2 is closer to 60%. This model fitted between seedling emergence and TT-CSE suggested that, increasing TT up to 300 °Cd may increase percentage seedling emergence but increasing TT beyond this point can reduce percentage of seedling emergence.

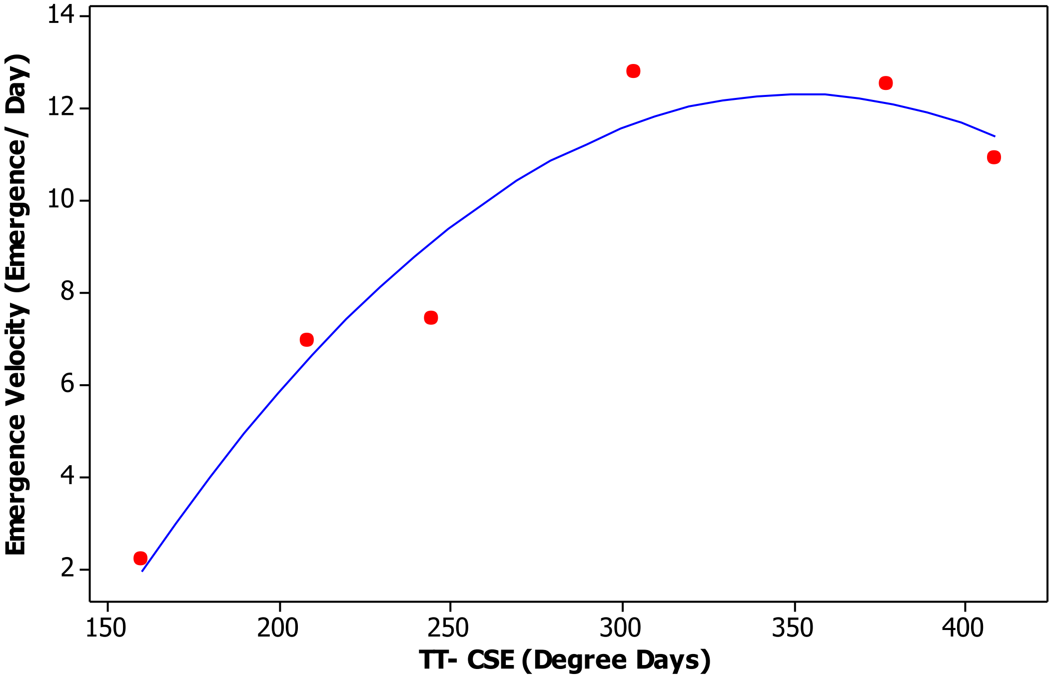

Figure 25: Second order polynomial regression for emergence velocity vs TT- CSE at each temperature, model fitted was $EV = - 22.63 + 0.2\ TT - 0.0003\ TT^2$

Regression analysis between emergence velocity and TT-CSE (figure 25) showed a significantly positive quadratic ($P = 0.013$, $R^2 = 94.4\%$) relationship showing that , increasing TT up to 350 °Cd increased emergence velocity but increasing TT beyond 350 °Cd may reduce emergence velocity confirming the model suggested by figure 24.

4.4.3 Model Validation

TT to ISE in 2011 and 2012 were 97 °Cd and 125.25 °Cd whereas TT to CSE were 300.38 and 297.3 °Cd, respectively. The predicted seedling emergence (after 25 days of seeding/ 25 DAS) was 92% (figure 24). Under field conditions, in 2011 and 2012, 15 days after seeding, percentage seedling emergence of Triton at 85 seeds/ 30 cm when seeded at 2.54 cm depth under irrigated conditions for five different varieties to compare with the estimated seedling emergence as follows,

Table 16: Field experiment data on seedling emergence (SE) at 85 seeds/ 30 cm and 2.54 cm depth 15 DAS under irrigated conditions to validate the model

Variety	SE (%) 2011	SE (%) 2012
Triton	70.00	71.76
Honey snax	90.88	82.65
Honey snax enhanced	*	82.65
Upper cut	85.88	45.29
Sugar snax	75.00	52.25

This shows predicted seedling emergence was quite over estimated for all the other varieties except Honey snax but field estimation is only 15 DAS whereas growth chamber estimation is up to 25 DAS. However, the model fitted was not statistically significant at 5% level (figure 24) but having a $R^2 = 47.1\%$ (closer to 60%) which shows a little bit over estimation.

The TT calculated for ISE in 2011 under field conditions (97 °Cd) lies between TT estimated (figure 22) for 5 and 10 °C (table 14), whereas in 2012, TT to ISE (125.25 °Cd) under field conditions close to TT estimated for 20 °C. In both 2011 and 2012 showed TT-CSE, 300.38 and 297.3 °Cd respectively which is the TT-CSE estimated for 20 °C, suggesting that during field growing starting in July may provide the optimum temperature conditions to complete seedling emergence (table 18, 19 in Chapter 5).

4.5 Discussion

TT for ISE varied significantly (P= <0.001) depending on ambient temperature at which emergence occurred. The minimum TT needed to initiate seedling emergence was 92.24 and 99.75 °Cd (table 14), which were recorded at 10 and 5 °C, respectively. The highest

TT for ISE 213.53 °Cd was observed at 30 °C, whereas TT to seedling emergence initiation was not significantly different at 15, 20, 25 °C. ISE was delayed at 5 and 10 °C as discussed in chapter 3 (section 3.5.3.1) by 34 and 11 days respectively which may be due to accumulation of minimum number of heat units required for ISE. Regression analysis between TT-ISE and their set temperatures showed a significant ($P = 0.046$) linear relationship suggesting that increasing temperature can increase TT.

Mean TT to CSE was significantly different ($P = <0.001$) at set ambient temperatures. TT for CSE, 377.03 and 408.47 °Cd at 25 and 30 °C, respectively were the highest mean TT-CSE whereas the lowest TT-CSE, 159.6 °Cd was recorded at 5 °C. However, mean TT-CSE was not significantly different at 10, 15 and 20 °C. Regression analysis between TT-CSE and set ambient temperature showed a significant ($P = <0.001$) linear relationship suggesting, increasing temperature may increase TT-CSE. The minimum TT required for initiating seedling emergence was 92 °Cd (at 10 °C) and the minimum heat units needed to complete seedling emergence was observed as 159.6 °Cd at 5 °C. This, suggest in overall increasing temperature increases TT for both ISE and TT for CSE.

Regression analysis conducted between Seedling Emergence (SE) and TT-CSE showed a quadratic relationship ($R^2 = 47.1\%$) which may suggest, increasing TT to CSE up to 300 °Cd may increase percentage seedling emergence and increasing temperature beyond this point can reduce percentage seedling emergence. At the same time regression analysis between emergence velocity (EV) and TT to CSE showed a significant positive ($P = 0.013$) quadratic relationship suggesting increasing TT to CSE may increase EV up to 350 °Cd but increasing TT-CSE beyond this point may reduce EV. Moreover, effect of temperature on seedling emergence, emergence percentage and emergence velocity discussed under the section 3.5.3 showed a similar relationship as of TT. However, TT with degree days can better explain the variations in seedling responses with respect to different temperature regimes and as different dates for seedling emergence and completion.

Previous studies on carrots were used TT concept and they estimated TT required for germination and post germination growth under natural environmental conditions. In that they tested effect of irrigated and non-irrigated conditions with different sowing dates on seed germination and seedling emergence and estimated TT to complete these stages of emergence (Finch- Savage et al., 1998). However, their TT was under estimated and did not adequately describe the pattern of carrot germination in the field since they did not use meteorological data and also due to inaccuracy. Number of studies carried out to study the response of pre-emergence growth to temperature (Wanjura et al., 1970; Black low, 1972; Hsu et al., 1996; Wheeler and Ellis, 1991; Weaich et al., 1996; Finch-Savage et al., 1998 and 2001) and different methods used to describe from different species where in many cases thermal time (TT) approach has been adopted assuming growth rate is linearly related to temperature (Finch-Savage et al., 2001) whereas, this study confirmed all those assumption. However, in practice they suggested use of thermal time for seedling emergence is limited since soil moisture varies greatly in surface layers of soil (Finch-Savage et al., 2001).

4.6 Conclusion

Carrot seeds may need a minimum TT (92 °Cd) to initiate seedling emergence. Therefore at low temperatures seedling emergence initiation can be delayed until they accumulate required amount of heat units. Optimum TT to complete seedling emergence may be 300 ± 25 °Cd and beyond this point percentage seedling emergence and seedling emergence velocity can decline. Model developed for percentage seedling emergence and TT to CSE for prediction of percentage seedling emergence with respect to TT ($R^2 = 47.1\%$), had overestimated the percentage seedling emergence, except for variety Honey snax. Regression model fitted between emergence velocity and TT-CSE showed the optimum TT as 350 °Cd proving that estimation using model fitted for SE and TT-CSE was approximately similar.

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Chapter 5

Effect of Genotype, Seeding Depth, Seeding Rate, Soil Moisture, Soil Temperature on Seedling Emergence and Root Grades under Field Conditions

5.1 Abstract

This experiment was designed to test the hypothesis that seeding depth, seeding rate, soil moisture and soil temperature modulate seedling emergence and thus affect the root grades, depending on genotypes, directly or interactively of cut and peel carrots. A field experiment was conducted in New Minas, Nova Scotia during 2011 and 2012. Experiments were set to a split-split-split plot design due to three randomization restrictions and two years served as blocks. Two main plots were irrigated and non-irrigated. Five varieties used were Triton, Honey snax, Honey snax enhaced, Upper Cut and Sugar snax seeded at two seeding depths (1.9 cm and 2.5 cm) at two seeding rates (55 seeds/30cm and 85 seeds/30cm). Seedling emergence was significantly influenced by the genotype (P = <0.0001) and seeding rate (P = <0.0001). Honey snax seeded at 85 seeds/ 30 cm gave the highest mean seedling emergence. Yield was significantly influenced by the genotype (P = <0.0001) and seeding depth (P = 0.0117). Triton seeded at 2.5 cm depth gave the highest mean seedling emergence, suggesting that deeper seeding may have minimized seed/ seedling dehydration naturally selecting more vigorous seedlings. The best seeding rate that recorded the highest mean yield was 85 seeds/ 30 cm, which may be due to optimal population stand. The significantly highest (P = <0.0001) yield of most preferable Fancy grade was recorded with variety Triton and seeding rate 85 seeds/ 30 cm was also having a significant (P = 0.0175) influence on highest Fancy grade yield suggesting seed population of 85 seeds within 30 cm as the suitable plant population to produce ideal size of carrot roots to produce Fancy grade. Variety Honey snax gave the second highest Fancy grade yield.

5.2 Introduction

Response of seedling emergence to various temperature and moisture conditions was discussed in chapter 3. This study was designed to understand seedling emergence and yield and quality of cut and peel carrots as influenced by genotype, certain management and environmental factors on root yield and grades under field conditions. Complex interaction between genotype, plant population and growing environment influences root yield and grade (Rajasekaran et al., 2006). Increasing plant population increases yield per unit area until it reaches threshold in most of the crops. Competition between adjacent plants limits resources (Pant, 1979) with high plant population while reaching a yield plateau or declining yields (Weiner, 1990). Even though in carrots, plant density determines both total yield and mean root size (Bleasade, 1967) variation in timing of seedling emergence can also influence the uniformity of root size at harvest (Benjamin, 1982). Lower plant population densities can produce over size roots while higher plant population densities can produce thinner roots (Rajasekaran et al., 2006), but root size can also be varied depending on carbon fixation rate by leaves and allocation to roots due to plant competition for nutrients, light, space and water (Rajasekaran and Blake, 2002). Study conducted using seeding rates and seed spacing to modulate root yield and recovery of slicer (variety Caro Choice) and dicer carrots (variety Red Core Chanteney) found that main effects of seeding rate and line spacing had a significant influence on total yield and supreme quality slicer carrots whereas interaction between seeding rate and line spacing had a significant influence on total yield and supreme quality dicer carrots (Rajasekaran et al., 2006). Nonetheless, increasing seeding rate from 18 to 22 seeds/ 30 cm, significantly increased total yield and supreme quality root yields, but further increase in seeding rate did not significantly increase the total yield (Rajasekaran et al., 2006).

Seeding depth has a major role to play in successful emergence of a seed, since seeds should have sufficient energy to provide germination seedlings to reach the soil surface (Forcella et al., 2000). Seeds ability to generate sufficient amount of energy from reserves to supply energy demand during emergence is the basis for successful emergence. Pre-emergence mortality is the result, if the energy supply does not meet the energy demand for hypocotyl elongation (Forcella et al., 2000). Grundy et al., 1996, developed a model which assumes that maximum emergence potential is at the soil surface for all the species and logarithmic decrease in emergence occurs with increasing seeding depth. However, this does not occur with larger seeds, as they are having more reserves than smaller seeds like carrots. Seeds at soil surface are exposed and have a greater risk for dehydration than the buried seeds (Buhler, 1995). Moreover, carrot seedlings have the ability to emerge through 4.5 – 5 cm of soil in the absence of soil crust, without reducing percentage of seedling emergence significantly (Tamet et al., 1996). Nonetheless, extension of hypocotyl within the soil more than 1 cm before penetrating the soil can result in reduced subsequent growth and or can reduce its ability to penetrate soil crusts (Finch- Savage et al., 2001). Further, delayed seedling emergence can also reduce post emergence growth due to their reduced efficiency of photosynthesis (Tamet et al., 1996). An experiment conducted on post emergence growth of carrot seedlings showed growth rates can be varying in the bulk of the population but it did not show any association with germination time (Finch- Savage et al., 2001).

Seedling emergence pattern within a population is a result of complex interactions between ambient weather conditions, soil, seed, and seedling characteristics (Finch-Savage et al., 1998) but these interactions are little understood in natural environments.

5.3 Hypothesis and Objectives

Hypothesis: Genotypes, soil moisture, seeding depth and seeding rate all influence seedling emergence, yield and root grades, of cut and peel carrots, independently or interactively.

Objective: To understand the effect of seed variety, seeding depth, seeding rate, irrigation on baby carrot seedling emergence, final root grades and yield.

5.4 Materials and Methods

Field experiments were conducted during 2011(June 26th to September 28th) and 2012 (July 5th – October 23rd). The field selected for this experiment was located in Bill town, NS (Latitude: 45.1224° N, Longitude: -64.500084° W) near Kentville. This experiment was designed as a split-split-split plot design due to three randomization restrictions. A weather station (Watch Dog, Spectrum Technologies Inc., USA) was installed at the experimental site permanently through-out the experiment (figure 26) to record daily soil and air temperatures, RH, wind, light intensity and rainfall.

Figure 26: Weather station installed at the experimental site

The spectrum thermocouple (Watch Dog, Spectrum Technologies Inc., USA) attached to the data logger recorded daily soil temperature variations whereas water mark soil moisture sensors installed at seeding depths (2.5 cm and 1.9 cm) and attached to the data logger (Spectrum Technologies Inc., USA) recorded daily soil moisture potential fluctuations. Four varieties: Triton, Honey snax, Honey Enhanced (primed), Sugar snax and Upper Cut (Stokes seeds, Ontario, Canada) were used in this experiment at two seeding rates (85 seeds/ 30 cm and 55 seeds/ 30 cm) and seeded at two seeding depths

(2.5 cm and 1.9 cm). These seeds were pre-treated with Thiram, Iprodione and Matalaxyl by the seed producers, to protect seeds and emerging seedlings from pest and disease attacks.

Table 17: Details of seed varieties provided by the seed producers (Stork seeds, ON).

Variety	Seed Size (seeds/ Kg)	Germination (%)
Triton	484,180	94
Honey snax	619,355	93
Upper cut	597,355	93
Sugar snax	527,714	93

Land preparation was carried out following three main steps; the first step was land harrowing, one pass with a tandem disk harrow to incorporate poultry manure (5 t/ha) and the broccoli crop residue (previous crop) in to the soil. Then, land ploughing was conducted to mix manure with soil and to break soil clods to make an even soil surface using a chisel plough equipped with medium crown sweeps. Finally, two passes of S-tine cultivator, equipped with a finger harrow and rolling baskets were used to make even beds further bringing them in to fine textured seed beds. Seeding was done in ridge – rows (figure 27) and those beds were prepared using nine row bed-former equipped with Ecolo-till ripper shanks on each row.

Figure 27: Emerged seedlings in ridge-rows.

Soils were checked for compaction using an analogue soil compaction meter (Spectrum Technologies Inc., USA) that reads the pressure exerted to penetrate the seed bed at the desired seeding depths (it did not give any reading may be due to well-prepared seed beds or less sensitivity of analogue compaction meter for mild compaction). Soil fertility within sub blocks were also analyzed by collecting random soil samples from all sub blocks and sending them to the soil analyzing laboratory. At the 7th leaf stage plants were top dressed at the rate of 34:0:0 (N: P: K) and 150 kg/ ha.

5.4.1 Experimental Design and Statistical Analysis

Experiment was designed as a split-split-split plot design due to 3 randomization restrictions and year 2011 and 2012 experiments were considered as the two external blocks. Whole field was separated into two main plots as irrigated (I) and non-irrigated (NI), alternatively known as rain-fed and those two main plots again divided into five sub-plots (figure 28) to accommodate five varieties of carrot including primed seeds of Honey Snax: Triton, Honey Snax, Sugar Snax, Upper Cut and Honey enhanced. Each of these sub-plots were sub-divided into four separate sub-sub plots for two different seeding depths (2.5 cm and 1.9 cm) and two different seeding rates (55 seeds/30cm and 85 seeds/30cm).

Figure 28: Field Lay-out with dimensions and treatments.

Each treatment was replicated four times and assigned random spots within the sub-sub plots. Total length of each sub-sub plot was 40 m and they were divided in to 10 m length sub-sub-sub plots for four replicates each. Space between two rows was maintained at 60 cm and each treatment was labelled using a different colour flag (figure 29) and permanent markers.

Figure 29: Different treatments labelled with different colour flags (for easy identification of different treatments).

Seeding was done mechanically using a 9 row seeder which was standardized and adjusted to deliver seeds in two seeding depths and two seeding rates. A sprinkler irrigation system was used to irrigate the main irrigation in designated irrigated plots. Forty soil moisture sensors (pre-calibrated) were permanently installed at seeding depths of each treatment, at irrigated and non-irrigated plots to monitor soil moisture potential at the seeding depth. Soil moisture potentials were monitored continuously using digital soil sensor reader until completion of seedling emergence and the field (irrigated block) was irrigated when soil moisture potential was below – 40 kPa. In year 2011, after 105 days carrots were harvested for baby grades and plants within 1m were uprooted to take readings. In Year 2012, carrots were harvested upon reaching equal amount of degree days to year 2011(harvested on 23rd Oct.).

Table 18: Daily mean Ψ, temperature and rainfall recorded by the weather station in 2012 from seeding to completion of seedling emergence.

Date	Daily mean – Ψ (- kPa)	Daily mean temperature (°C)	Rainfall (mm) or Field Irrigation
05-Jul	43	19.60	5.8
06-Jul	37	21.55	0
07-Jul	43	21.80	0
08-Jul	45	20.60	0
09-Jul	50	18.25	0
10-Jul	53	19.05	0
11-Jul	30	19.45	Irrigated (30 mm)
12-Jul	12	20.80	0
13-Jul	19	22.25	0
14-Jul	25	23.95	0
15-Jul	31	22.90	0
16-Jul	37	20.00	2.5
17-Jul	38	21.20	8.1
18-Jul	15	22.55	0
19-Jul	20	19.25	0
20-Jul	31	18.50	0

The weather station was installed in non-irrigated block.

Table 19: Daily mean soil Ψ, temperature and rainfall recorded by weather station in year 2011 from seeding to completion of seedling emergence.

Date	Daily mean Ψ (- kPa)	Daily mean temperature (°C)	Rainfall (mm) or Field Irrigation
26-Jun	*	*	0.3 mm
27-Jun	18.6	19.41	2.3 mm
28-Jun	26	26.58	0
29-Jun	33.7	34.04	0
30-Jun	30.7	27.12	5.9 mm and Irrigated (30 mm)
01-Jul	21.4	17.58	0
02-Jul	18.5	18.54	0
03-Jul	25.9	19.37	0
04-Jul	32	22.21	0
05-Jul	30.6	21.17	4.3
06-Jul	19.5	19.46	0
07-Jul	30.3	21.46	0
08-Jul	36.4	25.87	0.3
09-Jul	20.7	18.33	9.7
10-Jul	14.9	14.56	0
11-Jul	16.5	15.37	15.2

The weather station was installed in irrigated block.

5.4.2 Parameters Measured

5.4.2.1 Seedling Emergence

Number of seedlings emerged each day within 30 cm of each replicate were counted and 30 cm length was marked permanently using two steel pegs until completion of emergence. Soil moisture potentials of each treatment were also recorded daily.

5.4.2.2 Seedling Vigour

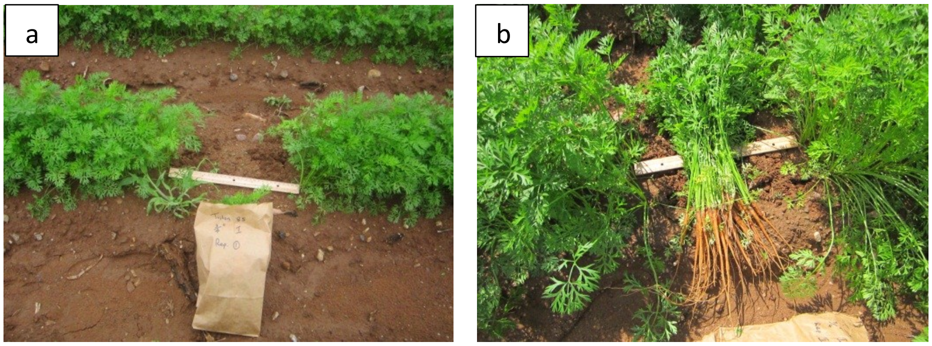

Figure 30: Plants at the 5th week (a) and at the begging of bulking stage (b)

Seedling samples within 30 cm were collected from each treatment (figure 30), 5 weeks after seeding and at the initiation of bulking stage to test the vigour of plants. Number of seedlings within 30 cm was counted and fresh and dry weights were also recorded for all 160 plots.

5.4.2.3 Yield Parameters

Figure 31: Carrot harvesting and grading; a- uprooting carrots within 1m, b- removing above ground plant parts and counting number of roots within 1m, c- testing carrots for its size using holes fitted for particular diameters, d- the carrot fitted for the size of fancy grade, e- cutting the top part which exceeded the diameter of fancy grade, f- top part removed and send to the next grade, baby choice

Roots within 1m from all 160 plots were harvested in year 2012, following similar degree days as of in year 2011. Total numbers of roots produced within 1m in all 160 plots were counted and roots within 1m were separated in-to 4 grades: undersize, fancy, choice and sliced, according to their diameters (figure 30); roots <1.27 cm in diameter were graded as undersize, roots having diameters between 1.27 and 1.9 cm were grades as Fancy and roots having diameters between 1.9 and 2.5 cm were graded as Baby Choice whereas roots having diameters > 2.5 cm graded as sliced.

In practice carrots for processing are harvesting and removing plant top by carrot harvester (figure 32) and directing them in to a separate tractor. All the cleaning and grading are done mechanically after sending them to the processing plant.

Figure 32: Machine operated carrot harvesting, a- carrot harvester with harvested carrots, b- carrots with top parts of the plant, c- conveyer belt to send carrots from the harvester to root collecting tractor, d- tractor to collect roots

5.4.3 Experimental Design and Statistical Analysis:

This experiment was designed as a split-split-split plot design due to 3 randomization restrictions. Two years, 2011 and 2012 experiments were considered as the two external blocks (determinant of error factor) and whole experimental field was divided in to two main plots, as irrigated and non-irrigated. Five sub-plots were created within those two main plots for 5 varieties and sub-sub plots for 2 seeding depths and 2 seeding rates. Analysis of variance was carried out using SAS 9.3 (SAS Institute Inc., NC, USA) with Proc Mixed GLM. LS means were used to compare the significance of main effects of treatments and their interaction effects on seedling emergence and final total yield. Data were tested for 3 normality assumptions and they met the requirements of normality assumptions.

5.5 Results

5.5.1 Seedling Emergence Responses

Table 20: Significance of mean seedling emergence with respect to four main treatments; variety, irrigation, seeding rate and depth and their interaction effects, considering years 2011 and 2012 field data.

Effect	DF	F Value	P Value
Variety	4	9.43	<0.0001
Irrigation	1	2.11	0.3839
Seeding Rate	1	45.69	<0.0001
Seeding Depth	1	1.80	0.1879
Variety*Irrigation	4	0.29	0.8815
Variety*Seeding Rate	4	0.40	0.8091
Irrigation*Seeding Rate	1	2.21	0.1453
Variety*Seeding Depth	4	0.38	0.8230
Irrigation*Seeding Depth	1	0.85	0.3627
Seeding Rate*Seeding Depth	1	0.52	0.4755
Variety*Irrigation*Seeding Rate	4	0.28	0.8871
Variety*Irrigation*Seeding Depth	4	0.51	0.7293
Variety*Seeding Rate*Seeding Depth	4	0.49	0.7406
Irrigation*Seeding Rate*Seeding Depth	1	0.00	0.9783
Variety*Irrigation*Seeding Rate*Seeding Depth	4	0.36	0.8357

Means are significant at (α=0.05) 5% level

None of the interactions among varieties*Irrigation*seeding depth*seeding rate on seedling emergence were not significant (table 20). The main effect of varieties and seeding rates were the only ones that were significant statistically (< 0.0001) suggesting that these are the two main factors that may influence seedling emergence.

According to the LS means of varieties, Honey snax showed the highest significant (P = <0.0001) mean seedling emergence (table 21) and Honey snax enhanced also showed the second highest mean which was not significantly different from Honey snax. The lowest mean seedling emergence was recorded with variety Upper cut.

Table 21: Significance of LS means of seedling emergence by variety and seeding rate together with letter groupings

Variety	Means seedling emergence together with letter grouping
Honey snax	15.61^{a}
Honey enhanced	13.71^{ab}
Triton	12.94^{b}
Sugar snax	12.20^{b}
Upper cut	8.76^{c}

(Means sharing same letter group are not significantly different at 5% level of significant with adjustments of LS means).

The highest significant (P = < 0.0001) mean seedling emergence (table 22) was observed at the seeding rate of 85 seeds / 30 cm.

Table 22: Mean seedling emergence as influenced by seeding rate together with letter groups

Seeding Rate	Mean seedling emergence together with letter groupings
85 seeds/ 30 cm	19.63a
55 seeds/ 30 cm	13.18^{b}

(Means sharing same letter group are not significantly different at 5% level of significant with least square means adjustments)

5.5.2 Testing Seedling Vigour over Time

Variety Triton maintained the highest dry weight at 85 seeding rate and 2.5 (1”) cm depth both under irrigated and non-irrigated conditions in year 2011 (figure 33 and figure 34). Most of the plants were at bulking stage under irrigated conditions and have exceeded 20 g / 30cm dry weight under irrigated conditions (figure 34).

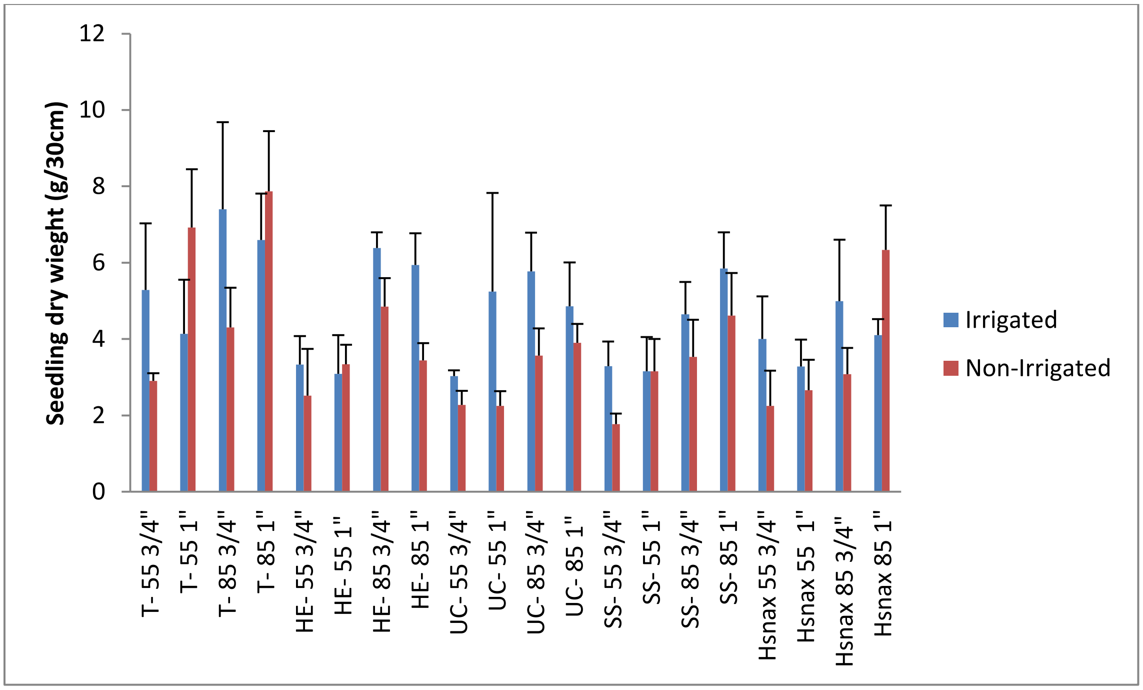

Figure 33: Dry weight of seedlings at 5th week following seeding, under different 4 different treatments (variety, irrigation, seeding rate and depth) - Year 2011.

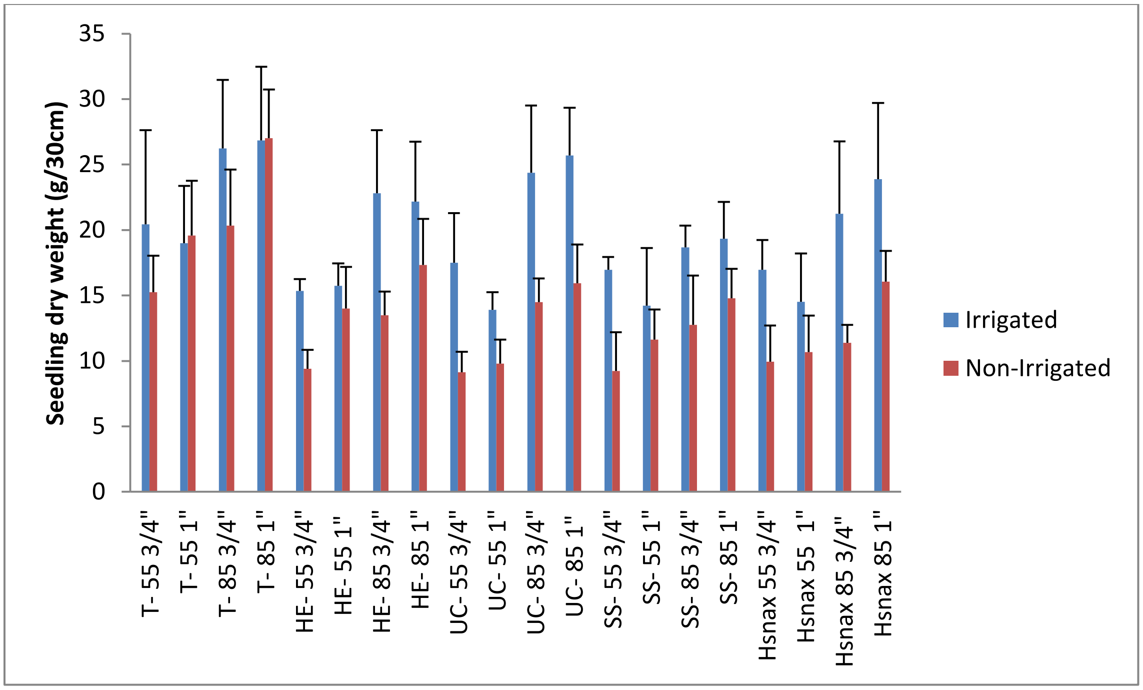

Figure 34: Dry weight of seedlings at bulking stage (8 weeks after seeding) under 4 different treatments- Year 2011.

5.5.3 Yield Response

Analysis of variance was carried out to test the statistical significance of final total yield of different carrot varieties with respect to different environmental and management conditions under this experiment.

None of the interactions were significant statistically (table 23). The main effects that showed statistically significant effect on total yield were variety (P = <0.0001) and seeding depth (P = 0.0117).

Table 23: Significance of mean total yield in response to variety, irrigation, seeding rate and depth and their interaction effects.

Effect	DF	F Value	P Value
Variety	4	27.09	<0.0001
Irrigation	1	1.65	0.4212
Seeding Rate	1	0.89	0.3503
Seeding Depth	1	7.02	0.0117
Variety*Irrigation	4	0.65	0.6297
Variety*Seeding Rate	4	1.89	0.1322
Irrigation*Seeding Rate	1	1.80	0.1877
Variety*Seeding Depth	4	1.17	0.3384
Irrigation*Seeding Depth	1	0.05	0.8230
Seeding Rate*Seeding Depth	1	0.00	0.9766
Variety*Irrigation*Seeding Rate	4	0.47	0.7543
Variety*Irrigation*Seeding Depth	4	1.43	0.2415
Variety*Seeding Rate*Seeding Depth	4	0.08	0.9893
Irrigation*Seeding Rate*Seeding Depth	1	0.16	0.6958
Variety*Irrigation*Seeding Rate*Seeding Depth	4	0.82	0.5190

Effects of treatments are significant at 5% level of significant.

Varieties had a highly significant (P = <0.0001) influence on final root yields of baby carrots. Seeding depth also significantly (P = 0.0117) influenced final root yield (table 23).

Table 24: Significance of least square means of total yields (t/ha) by variety together with letter grouping.

Variety	Estimated means for total yield (t/ha) with letter grouping
Triton	28.67^{a}
Honey Enhanced	24.94^{b}
Honey snax	23.63^{bc}
Sugar snax	23.40^{c}
Upper Cut	22.16^{c}

Means sharing same letter group are not significantly different at 5% level of significant with LS means adjustments.

Triton yielded the highest (28.67 t/ha) while uppercut showed the lowest (22.16 t/ha) mean total yield (table 24). Honey enhanced and Honey snax gave the 2nd and 3rd largest least square means of total yields, respectively, which however were not significantly different (table 24) from each other. There is no significant yield advantage due to use of enhanced seeds (primed seeds) as seen from the Honey snax enhanced and Honey snax as the yield was not statistically different (table 24).

Table 25: Mean total yield with respect to seeding depth together with letter groups.

Seeding Depth	Mean total yield (t/ha) with letter grouping
2.5 cm	27.07a
1.9 cm	25.85^{b}

Means sharing same letter are not significantly different at 5% level of significant with LS adjustments.

Seeding at 2.5 cm deeper showed a significantly higher mean yield compared to seeding at 1.9 cm (table 25).

5.5.3.1 Yield of Fancy Grade

Analysis of variance with LS means was conducted in Proc-Mixed GLM to test the significance of mean Fancy yield as influenced by four main effects and their interaction effects. None of the interaction effects were significant statistically (table 26).

Table 26: Significance of mean Fancy grade yield as influenced by variety, seeding rate, seeding depth and irrigation.

Effect	DF	F Value	P Value
Variety	4	8.28	<0.0001
Irrigation	1	7.66	0.2207
Seeding Rate	1	6.17	0.0175
Seeding Depth	1	0.00	0.9983
Variety*Irrigation	4	0.28	0.8879
Variety*Seeding Rate	4	0.38	0.1322
Irrigation*Seeding Rate	1	0.11	0.7406
Variety*Seeding Depth	4	0.68	0.6104
Irrigation*Seeding Depth	1	0.44	0.5134
Seeding Rate*Seeding Depth	1	3.33	0.0758
Variety*Irrigation*Seeding Rate	4	0.05	0.9956
Variety*Irrigation*Seeding Depth	4	0.01	0.9999
Variety*Seeding Rate*Seeding Depth	4	0.17	0.9511
Irrigation*Seeding Rate*Seeding Depth	1	0.76	0.3890
Variety*Irrigation*Seeding Rate*Seeding Depth	4	0.26	0.8986

Treatment effects are significant at 5% level.

Interaction effects on Fancy yields were not significant statistically (table 26) at 5% level but seeding rate* seeding depth showed a mildly significant ($P = 0.0758$) influence on Fancy yield. Varieties showed a significant influence on Fancy yield ($P = < 0.0001$).

Triton recorded the highest (38.98) while Sugar snax (30.65) yielded the lowest mean Fancy yield (table 27). Seeding rate (P = 0.0175) was also showed a significant influence on fancy yield (table 28) and seeding rate 85 seeds/ 30 cm showed significantly higher (35.03) fancy yield compared to 55 seeds/ 30 cm (table 23).

Table 27: Least Square means of Fancy grade together with letter groups with respect to variety or genotype.

Variety	LS means together with letter groups (t/ha)
Triton	38.98^{a}
Honey Snax	34.29^{b}
Honey Enhanced	33.83^{bc}
Upper Cut	30.85^{c}
Sugar Snax	30.65^{c}

Means sharing same letter groups are not significantly different at 5% level.

Table 28: Mean Fancy yield together with letter groups as influenced by seeding rate.

Seeding Rate	LS means together with letter groups (t/ha)
85	35.03^{a}
55	32.41^{b}

Means sharing same letter group are not significantly different at 5% level with LS means adjustments.

Data collected on different root grades from years 2011 and 2012 were plotted for five varieties to compare yields of different root grades at the seeding rate of 85 seeds/ 30 cm with population standard deviations (representing error bars) as follows:

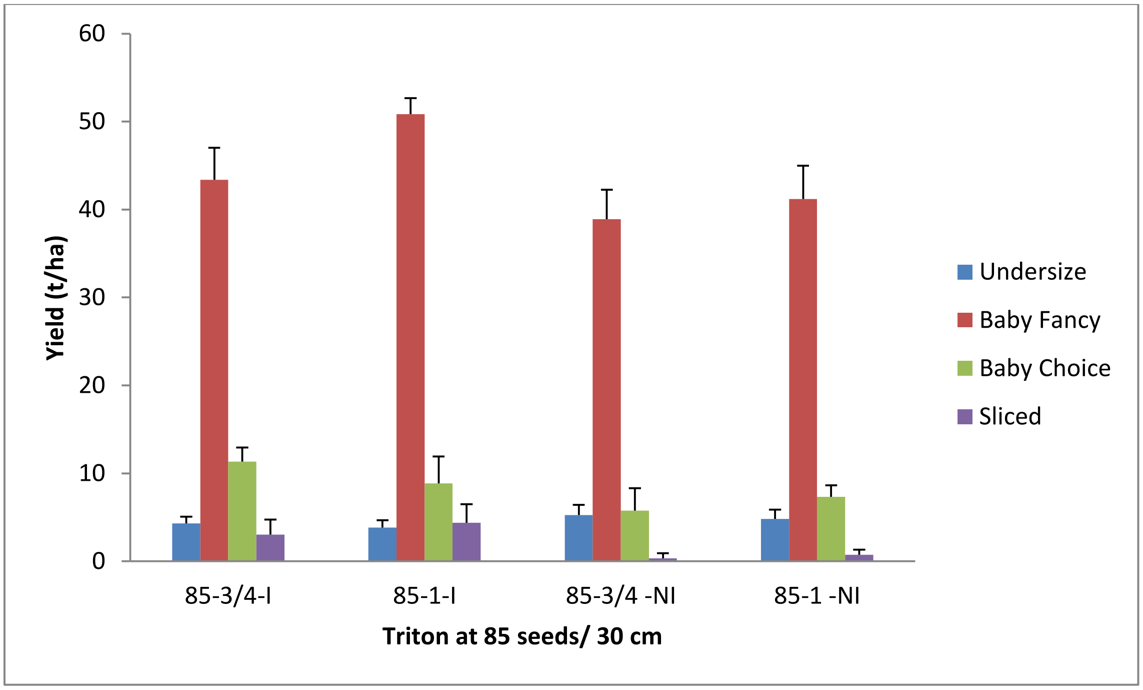

Figure 35: Yields of different root grades in year 2012 as influenced by seed variety, seeding rate, depth and irrigation (four different treatments).

Triton as the best variety, gave the highest fancy grade yield of 50.85 t/ha (figure 35) at 2.5 cm seeding depth under irrigated conditions in year 2012 out of all varieties. However, yield of fancy grade exceeded 40 t/ha at 1.9 cm depth irrigated and at 2.5 cm depth non-irrigated conditions as well.

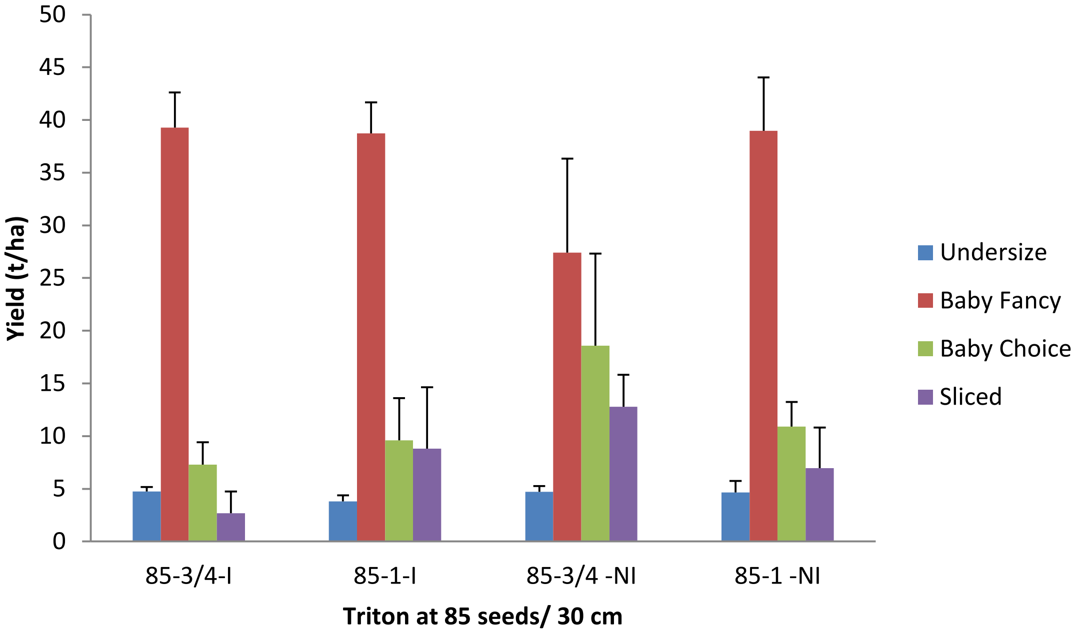

Figure 36: Yields of different baby grades as influenced by seeding depth and irrigation in 2011.

Yield of fancy grade did not exceed 40 t/ ha under any of above treatments in 2011(figure 36) and fancy yield in 2011 was lower (38 t/ha) compared to 2012. However, it showed higher yields of other grades compared to 2011, especially at 1.9 cm depth under non-irrigated condition.

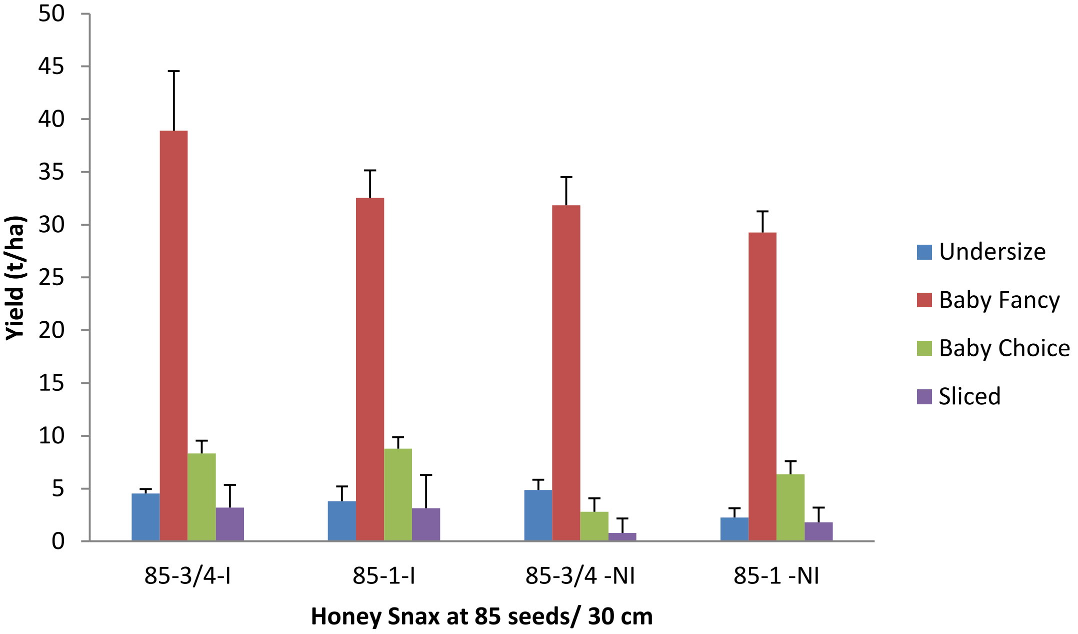

Figure 37: Yields of different baby grades of Honey snax in year 2012 with respect to two seeding depths and irrigation.

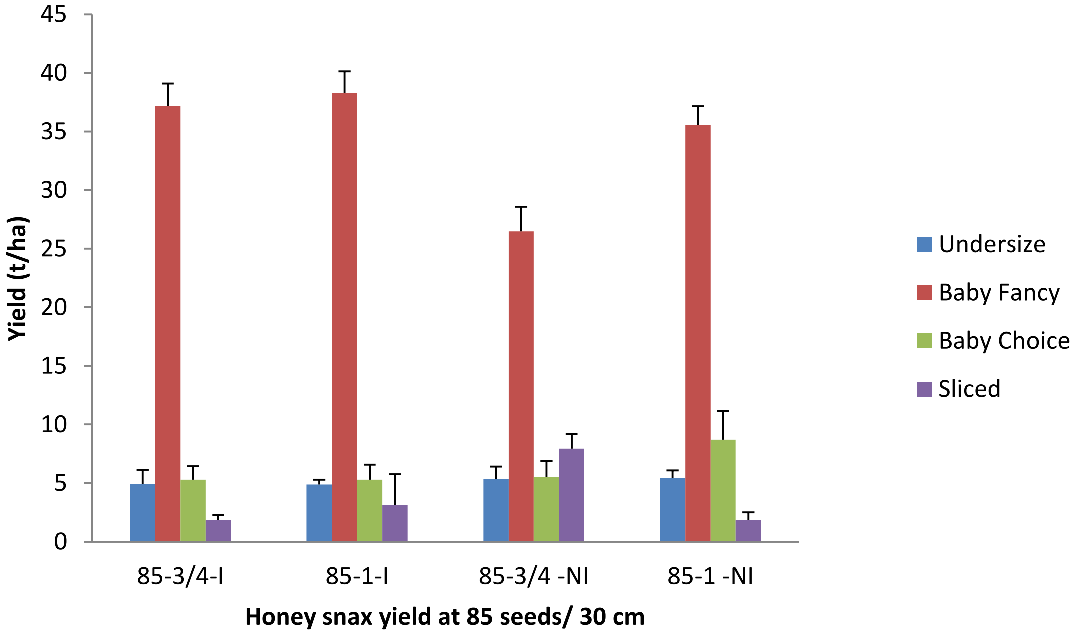

Figure 38: Yield of different baby grades of Honey snax in year 2011 as influenced by 2 seeding depths and irrigation.

The highest yield of Honey snax fancy grade was given by Honey snax is 38.9 tons/ha in year 2012 at 1.9 cm depth and 38.3 t/ha in year 2011 at 2.5 cm depth under irrigated conditions.

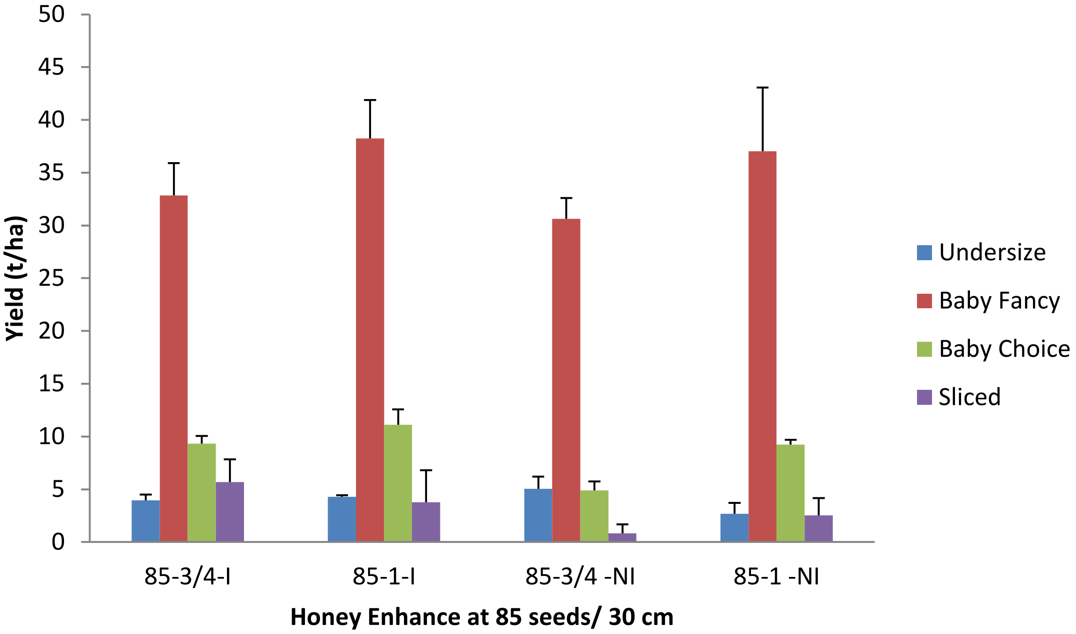

Figure 39: Yields of different baby grades of Honey enhanced in year 2012 as influenced by 4 different treatments.

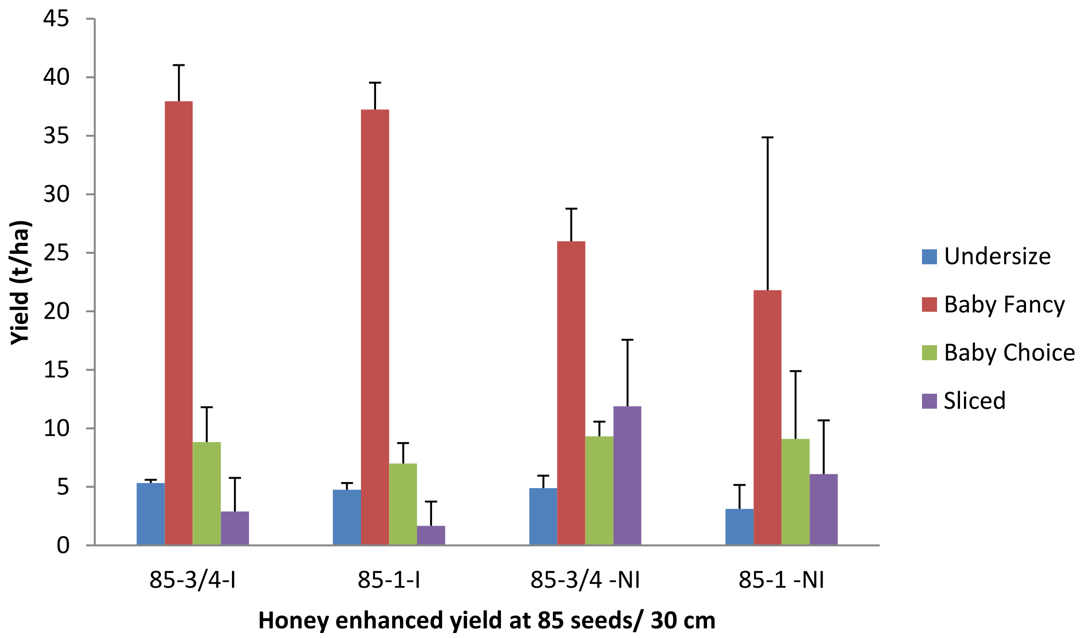

Figure 40: Yields of different grades of Honey enhanced in 2011 as influenced by 2 seeding depths and irrigation.

Yield of fancy grade was recorded 38 t/ha in 2012 at 2.5 cm depth and 37 t/ha at 1.9 cm, both under irrigated conditions as the highest. In overall, fancy yield is low compared to Triton (figure 39 and 40).

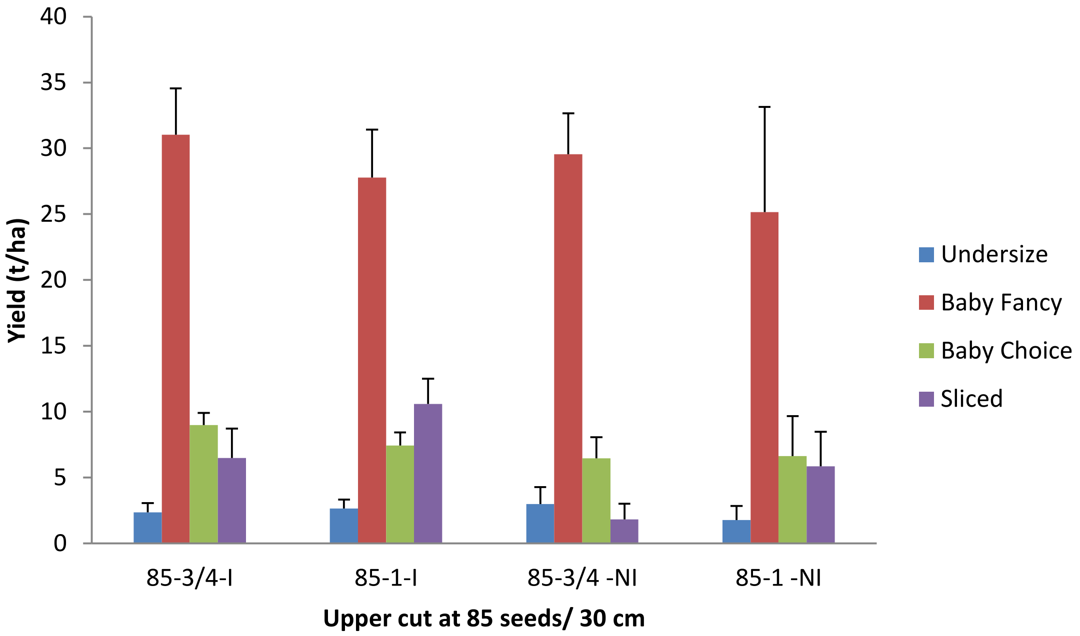

Figure 41: Yields of different baby grades of Upper cut in year 2012 as influenced by 2 seeding depths and irrigation.

The yield of fancy grade given by upper cut was 31 t/ha in 2012 at 1.9 cm and was 34 t/ha in 2011 at 1.9 and 2.5 cm, as the highest yield. The yield of fancy grade is low in Upper cut compared to Honey snax (figure 41).

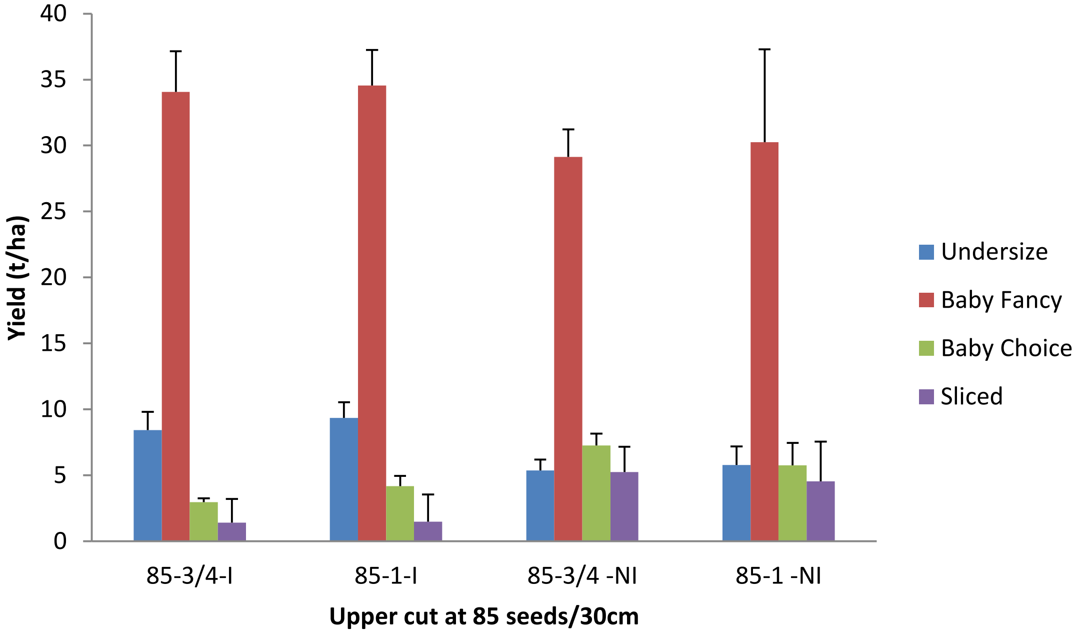

Figure 42: Yields of different baby grades of Upper Cut in year 2011 as influenced by 4 treatments.

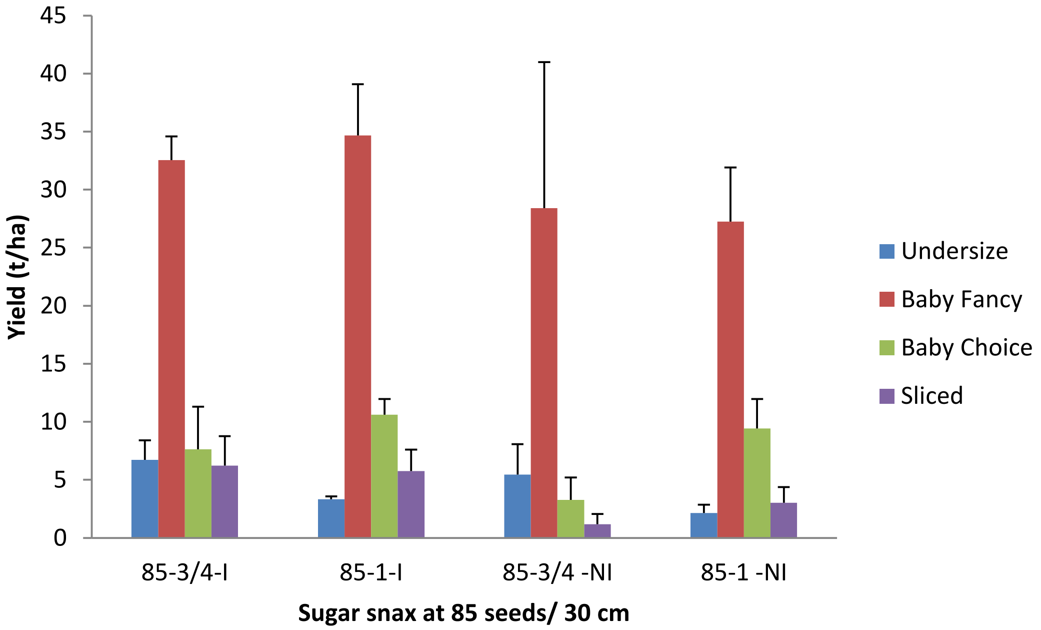

Figure 43: Sugar snax yields of different baby grades in year 2012 at two seeding rates and irrigation.

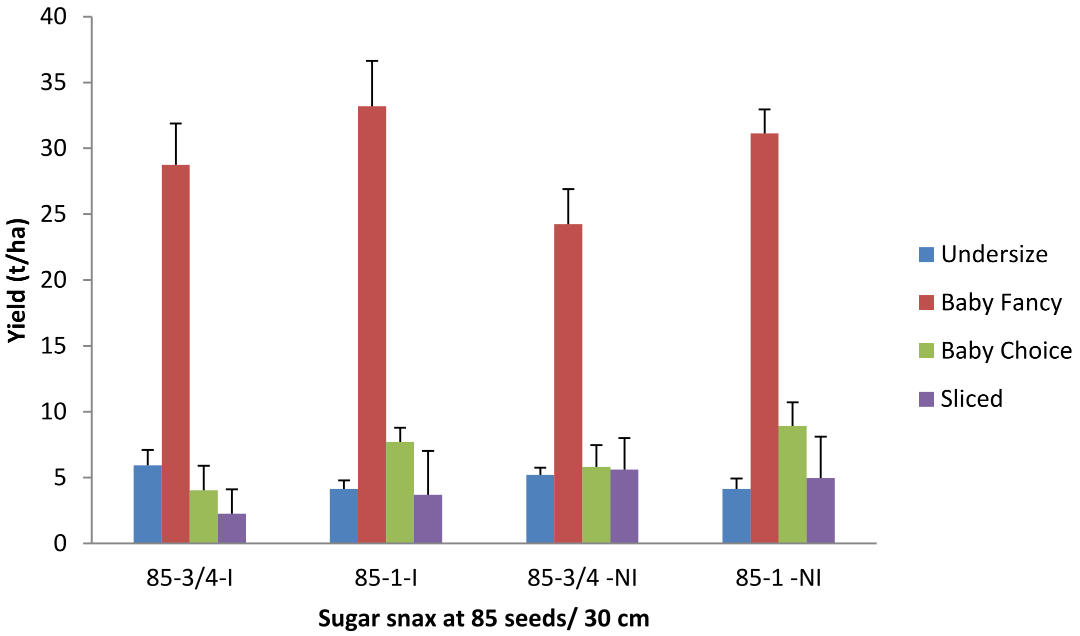

Figure 44: Yields of different baby grades of Sugar snax in year 2011 at 4 treatments.

The highest fancy yield of for Sugar snax was recorded as 33 t/ ha at 2.5 cm in 2011 and 34 t/ha at 2.5 cm in 2012 under irrigated condition (figure 43 and 44). The yield of fancy grade is low in Sugar snax and Upper cut compared to other three varieties.

Overall, yield of fancy grade was low at non-irrigated conditions compared to irrigated condition.

5.5.3.2 Relationship between Seedling Emergence and Total Yield

Regression analysis between seedling emergence and total yield of Triton was not significant (P = 0.542, R^2 = 38.4 %) at 5% level. Cubic relationship between Triton total yield and number of seedling emerged (figure 45) was not statistically significant suggesting number of seedling emerged may not be the only factor that influences total yield.

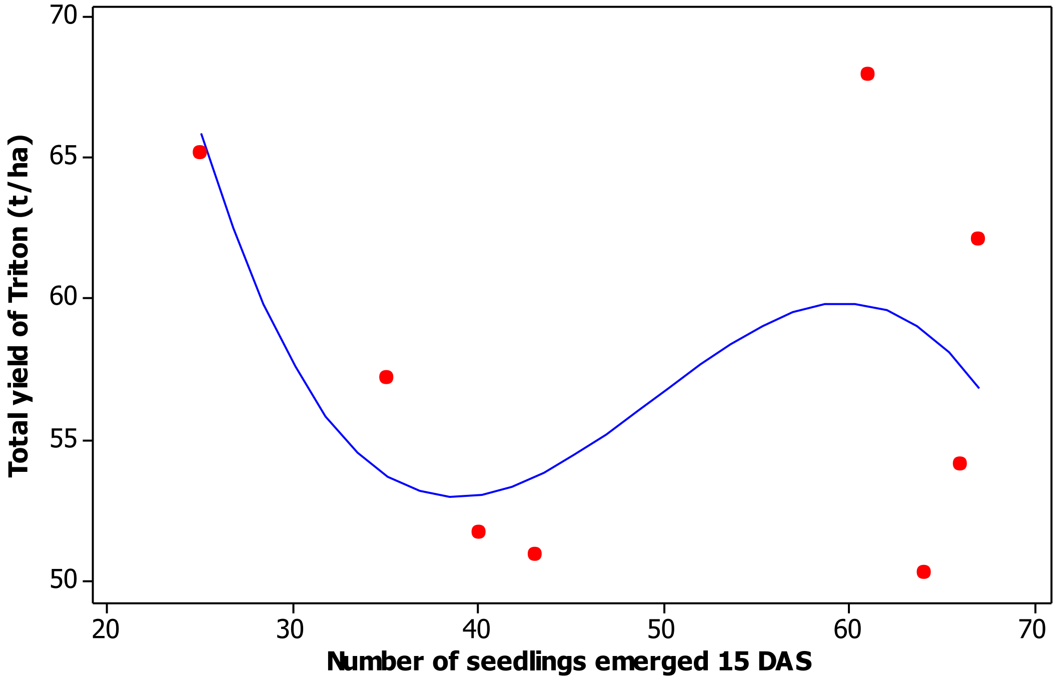

Figure 45: Regression model between seedling emergence and total yield, Regression model fitted for Triton; Total Yield = 211.7 – 10.45 SE + 0.222 SE^2 – 0.0015 SE^3 (2012 yield data).

Table 29: Triton seedling emergence and total yield with respect to three different treatments (in 2012) used in figure 45.

Treatments of Triton (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Total Yield (t/ha)
55-3/4 - I	43	50.88
55-1 - I	25	65.17
85-3/4-I	67	62.07
85-1-I	61	67.95
55-3/4 -NI	40	51.65
55-1 -NI	35	57.17
85-3/4 -NI	64	50.23
85-1 -NI	66	54.08

Regression analysis between seedling emergence and total yield of Honey snax was also not significant (P =0.495, R^2 = 29%) at 5% level. However, it showed a non-significant cubic relationship (figure 46) suggesting as above for Triton.

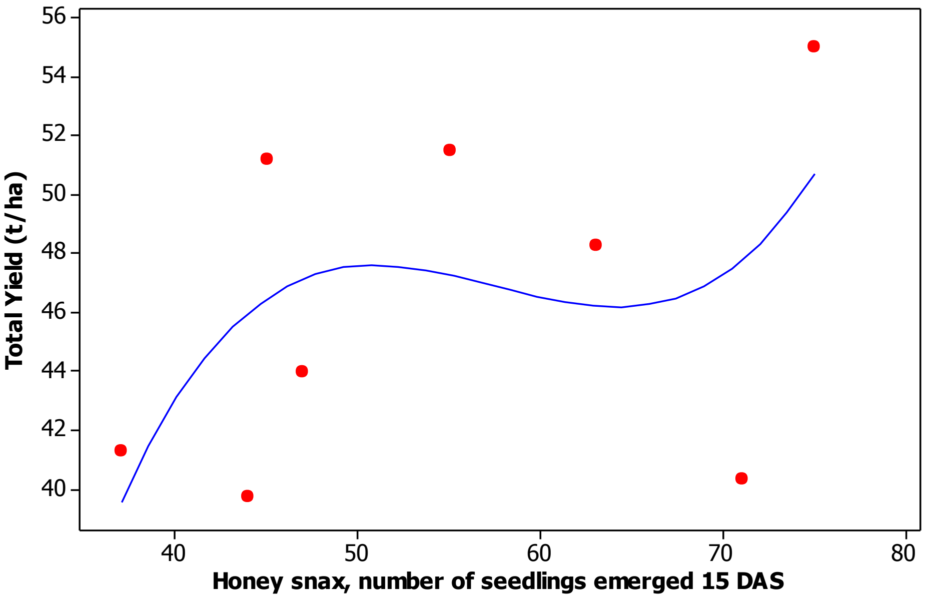

Figure 46: Regression model fitted for Honey snax seedling emergence vs. total yield, Regression equation for Total yield of Honey snax, Total Yield = -179.9 + 12.6 SE – 0.2143 SE^2 + 0.001243 SE^3.

Table 30: Honey snax seedling emergence and total yield with respect to three different treatments (in 2012) used in figure 46.

Treatments of Honey snax (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Total Yield (t/ha)
55-3/4 - I	55	51.46
55-1 - I	45	51.16
85-3/4-I	75	54.97
85-1-I	63	48.25
55-3/4 -NI	47	43.96
55-1 -NI	37	41.25
85-3/4 -NI	71	40.33
85-1 -NI	44	39.69

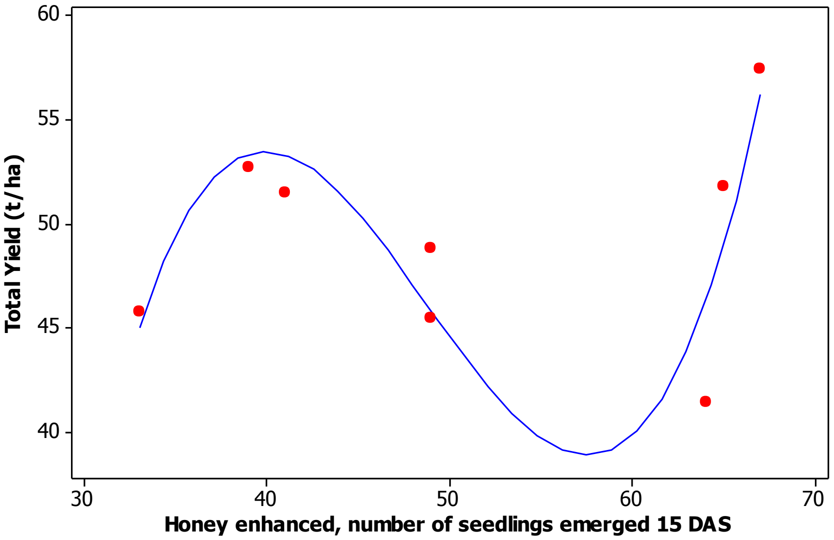

Figure 47: Regression model between Honey snax enhanced total yield and number of seedlings emerged, Regression equation for Honey snax enhanced; Total Yield = -510.1 + 36.75 SE – 0.7802 SE^2 + 0.005341 SE^3.

Regression analysis between total yield and Honey snax seedling emergence showed a cubic relationship (P = 0.115, R^2 = 74 %), which was mildly significant suggesting, number of seedlings emerged 15 days after seeding (DAS), may not be the only fact that affecting total root yield (figure 47).

Table 31: Honey enhanced seedling emergence and total yield with respect to three different treatments (in 2012) used in figure 47.

Treatments of Honey enhanced (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Total Yield (t/ha)
55-3/4 - I	49	48.79
55-1 - I	39	52.69
85-3/4-I	65	51.81
85-1-I	67	57.4
55-3/4 -NI	49	45.44
55-1 -NI	33	45.77
85-3/4 -NI	64	41.4
85-1 -NI	41	51.5

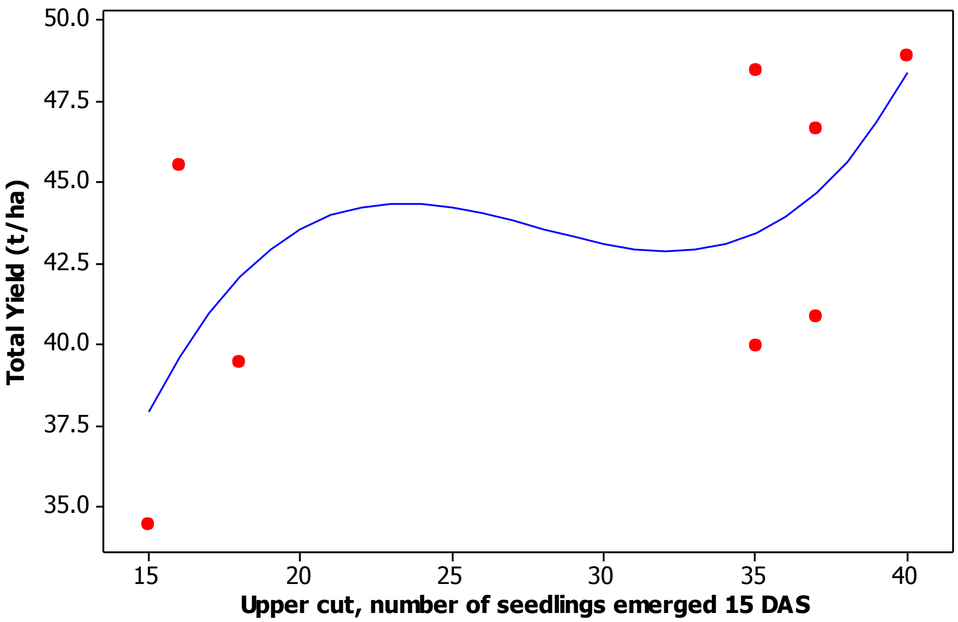

Figure 48: Regression model for Upper cut total yield and equation for Upper cut, Total Yield = -41.1 + 9.66 SE – 0.3569SE^2 + 0.004285 SE^3.

Regression analysis between Upper cut total yield and number of seedlings emerged was also not significant ($P = 0.517$, $R^2 = 40.2\%$) statistically at 5% level (figure 48).

Table 32: Upper cut seedling emergence and total yield with respect to three different treatments (in 2012) used in figure 48.

Treatments of Upper cut (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Total Yield (t/ha)
55-3/4 - I	37	46.62
55-1 - I	16	45.48
85-3/4-I	40	48.87
85-1-I	35	48.44
55-3/4 -NI	35	39.92
55-1 -NI	15	34.44
85-3/4 -NI	37	40.85
85-1 -NI	18	39.44

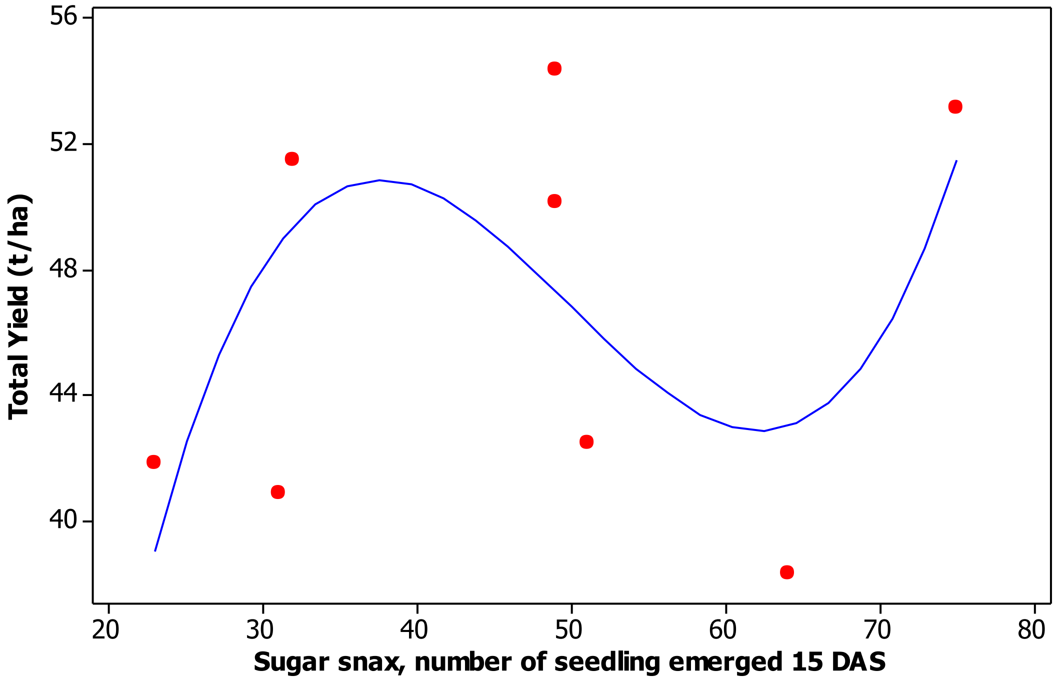

Figure 49: Regression model fitted for Sugar snax total yield vs. number of seedling emerged, Regression equation, Total Yield = - 62.12 + 7.518 SE – 0.1603 SE^2 + 0.00107 SE^3.

Regression analysis between total yield of Sugar snax and number of seedlings emerged was not statistically significant (P = 0.541, R^2 = 38.5%) at 5% level (figure 49), suggesting total yield is not totally related to number of seedlings emerged 15 DAS.

Table 33: Sugar snax seedling emergence and total yield with respect to three different treatments (in 2012) used in figure 49.

Treatments of Sugar snax (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Total Yield (t/ha)
55-3/4 - I	49	50.1
55-1 - I	32	51.47
85-3/4-I	75	53.14
85-1-I	49	54.36
55-3/4 -NI	51	42.48
55-1 -NI	31	40.83
85-3/4 -NI	64	38.31
85-1 -NI	23	41.85

Data from year 2012 were used to understand relationship between total yield and seedling emergence since it was a dry year which can better represent effect of soil moisture.

5.5.3.3 Relationship between SE and Fancy Yield

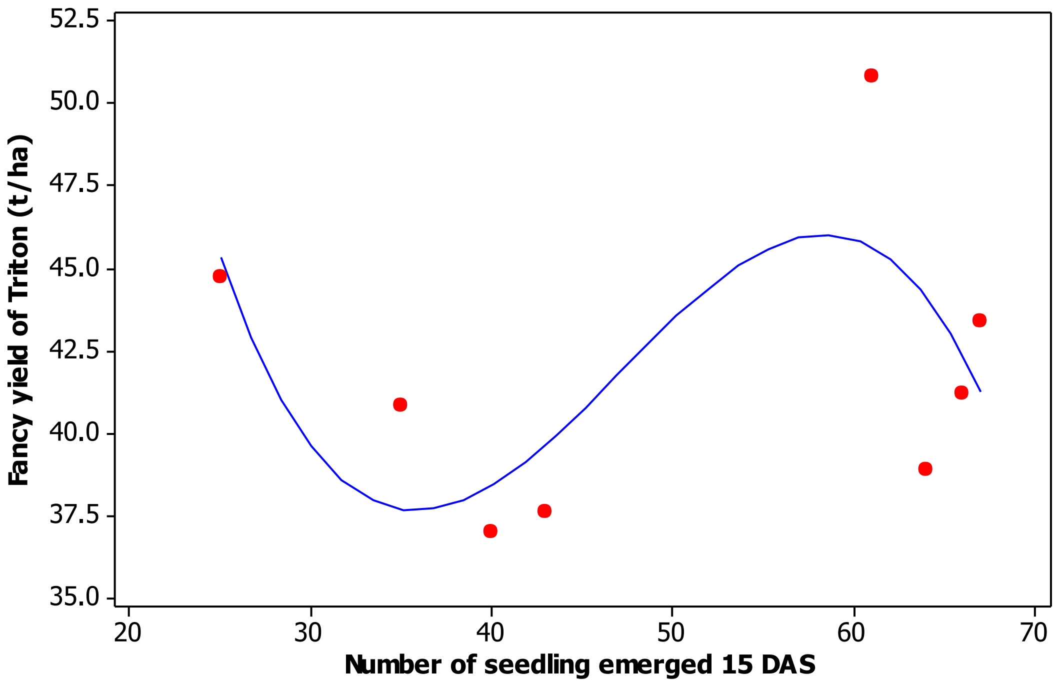

Figure 50: Cubic regression fit for seedling emergence vs. Fancy yield, Model fitted for Fancy yield = 169.4 – 9.255 SE + 0.2086 SE^2 – 0.001478 SE^3.

Regression analysis between Fancy yield of Triton and number of seedling emerged was not statistically significant (R^2 = 46.4%, P = 0.43) at 5% level (figure 50), suggesting number of seedlings emerged 15 days after seeding may not be the only factor that affects fancy yield.

Table 34: Triton seedling emergence and yield of Fancy grade with respect to three different treatments (figure 50) in 2012.

Triton treatments (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Yield (t/ha) of Fancy grade
55-3/4 - I	43	37.6
55-1 - I	25	44.7
85-3/4-I	67	43.4
85-1-I	61	50.8
55-3/4 -NI	40	37.0
55-1 -NI	35	40.8
85-3/4 -NI	64	38.9
85-1 -NI	66	41.2

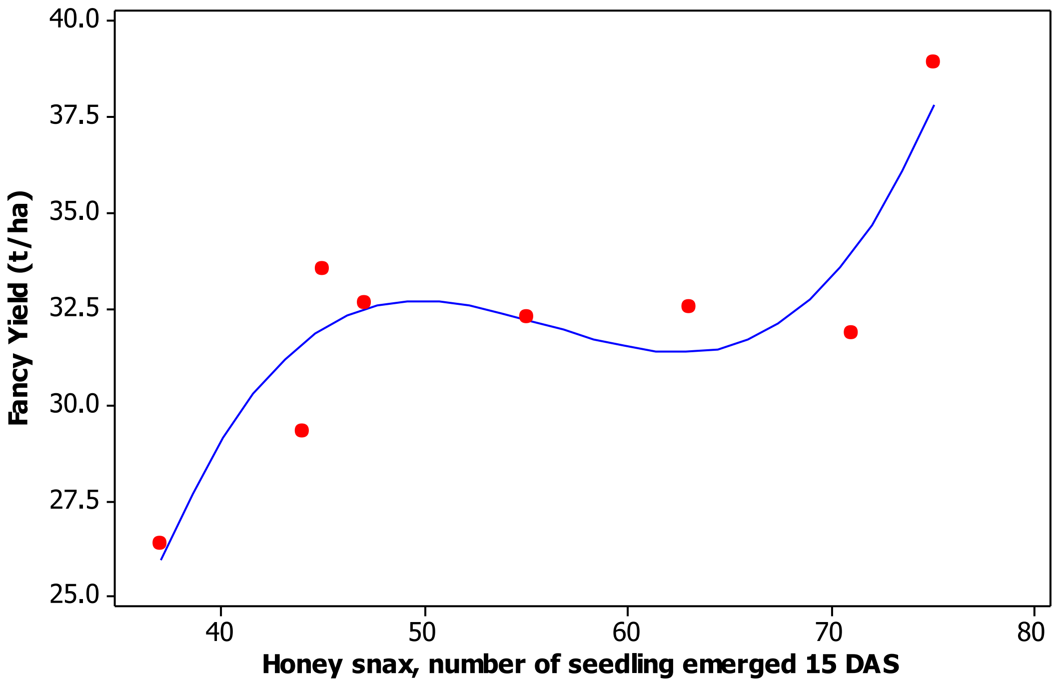

Figure 51: Cubic regression fit for Honey snax fancy yield and number of seedlings emerged, model fitted was, Fancy Yield = -189.7 + 12.17 SE – 0.2196 SE^2 + 0.0013 SE^3.

Regression analysis between Honey snax fancy yield and number of seedling emerged 15 DAS showed a significant ($P = 0.04$, $R^2 = 83.2\%$) positive cubic relationship suggesting (figure 51), increasing number of seedlings up to 50 may increase fancy yield and then become a yield plateau and again will increase fancy yield when seedling number is above 70.

Table 35: Honey snax seedling emergence and yield of Fancy grade with respect to three different treatments (figure 51) in 2012.

Honey snax Triton treatments (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Yield (t/ha) of Fancy grade
55-3/4 - I	55	32.27
55-1 - I	45	33.51
85-3/4-I	75	38.92
85-1-I	63	32.54
55-3/4 -NI	47	32.62
55-1 -NI	37	26.35
85-3/4 -NI	71	31.85
85-1 -NI	44	29.27

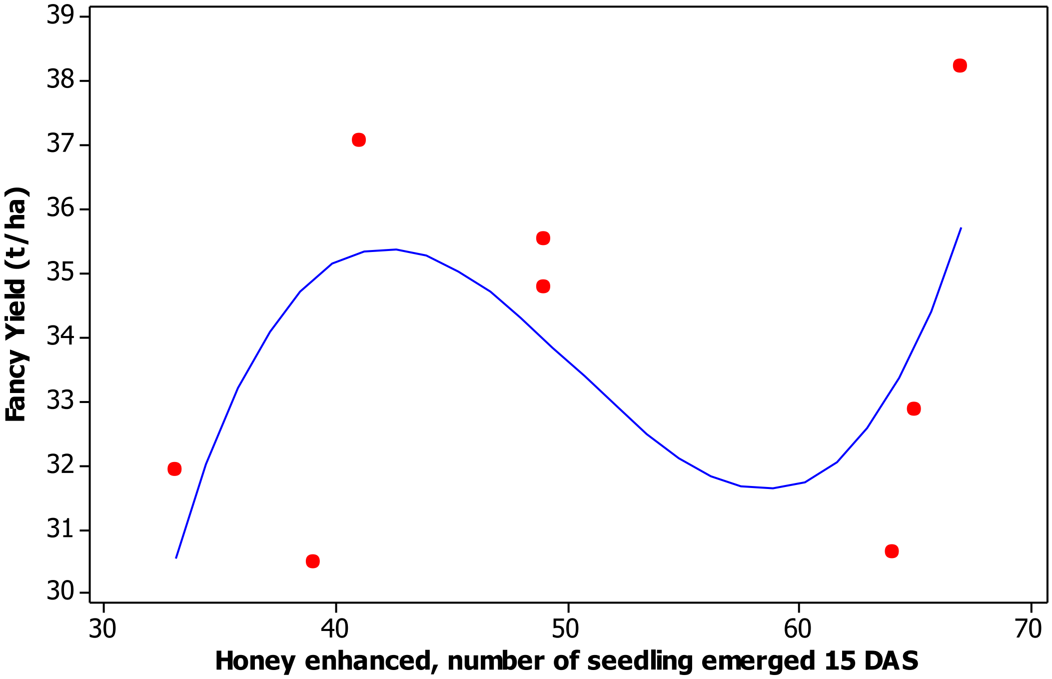

Figure 52: Cubic regression model fitted for Honey enhanced fancy yield and number of seedling emerged 15 DAS, regression equation is, Fancy Yield = -168.1+ 12.71 SE – 0.2594 SE^2 + 0.001718 SE^3.

Regression analysis between fancy yield of Honey enhanced and number of seedling emerged was not statistically significant (P = 0.658, R^2 = 30.4%) at 5% level (figure52).

Table 36: Honey enhanced seedling emergence and yield of Fancy grade with respect to three different treatments (figure 52) in 2012.

Honey enhanced treatments (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Yield (t/ha) of Fancy grade
55-3/4 - I	49	35.52
55-1 - I	39	30.48
85-3/4-I	65	32.85
85-1-I	67	38.23
55-3/4 -NI	49	34.77
55-1 -NI	33	31.9
85-3/4 -NI	64	30.62
85-1 -NI	41	37.04

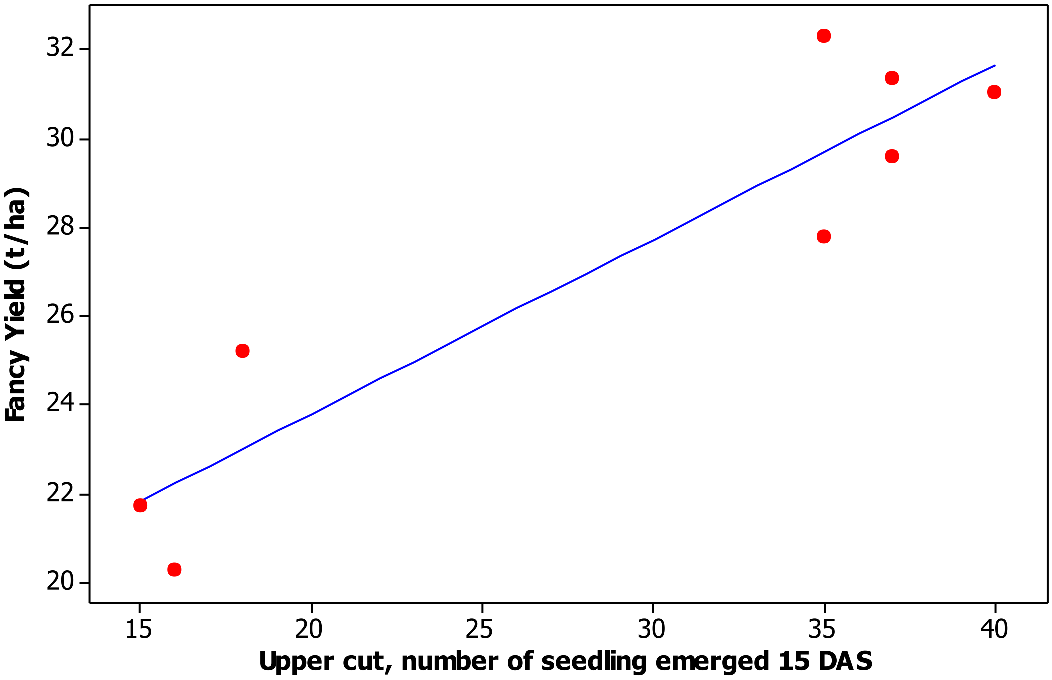

Figure 53: Regression model fitted for fancy yield of Upper cut and number of seedling emerge, Regression equation is Fancy Yield = 15.93 + 0.3932 SE.

Regression analysis between Upper cut fancy yield and number of seedling emerged showed a significant (P = 0.001, R^2 = 85.7 %) positive linear relationship at 5% level (figure 53), suggesting with increasing number of seedling emergence, yield of fancy grade may increase.

Table 37: Upper cut seedling emergence and yield of Fancy grade with respect to three different treatments (figure 53) in 2012.

Upper cut treatments (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Yield (t/ha) of Fancy grade
55-3/4 - I	37	31.31
55-1 - I	16	20.25
85-3/4-I	40	31.02
85-1-I	35	27.77
55-3/4 -NI	35	32.27
55-1 -NI	15	21.69
85-3/4 -NI	37	29.56
85-1 -NI	18	25.17

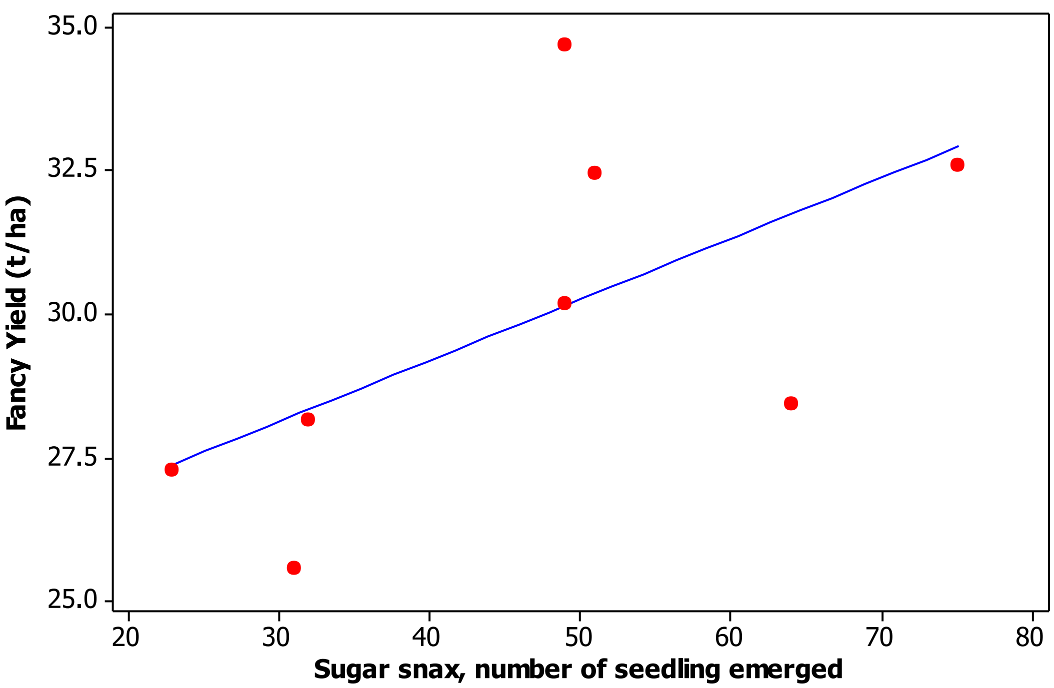

Figure 54: Regression model fitted for Sugar snax fancy yield and number of seedling emerged, regression equation is Fancy Yield = 24.93 + 0.1063 SE.

Regression analysis between Sugar snax fancy yield and number of seedling emerged showed a positive linear relationship which is mildly significant (P = 0.115, R^2 = 36.1%) (figure 54).

Table 38: Sugar snax seedling emergence and yield of Fancy grade with respect to three different treatments (figure 54) in 2012.

Sugar snax treatments (respectively seeding rate, depth and irrigation)	Number of Seedling Emerged	Yield (t/ha) of Fancy grade
55-3/4 - I	49	30.15
55-1 - I	32	28.14
85-3/4-I	75	32.56
85-1-I	49	34.67
55-3/4 -NI	51	32.44
55-1 -NI	31	25.56
85-3/4 -NI	64	28.42
85-1 -NI	23	27.25

5.6 Discussion

Seedling emergence of baby carrots considered within first 13 days after seeding, was significantly influenced by genotype or variety (P = <0.0001) and seeding rate (P = <0.0001) under field conditions. Variety, Honey snax showed the highest mean seedling emergence whereas Upper Cut showed the lowest mean seedling emergence (table 21), despite the rate and depth of seeding were kept similar. Variety Honey snax is the smallest seed with low weight out of all five varieties (table 17) and seeds may have more negative moisture potentials thus able to imbibe compared to other three varieties. Therefore, it may possess properties of quick emergence even under drought conditions due to lack of moisture requirement to initiate seedling emergence and moisture potential difference between seed and environment. This suggests that Honey snax has the capability to maintain significantly higher mean seedling emergence during both years under irrigated and non-irrigated conditions at 85 seeds/ 30 cm rate. Effect of seeding rate showed a significant influence on the highest mean seedling emergence suggesting that the higher seed population may have enhanced the collective ability of seedlings to exert more pressure through soil even on dry crusted soils. Previous studies found that there is a reversible moisture sensitive block in germinating carrots which prevents germination of carrot seeds in drying soils (Ross and Hegarty, 1979; Finch- Savage and Phelps, 1993; Finch-Savage et al., 1998) and then, they have the ability to resume germination following rain or irrigation (Finch- Savage et al., 2001). When it comes to seedling vigour, variety Triton showed the highest dry matter content, 5 weeks after seeding and at the initiation of bulking stage (8 weeks after seeding) in year 2011 under both irrigated and non-irrigated conditions suggesting Triton may have the ability for a following seedling emergence after receiving favorable weather conditions (e.g. rainfall) and also to recover in its post emergence growth. This can be due to possession of the highest seed weight (table 17) and its large size out of all other four varieties and composition of more reserved food in cotyledons.

Even though, Honey snax showed a significantly higher seedling emergence, dry matter accumulation, 5 weeks after seeding and at bulking stage was low (except dry matter amount at 85 seeds/ 30 cm rate under irrigated conditions) compared to Triton. Since seeding depths were 1.9 cm and 2.5 cm, when seedling emerge in both irrigated and non-irrigated treatments seeds may have used their food reserves to elongate hypocotyl and to penetrate soil crusts reducing Honey snax post emergence growth and photosynthesis.

Effect of seeding rate and irrigation on total root yield were not statistically significant, while variety (P = <0.0001) and seeding depth (P = 0.012) showed a significant influence on total yield. Triton showed the highest significant mean total yield at 2.5 cm (1”) seeding depth. ANOVA carried out to test whether any of above treatments have a significant influence on yield of Fancy grade showed effect of variety (P = <0.0001) and seeding rate (P = 0.0175) on Fancy yield were significant whereas seeding depth*seeding rate showed a mildly significant (P = 0.0758) influence on Fancy yield. Again, Triton showed the highest significant mean Fancy yield at the seeding rate of 85 seeds/ 30 cm. In the absence of rain hydraulic conductivity of surface layers of soil can fall to a very low level but at the same time this can reduce the rate of moisture losses from deeper layers of soil (Lascano and van Bavel, 1986). Although, Tamet et al., 1996, mentioned that there was no direct influence of seed weight on relative growth rate, pre-emergence seed reserve dependent growth of carrots and final length of seedling depends on seed weight (Tamet et al., 1996). According to these findings, only more vigorous carrot seedlings emerging from vigorous seeds have the ability to penetrate soil. Carrot seeded 2.5 cm deep, hypocotyl needed to extend > 1 cm within soil before reaching the soil surface, which can possibly reduce subsequent growth and or reduce the ability to penetrate soil (Tamet et al., 1996). Triton demonstrated the ability to recover its growth, which may be due to its high seedling vigour. On the other hand, deeper seeding (2.5 cm) can prevent drying of seeds due to surface soil drying as a result of lack of rain or higher soil temperatures (Finch- Savage et al., 2001). In this study, Triton showed the significantly highest yield at 2.5 cm seeding depth. Tamet et al., 1996, found 3 cm depth as the beginning of the drop of emergence forces of carrots. Triton showed the highest Fancy yield at 85 seeds/ 30 cm rate, which suggest that higher seedling population densities have the ability to exert more pressure on crusted soil rather than less number of seed populations, without losing much of their vigour before emerging. Seeding rate 85 seeds/ 30 cm showed a significant impact on percentage seedling emergence as well as the yield of Fancy grade, suggesting this can be the ideal seeding rate to produce fancy grade (roots having diameter 1.3 – 1.9 cm) under field conditions. With lower seeding rates (55 seeds/ 30 cm), there is a possibility to produce oversize roots as explained in Rajasekaran et al., 2006.

In this study Honey snax was identified as the second best variety, after Triton in terms of seedling emergence, total yield and Fancy grade yield. Considering overall performances of five genotypes, variety Triton has the best ability to recover over time under irrigated and non-irrigated conditions producing the highest root yield at the end compared to Honey snax. Use of primed or enhanced seeds (of Honey snax) did not make a significant difference in seedling emergence, total yield or Fancy grade yield.

Relationship between total yield and number of seedling emerged (15 days after seeding) showed a cubic relationship for all five varieties but that relationship was not statistically significant at 5% level but Honey snax enhanced showed a mildly significant relationship suggesting increasing number of seedling may not be the only reason to increase total yield since there is a possibility to loss of vigor after emergence. However, ANOVA showed a significant influence of seeding depth on total yield. In this regression analysis two seeding depths at two seeding rates, irrigated and non-irrigated conditions were used due to lack of data points and it clearly showed total root yield of carrots were high at seeding depth 2.5 cm (Figure 47 and table 31), irrespective of seeding rate (number of seedling emerged 15 DAS).

Relationship between Honey snax fancy yield and number of seedling emerged showed a significant (P = 0.04) cubic relationship suggesting increasing number of seedling emerged up to 50 may increase Fancy yield and then Fancy yield may remain constant up to 65 with increasing number of seedlings but increasing number of seedling emerged beyond 65 showed a rapid increase in Fancy yield suggesting higher seedling populations may have the ability to minimize the chance of producing oversize roots. Upper cut fancy yield and number of seedling emerged showed a significant (P = 0.001) linear relationship at 5% level suggesting increasing number of seedling emerged may increase yield on Fancy grade.

There were few defects observed in harvested carrot roots (figure 55) such as multi roots or forking (figure 55a), root split or clean split (figure 55b) and twisted roots (figure 55c). Out of these three, forking of roots can occur due to physiological barriers in soil or growing medium which can be avoided by using fine textured seed beds. Clean split is a physiological defect that occurs due to moisture stress at the time of seedling emergence. When soil moisture potential is < -800 kPa (under laboratory conditions in polyethylene glycol/ PEG) radicle tip turned to brown and regrowth occurred in a second initial. Production of split roots is the consequence of partial drying of newly germinated roots (Globerson and Feder, 1987). Twisted roots can be occurred due to competition for space at higher seedling populations. These roots at harvest reduce the value of carrot crop since they cannot use for any purpose. Therefore, it is always advisable to have lower percentage of these defects and models developed for seed germination and emergence can be used to avoid interruptions to seedling growth due to drought and thereby to prevent root damage.

Figure 55: Root defects, a-Forking or Multi roots, b- Clean split, c-Twisted roots.

5.7 Conclusion

Variety Triton showed the highest mean total root yield and Fancy grade yield out of all 5 varieties. Even though number seedling emergence was low 15 days after seeding compared to Honey snax, Triton has the ability to recover post emergence growth over time under both irrigated and non-irrigated conditions. Use of Enhanced (primed) varieties under field conditions did not make any significant difference in seedling emergence, total root yield or Fancy grade yield. Fancy grade recovery of Triton at 85 seeds/30 cm and 2.5 cm depth was roughly around 75%.

According to hypothesis of this experiment, only variety and seeding rate have a significant influence on seedling emergence, only variety and seeding depth have a significant influence on total carrot yield and only variety and seeding rate showed significant influence on fancy yield at 5%, but there was a mildly significant influence of seeding depth* seeding rate on Fancy yield (P = 0.07).

There was a significant cubic relationship between fancy yield of Honey snax and number of seedling emerged whereas fancy yield of Uppercut showed a significant linear relationship with number of seedling emerged. Relationship between total yield and number of seedling emerged was not significant statistically for all five varieties at 5% level, but there was a mildly significant relationship between Honey snax enhanced total yield and seedling emergence.

Undersize carrots do not use for processing and sliced grade do not consider as a baby grade. Thus, management practices that give higher fancy grade should be followed during farming to have a successful IQF baby carrot industry.

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Chapter 6

General Discussion

The effect of soil moisture on seedling emergence (SE) was significant and lower more negative soil moisture reduced seedling emergence significantly at or below -120 kPa. When moisture potential (Ψ) was -156 kPa, carrot seedling emergence was totally inhibited while Ψ above -120 kPa did not show a significant influence on carrot seedling emergence and completion. Therefore, -120 kPa can be considered as the base water potential (Ψ_b) for baby carrot SE and Ψ above the Ψ_b, did not show any significant influence on SE. Finch-Savage et al., 1998, was also identified that carrot seed germination and post germination growth were unaffected by Ψ as long as moisture level of soil remained above Ψ_b. Emergence velocity was significantly low at - 5 and -90 kPa suggesting, both excess availability of soil moisture as well as moisture deficits can negatively influence seedling emergence. Excess soil moisture can reduce soil air and available O_2 while lack of soil moisture can delay seed imbition and biochemical reactions which needs to break down stored food.

Effect of temperature on seedling emergence was highly significant and SE was delayed at 5 °C whereas SE was totally inhibited at 35 and 40 °C. The best temperature range for seedling emergence was identified as 15 – 20 °C and the highest emergence velocity (EV) was observed at 20 °C. Carrots as a temperate type vegetable may have evolutionary adapted to respond extremely low and high temperatures while inhibiting or lowering biochemical reactions or enzymatic activities within the seed or emerging seedlings under extremely temperatures. Thus, threshold temperatures for carrot seedling emergence may be 5 (lower) and 30 °C (upper). Thermal Time (TT) can be used to better explain the effect of temperature on Initiation (ISE) and completion (CSE) of SE since TT was calculated using number of days taken to emerge and complete SE at different set temperatures. Both SE and completion needed minimum number of heat units for ISE and CSE and therefore, seedling emergence was delayed at 5 °C, until seeds accumulate required amount of heat units to initiate biochemical reactions within seeds. Regression models fitted for TT were also suggested that increasing TT can increase SE and EV up to 300 °Cd but beyond this, SE can be negatively influenced by increasing TT. TT models were developed for SE and EV and they were validated using year 2011 and 2012 field experiment data. These models will be useful in predicting SE under field conditions and avoid periods with extreme temperatures. Also, this field experiment followed organic practices such as crop rotation, incorporation of previous crop residuals during tillage and use of organic fertilizers, allowing these models to be used even in organic carrot fields.

Carrot SE and completion of SE was not significantly affected by interactive effect of soil moisture and temperature. This can be mainly due to effect of soil moisture above Ψ_b, on SE was not statistically significant whereas effect of temperature played a major role in carrot seedling emergence, fixing threshold levels for ISE or CSE. However, when ambient temperature is high there is a tendency to rapid drying of surface soil which may suggest an interactive effect of soil moisture and temperature but based on the results of this study, there is more chance to inhibit or decline SE at warmer temperatures before the effect of drying soil and also Ψ_b can be changed depending on ambient temperature. Nonetheless, these results are based on only two temperatures (20 and 30 °C) and five Ψ (-5, -20, -30, -40, -60 kPa). Effect of temperature and soil moisture at or below Ψ_b on SE is also difficult to explain with these results.

Carrots grown under field conditions showed that effect of irrigation on carrot SE, total yield and Fancy grade yield was not significant. Following proper management practices; seeding rate, 85 seeds/30cm and depth, 2.5 cm and also by selecting suitable genotypes (Triton or Honey Snax), can overcome abiotic stresses such as soil drying and crust formation. Regression analysis between SE and total yield did not show a significant relationship but it suggested total yield was higher at 2.5 cm seeding depth, irrespective of number of seedlings merged or seeding rate. Regression analysis between SE and Fancy yield showed a significant linear relationship with Upper cut and cubic relationship with Honey snax suggesting, increasing number of seedlings may increase yield of Fancy grade. However, this study did not provide enough data points to conduct regression analysis using only seeding depth or seeding rate to test the relationship with total yield and Fancy yield, although ANOVA showed that main effect of seeding depth and seeding rate have significant influences on total yield and Fancy yield respectively.

6.1 Future Research Needs

1. Experiments can be designed to test the interactive effect of soil moisture and temperature on seedling emergence using wide range of temperatures and soil moisture potentials closer to Ψ_b . It is advisable to add more moisture potentials below – 90 kPa since the influence of moisture potential below – 90 kPa was significant.

2. Since the effect of seeding depth on total yield was significant, it is also suggested to test total yield for at least 7 different seeding depths to understand its relationship to total yield.

3. Further, effect of seeding rate on Fancy yield was also significant and to understand relationship between seeding rate and Fancy yield, it is advisable to use at least 7 different seeding rates.

4. Finally, since field experiment for 2011 and 2012 was conducted in the same location, Bill-Town, Kentville and I would suggest to choose two locations may be from two provinces to see the effect of abiotic and/ or biotic stresses, on baby carrot production as well as to understand how these findings can be varied depending on location

5. Moisture experiment and temperature experiment showed a moisture reduction within containers overtime and this can be corrected using computer operated system to maintain appropriate moisture potentials within the experimental units.

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Appendix 1: Soil test results for the carrot field of the field experiment conducted in Billtown, Kentville.

Soil Test	Year 2011	Year 2012
Soil pH	6.20	6.00
Organic Matter (%)	2.60	2.50
P_2O_5 (Kg/ha)	910.00	1169.00
K_2O (Kg/ha)	472.00	452.00
Ca (Kg/ha)	2311.00	2225.00
Mg (Kg/ha)	499.00	298.00
Na (Kg/ha)	34.00	48.00
S (Kg/ha)	34.00	22.00
Al (Kg/ha)	1602.00	1511.00
Fe (Kg/ha)	253.00	180.00
B (ppm)	0.50	0.67
Cu (ppm)	0.92	2.58
Mn (ppm)	46.00	31.00
Zn (ppm)	2.56	2.80
Cation Exchange Capacity	9.8	11.1