EFFECTS OF WATER STRESS ON TOMATO AT DIFFERENT GROWTH STAGES

BY

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ABSTRACT

M.Sc. Agricultural & Biosystems Engineering

MOLLA MD NURUDDIN

Effects of Water Stress on Tomato at Different Growth Stages

The study sought to identify the effects of deficit irrigation on the yield and quality of tomatoes. A greenhouse experiment was conducted during the summer of 1999 and repeated in winter 2000 using nine treatments. Two threshold soil moisture deficit levels, 65% and 80% depletion of plant available water, were factorially combined with 5 irrigation timing patterns: (i) no water stress (ii) stress throughout season, (iii) stress during flowering and fruit set (iv) stress during fruit growth and (v) stress during fruit ripening. The treatments were set up in a randomized complete block design with 4 replicates. Crop yields, maximum and minimum equatorial diameter and fruit heights were measured. The quality parameters included: soluble solids, pH and the color index. Water stress throughout the growing season significantly reduced yield and fruit size but increased the level of soluble solids. No water stress throughout the growing season or stress only during the flowering stage provided highest tomato yield.

RESUME

M.Sc. Génie agricole et des biosystèmes

MOLLA MD NURUDDIN

Effet d'un stress hydrique appliqué à différents stades de croissance sur la tomate

Cette étude visa à identifier les effects d'une irrigation déficitaire sur le rendement et la qualité de la tomate de serre. Une expérience en serre, comportant neuf traitements, fut entreprise à l'éte 1999 et répétée durant l'hiver 2000. Deux niveaux de déficit en eau disponible, soit de 65% ou de 80%, auquels une irrigation jusqu'à la capacité au champ fut imposée furent combinés en un plan à facteurs multiples avec cinq modes d'irrigation: (i) aucun stress hydrique, (ii) stress hydrique durant toute la saison, (iii) stress hydrique seulement durant la floraison et nouaison, (iv) stress hydrique seulement durant la croissance du fruit, (v) stress hydrique seulement durant le mûrissement. Les deux traitements sans stress furent consolidés en un seul traitement, et les 9 traitements restants furent organisées en un dispositif à blocs aléatoires complets avec 4 répétitions. Le rendement, le diamètre équatorial maximum et minimum, ainsi que la hauteur des tomates furent mesurés. La qualité des fruits fut évalue en mesurant l'extrait sec soluble, le pH, et l'indice de couleur. Le stress hydrique durant toute la saison reduisi le rendement et les dimensions des fruits de façon significative, mais haussa le niveau d'extrait sec soluble. Le rendement le plus élevé fut enregistré sans aucun stress durant toute la saison et pour les plantes ne recevant de stress hydrique qu'à la floraison/nouaison.

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NOMENCLATURE

A	Ampere
AM	Arbuscular mycorrhizal
ANOVA	Analysis of variance
AW	Available water
BER	Blossom end rot.
BORD	Border
Ca	Calcium
CWSI	Crop water stress index.
DI	Deficit irrigation
DOY	Day of the year
DSS	Decision support systems
EC	Electrical conductivity
ET	Evapotranspiration
ET_c	Crop evapotranspiration
FC	Field capacity
F_{65}	65% moisture depletion at flowering stage
F_{80}	80% moisture depletion at flowering stage
FGR_0	Full irrigation throughout the season
FGR_{65}	65% moisture depletion throughout the season
FGR_{80}	80% moisture depletion throughout the season
F_m	Fluorescence maximum level
F_0	Fluorescence initial level
F_v	Variable fluorescence
G_{65}	65% moisture depletion at growth stage
G_{80}	80% moisture depletion at growth stage
K_a	Dielectric constant
K_c	Crop factor
LSD	Least significant difference
MDL	Moisture depletion level
PAW	Plant available water
P_r	Photosynthetic rate
P_n	Net photosynthetic rate
RCBD	Completely randomized block design
R_{65}	65 % moisture depletion at ripening stage

R_{80}	80 % moisture depletion at ripening stage
R_s	Stomatal resistance
SAW	Soil available water
SPAC	Soil-plant-atmosphere continuum
SWC	Substrate water content
T_a	Air temperature
T_c	Canopy temperature
TDR	Time domain reflectrometer
TEM	Time of electromagnetic mode
TCI_f	Tomato color index of whole fresh fruit
T_r	Transpiration rate
T_l	Leaf temperature
V	Voltage
VPD	Vapor pressure deficit
W	Watt
WUE	Water use efficiency
Ψ_w	Water potential
Ψ_m	Matric water potential
Ψ_o	Osmotic water potential
Ψ_p	Pressure water potential
Ψ_g	Gravitational water potential
η_D	Index of refraction
θ_A	Quinone type acceptor
θ_{fc}	Moisture content at field capacity
kPa	Kilo Pascal
θ_{pwp}	Moisture content at permanent wilting point
θ_v	Volumetric water contents

CHAPTER I

INTRODUCTION

A growing scarcity of water relative to human demand is evident in many parts of the world (Postel, 2000). Extracting more fresh water for agriculture, industry or cities presently threatens the health of aquatic ecosystems. Food production is a very water intensive activity. Doorenbos and Kassam (1979) reported that for 1 Mg of edible grain, 1 Gg water was used in the form of soil moisture. An additional 500 km^3 (equivalent to 28 times the annual flow of the Colorado river) will be needed to produce the food required to feed the world population in 2025 (Shiklomanov, 1996). It will be very difficult to provide this additional irrigation water on a sustainable and ecologically sound basis. Water management practices are the tools which can serve to protect our natural capital in water resources and avoid the critical situation for the survival and sustainability of agriculture and economic activities which would ensue from their decline (Postel, 2000).

Although only 20% of all cultivated land in the world is under irrigation, water is required in 35-40% of all crop production. Because of the higher yields under irrigated agriculture, investments for irrigation are usually a top priority. However, it has become a matter of serious concern in recent years that, in spite of their high costs, the performance of many irrigation systems has fallen short of expectations. This has been a result of inadequate water management at both farm and system levels. Consequently, increases in crop production have been well below the projected targets (Kirda et al., 1998).

Water deficits and insufficient water are the main limiting factors affecting worldwide crop production. While these are truisms, the importance and relevance of studying soil-plant–water relations are not diminished in the least. A better understanding of how soil-water deficits affect plant growth, nutrition, and water use is fundamental to the development of techniques to minimize the negative effects of this stress.

No horticultural crop has received more attention and detailed study than tomato (Lycopersicon esculentum Mill.). It is a model crop for many experimental studies and the knowledge and information gathered from these studies have contributed to the dramatic improvements in production that have occurred during this century (Tigchelaar and Foley, 1991).

In addition to its economic importance, the tomato is an ideal research material for physiological, cellular, biochemical and molecular genetic investigations. It is easy to cultivate, has a short life cycle and is amenable to varied horticultural manipulations, including grafting, or cutting. Various types of explants can be cultured in vitro and plant regeneration is feasible, allowing the development of transformation procedures (Hillel et al., 1990).

In many regions, irrigation accounts for a large proportion of total irrigation water use for all purposes (Van Schilfgaarde, 1994). Deficit irrigation (DI) could help not only in reducing production costs, but also in conserving water and minimizing leaching of nutrients and pesticides into ground water. In water-limiting production systems, establishment of DI as a management tool for tomatoes could be very effective in this respect, because, as a popular vegetable, tomatoes are planted extensively throughout the world. However, before DI can be adopted as a management tool, its effect on fruit yield and quality should be examined. Water management is a very important aspect of tomato production. The primary aim in water management is to make the most effective use of available water for crop production.

Irrigation is a costly agricultural input, so its judicious application is necessary. With this in view, it was felt necessary to study the response of tomato plants to both quantitative and temporal variation in soil moisture. By restricting moisture at a non-susceptible phenological stage it may be possible to reduce irrigation water quantity and increase water-use efficiency (WUE). Water–use efficiency is defined as the marketable yield (kg) produced per unit amount of water (m^3) applied, and reflects the characteristics of the irrigation method adopted and the volume of irrigation water applied.

1.1. Objectives of the study:

The objective of this study was to clarify the soil moisture depletion that can be allowed in irrigating tomatoes with a view to maximizing production as well as water use efficiencies. The specific objectives of this study are to:

i) Determine the effects of water stress at different phenological stages of tomato plant development.

ii) Determine the influences of water stress on yield, biomass and quality of tomato.

CHAPTER II

LITERATURE REVIEW

2.1. Irrigation and world food demand

The present world population of 5.3 billion is projected to increase to 9 billion over the next 40 years. Developing countries account for 95% of this growth. Therefore, world food production will need to more than double in the next few decades to feed everyone. To meet this expanding food demand yields and acreage must be increased. The potential for expanding food production in the world exists (Luis et al., 1996). Food security in the world is one of the most important goals of our time. One tool to achieve these goals is irrigation. Appropriate irrigation technology has an important role to play in the achievement of this goal.

Irrigated land, about 250 million ha, which makes up about 17% of the total area cropped worldwide. These areas provide 36% of the world's food production. Almost 75% of the irrigated area is in the so-called developing countries. North Africa and the Near and Far East account for 90% of this area. Differences in the level of irrigation technology between these areas and developed countries are due to climatological, historic and socio-economic influences (Field, 1990).

2.2. Soil-plant-water relationships

Boyer (1985) recently reviewed the subject of pathways for water flow in plants. The driving forces for water flow in the soil-plant-atmosphere continuum (SPAC) is a difference in water potential. Water potential (Ψ_w) is the potential energy per unit mass, volume, or weight of water. Water potential is the sum of several component potentials.

$$\Psi_w = \Psi_m + \Psi_0 + \Psi_p + \Psi_g \quad \text{.......(2.1).}$$

Where the subscripts, m, o, p and g are for matric, osmotic, pressure, and gravitational potential components. Different components of the water potential are important at different points in the transpiration stream. Water flows in soil to absorbing plant roots mainly from points of high to low matric potential. As water flows from the soil into the root, living membranes, probably at the endodermis, control the flow of solutes and maintain osmotic potential differences between the soil and the root xylem. Osmotic and matric potentials outside the root are therefore important components of the water potential, while the water potential inside the root is primarily due to low pressure or tension in the xylem water. Matric forces provide the driving force for flow through cell walls.

Within plant tissues, water in cell walls is thought to be in equilibrium with the water in the cells but resistance to water flow from cell to cell is thought to be quite high, so differences in water potential between xylem and sites of evaporation can be substantial (Boyer, 1985).

Plant resistance to water uptake can sometimes be inadvertently altered by an irrigator, with deleterious effects to the crop. Since water crosses living membranes, resistance to water flow can be altered by practices which reduce the root respiration rates. Irrigation can cool the soil as well as decrease its oxygen content. Root respiration is reduced in both cases, and increased root resistance can result. It is therefore possible to cause water stress with too much water as well as with too little (Campbell and Turner, 1990).

2.2.1. Water and the Root Zone.

In container crops, the entire root zone is located in a pot. To meet the water demands, air, nutrition, and physical support, the soil mix of the rooting zone in such ground beds is generally designed within specific parameters. It is rare that the soil where the greenhouse is built has exactly the desired properties. To achieve desired soil characteristics the ground beds are generally replaced with a specific rooting mix.

Plants that are grown in containers have a much smaller root zone than in-ground plants which makes the design of the rooting medium more critical. Container media need to have a high infiltration rate, high water holding capacity, high hydraulic conductivity, and high air-filled porosity.

2.3. Irrigation scheduling

Irrigation scheduling concerns the farmers decision process concerning "when" to irrigate and "how much" water to apply in order to maximize profit. Knowledge on crop water requirements and yield responses to water, limitations relative to the water supply system and the economic implications of the irrigation practice are very important in this regard. Irrigation scheduling becomes a very complex decision-making process. In third world countries, only a few farmers can understand and therefore adopt this technology (Pereira et al., 1995).

There exists a large number of tools including procedures to compute crop water requirements by simulating the soil water balance, to estimate the impact of water deficits on yields and to estimate the economic returns of irrigation (Hoffman et al., 1990). Notwithstanding the vast number and variety of tools existing irrigation scheduling is not yet used by the majority of farmers. In fact, limited irrigation information is utilized worldwide by irrigation system managers, extensionists or farmer advisers.

Martin et al. (1990) and Todd and Heerman (1988) defined irrigation scheduling as the science of specifying future irrigation timing and amounts in the implementation of a water management strategy. If the proper amount of water is applied at the most appropriate time, water is not wasted and the crop yield will be optimum. Hillel (1990) stated that soil water dynamics should be well defined to regulate the water supply of water crops. A growing plant must be able to balance the atmospheric demand for water with the amount it can extract from the soil.

Phene et al. (1990) stated that irrigation scheduling involves two major decisions: how much water to apply and, when to apply water (frequency). Irrigation timing is usually based on soil water measurements, soil water accounting or various combinations of these methods. Irrigation quantity is usually based on the type of irrigation system, plant responses to water deficit, plant growth stage, soil infiltration characteristics, salinity control and soil water deficit (Phene et al., 1990).

2.3.1. Water conservation in irrigation scheduling

Water usage increases along with the expansion of agricultural activities. Higher irrigation efficiency is needed due to the competition between agriculture and industry for available water. As crop dry matter production is strongly influenced by available soil moisture, better irrigation is required to obtain the optimum yield (Wesseling and Van den Broeck, 1988). Joshi et al. (1995) stated that a water-efficient system is a basic tool for maximizing crop production. Salisu (1989) stated that irrigation scheduling is the technique, which enables an irrigator to know when to irrigate the crop and how much water to apply.

Several methods and techniques are used to predict the date and amount of irrigation water to apply (Heerman et al., 1990). A variety of methods and devices are available for irrigation scheduling. These methods are based on i) soil monitoring ii) crop monitoring iii) soil water balance computations and iv) meteorological methods and finally v) computer simulation approaches.

2.3.2. Modern irrigation scheduling

2.3.2.1. Simulation modeling

A number of simulation models are being used for the soil-water-plant atmosphere relationship as it relates to crop water requirements (Coleman et al., 1987; Nwabuzor, 1988). These models include weather records, for budgeting soil water content and evapotranspiration. In irrigation scheduling soil moisture and crop growth simulation models are successfully used (Foroud et al., 1992; Mastrorilli et al., 1992). Computer based irrigation scheduling models are one of the most effective techniques to improve irrigation efficiency (Field et al., 1988; Wesseling and Van den Broeck, 1988).

2.3.2.2. GIS and Remote sensing techniques

Recently irrigation scheduling are being done upon the availability of computerized soil, agro-climatic and land use data and remotely sensed data. Hashemi et al. (1994) and Knox et al. (1996) stated that the development of geographic information system (GIS) as a data interpretation and spatial analysis tool makes it possible to predict changes in land use and for irrigation practices to be modeled and mapped, either nationally, regionally or even at a river or catchment level. Remote sensing techniques were used with a barley crop to monitor the irrigation scheduling over the region. Also computerized decision support systems (DSS) for field level water and crop management are used nowadays. DSS reduces time to analyze and reduces the human error and inconsistency (Plant et al., 1992). To predict the timing and magnitude of irrigation needed for a given crop, neural network programming is also being used (Williams et al., 1996).

2.4. Crop yields under deficit irrigation

Water is a vital substrate in the photosynthetic process. Crop production as well as plant growth are restricted by water scarcity. If deficit irrigation programs are in practice, throughout the growing season or during a particular growth period, plants are exposed to specific levels of water stress. This occurs where evapotranspiration demand or crop water requirements are significantly reduced. Close to optimum yields can be obtained under deficit irrigation, providing a specific amount of yield reduction of a given crop with a certain amount of water-saving. The saved water can be used in irrigating other areas or crops. This innovative concept has been given different name such as deficit irrigation, deficient evapotranspiration (ET) or irrigation and limited irrigation (English et al., 1990).

At present deficit irrigation is widely used. Deficit irrigation programs can allow the increase of irrigated area with a given quantity of water. Under deficiency irrigation practices, irrigated area can thus be increased without applying additional water where crop WUE is the highest. If there is a scarcity of water at the regional level, irrigation managers should adopt the same approach to manage their irrigation schemes to sustain regional crop production and the well-being of growers (Kirda and Kanber, 1998). This practice ensures optimum and sustainable agricultural production in a given region as well as maximizes the income of the growers when sources for irrigation water are limited or expensive (Stegman et al., 1980).

Reduction in irrigation water may lead to a decline in crop production; however, the benefits gained by diverting the water saved by deficit irrigation to irrigate other areas or other crops for which water is not sufficient to fill demands under normal irrigation practices, frequently outweigh yield losses of the original crop. It should be kept in mind that yield reduction due to plant diseases and pests, improper fertilization of fields and losses during harvest and storage are much greater than those one might expect under a mild deficit irrigation. Crop quality may increase with proper deficit irrigation practice. It has been observed that protein content and baking quality of wheat (Triticum aestivum L.) fiber length and strength of cotton (Gossypium hirsutum L.) and sugar concentration of sugar beet (Beta vulgaris L.) and grape (Vitis vinifera L) increase under deficit irrigation (Kirda and Kanver, 1998).

2.4.1. Dry matter production and water use

Tanner and Sinclair (1983) provided a useful method for predicting the effect of water deficit on dry matter production. The method is based on the observation that the substomatal CO_2 concentration of many species remains relatively constant even though environmental conditions may be highly variable (Wong et al., 1979). If it is assumed that the internal CO_2 concentration of a leaf remains relatively constant over the growing season, and that the temperature of the canopy is near air temperature, then Tanner and Sinclair showed that the rate of dry matter accumulation is equal to a constant multiplied by the transpiration rate and divided by the vapor pressure deficit (VPD) of the air. This is a very useful relationship for irrigation scheduling based on water stress. If irrigation were practiced for the purpose of minimizing losses in crop production, then a useful stress index would be a measure of the extent to which this goal has been met (Campbell and Turner, 1990).

A suitable dimensionless stress index might be:

$S = 1 - (P/P_m)$ ....(2.2)

Where P is total dry matter production and P_m is the dry matter production when no water stress has occurred. Using the Tanner-Sinclair relationship, equation 2.2 can be written as

$S = 1 - T/T_m$. ....(2.3)

Where T and T_m represents crop transpiration with and without water stress.

2.5. Water stress measurement

A variety of methods including, soil matric potential sensors, plant canopy temperatures with non contact infrared thermometer, crop water stress index (CWSI), stem diameter changes, leaf water potential, stomatal conductance and transpiration are currently used to monitor the water stress. The CWSI method is useful to schedule/ control irrigation or characterize water stress in tomato plants (Calado et al., 1990).

2.5.1. Crop Water Stress Index (CWSI)

Plant temperature has been long recognized as an indicator of water availability (Tanner, 1963). Kumar and Tripathi (1989) calculated CWSI from canopy (T_c) and air temperature (T_a) and VPD derived by infrared thermometer and dry-and-wet-bulb air temperature, respectively. They measured pertinent variables between 1330-1400 hr in four experimental wheat plots, with 0, 2, 3, or 5 post-emergence irrigations to create different degrees of water stress. Their study proved that CWSI is a reasonably quantitative evaluator of crop water stress and may provide an early warning of stress condition. Many scientists like Idso et al. (1977) and Jackson et al. (1977) have also used the difference in temperature between canopy and air (determined by infrared thermometry) as an index of crop water status. Their assumption was that environmental factors such as vapor pressure deficit, net radiation and wind would be largely manifested in the temperature difference. As this assumption was generally made for a severe water stress, Idso et al. (1981) developed the CWSI to account for this and reported that the CWSI was indicative of the "soil induced " plant water potential depression in wheat. Keener and Kircher (1983) and Reginate (1983) reported that CWSI was a good index for scheduling irrigation and estimating crop yield of many crops like corn, cotton, etc. Katerji et al. (1988) conducted an experiment on a tomato crop (cv. H30) grown at Coruche (Portugal) in order to test the usefulness of several plant and microclimate parameters as water stress indicators. Pre-dawn leaf water potential and stomatal conductance was very sensitive indicators of water stress. The most sensitive and easily determined of the indicators was, however, pre-dawn leaf water potential.

2.6. Tomato

Tomato is the second most important vegetable crop next to potato (Solanum tuberosum L.) in terms of production. It is a rapidly growing crop with total growing period varying from 90 to 150 days. It is a day-neutral plant. Tomato can be grown in a wide range of soils but a well-drained sandy loam with pH of 5 to 7 is preferred. Waterlogging leads to incidence of diseases such as bacterial wilt. The ideal population is about 40000 plants/ha and fertilizer requirements for high yielding varieties vary from 100 to 150 kg/ha N, 65 to 110 kg/ha P, and 160 to 240 kg/ha K, depending on the soil test. The crop has a fairly deep root system reaching as far as 1.5 m. The maximum rooting depth occurs about 60 days after transplanting resulting in a maximum ET of 5 to 6 mm/day. The plants are adversely affected when more than 40 percent of the total available soil water has been depleted (Doorenbos and Kassam, 1979).

Tomato is an important crop throughout the world in wide range of climatic conditions. In the Northern Hemisphere, in the winter and spring it is mainly cultivated inside greenhouses. Heating and CO_2 enrichment are current practices allowing higher yields during the resultant ten month indoor culture periods (Atherton and Rudich, 1986).

2.6.1. Growth stages and soil moisture

The tomato needs a controlled supply of water throughout the growing period for optimal quality and higher yield. Imposing DI in vegetative and ripening stages means a certain amount of water may be saved but tomatoes are very sensitive to water deficits during and immediately after transplanting, at flowering and during fruit development (Doorenbos and Kassam, 1979).

Tomatoes consume water at a lower rate at the beginning of growth and then increase gradually until flowering, after which they reach maximum usage during the peak of fruit ripening. Water consumption remains constant until the onset of ripening after which, in determinate varieties, it decreases (Rudich and Luchinsky, 1986). The approximate range of seasonal ET for tomatoes is 300 mm to 600 mm. This seasonal value takes into account the crop characteristics, time of planting, and stage of crop development and general climatic conditions (Doorenbos and Pruitt, 1977). According to Rudich et al. (1977), the growing season is divided into five stages.

1- Germination, emergence and establishment of the plants
2- Vegetative growth stage (end of stage 1 to flowering)
3- Reproductive growth (until first full size mature green fruit)
4- Fruit development (until 20% of fruit changes color)
5- Ripening stage

2.6.2. Germination stage

Through the germination process nutrients come primarily from within the seed, but once new cells become specialized, the seedling will seek nourishment from its surroundings (McCollum, 1980). Various seeds have different tolerances to dehydration and can be stored in dry conditions for several years. Generally, the newly generated tissue is more susceptible to dehydration after the seeds have germinated and the vacuolating of root cells occurs. Dorey (1980) reported that tomato seeds need a suitable amount of water and adequate supply of oxygen just after the germination has started.

2.6.3. Vegetative stage

Under proper environmental conditions when the seed produces a functional plant which has the capability to grow continuously then the seed is considered a fully germinated seed and at this stage the plant reaches the vegetative stage (Janick, 1986). This stage is identified by the most rapid growth rate in the plant's life cycle. There should be a balanced nutrient supply in the soil as well as different factors like soil pH, moisture, bulk density, and temperature, along with light which should be at appropriate levels (Adams, 1990).

In the vegetative stage, root growth is highly influenced by environmental conditions. A good soil environment favors growth of root systems, creating a greater area for nutrient absorption. A high water table limits root penetration at early stages in the growing season and later the shallow root system may not be able to provide the plant's moisture needs during the growing season (Hoffman et al., 1990).

Excessive water (water logging) adversely affects shoot growth by restricting internode elongation, leaf initiation and expansion, by inducing epinasty of leaf and petiole, leaf senescence, leaf chlorosis, and leaf abscission. In flooded tomato plants the stem base often swells. The most common type of root response in flood conditions is the development of adventitious roots on the stem above the soil and usually in the flood zone. When the plants are equipped with these roots it increases the tolerance of flooding and ability to recover more quickly and completely than if the roots were removed (Kozlowski, 1984). Tomato plants tend to grow a denser root system at soil water potentials which are slightly less than field capacity (Mcihelakis and Chartzoullakis, 1988).

2.6.4. Reproductive stage

The final stage of the growth stage is the reproductive stage, and it starts with the first floral primodia being formed (Janick, 1986). As the tomato plant gets older, the genetic control in charge of the flowering process will make the plant more likely to flower. The appropriate environmental conditions like water, light, and temperature are important at this stage in promoting floral initiation. High N inhibits flowering (Walton, 1988). This stage is particularly susceptible to water deficit stress. According to Doorenbos and Kassam (1979), the reproductive stage has a higher crop factor (k_c) than any other growth stage. The effects of water stress on floral initiation are little known, but evidence suggests that drought conditions reduce the number of flowers.

Rudich et al. (1977) observed that irrigation in reproductive and fruit development stages led to a 120% increase in yield. Irrigation caused a vigorous growth in the reproductive stages but has no significant influence on the number of inflorescence, or on the rate of flowering during the 24 days of flowering. Under-irrigation allowed the leaves and fruit to develop normally.

2.6.5. Water requirements of tomato

Few reports dealing specifically with tomato water requirements have been found. Miller et al. (1998) reported the crop evapotranspiration (ET_c) for the semi-arid region of Brazil, using a complete water balance approach. Cumulative Etc was found to be in the range of 451 to 626 mm as soil water tension increased from 300 kPa to 500 kPa, corresponding to 5.22 and 3.76 mm/day, respectively. For an average growing period of 130 days, the net total amount of applied irrigation water ranged from about 300 mm to

400 mm for good fruits in central Brazil (Silva and Marouelli, 1996). Doorenbos and Kassam (1979) reported that total water requirement for a tomato grown in the field for 90 to 120 days are 400 to 600 mm. This amount includes the pre-transplanting watering. Depending on the climatic demands the total water may vary for different locations. The k_c values vary from 0.40 (initial) to 1.25 (mid–season).

Karim et al. (1996) carried out a field experiment to determine the optimum soil moisture regimes and water requirement for achieving the maximum yield potential of tomato on a clayey terrace in Bangladesh. A maximum yield of 37.0 Mg/ha was obtained when allowing 30% depletion of soil available water (SAW). The total water use and the WUE were found to be 193.6mm and 1911 kg/ha/cm, respectively. They also concluded that at soil moisture depletions exceeding 40% of SAW, a severe water stress was placed on growing tomatoes, hence yield was significantly reduced.

Qasem and Judah (1985) found that the water applied and its uptake by plants are decreased with increasing soil moisture tension. Crop coefficients increased rapidly to reach a maximum at flowering, after that they declined. They also observed that the greatest stress (50 centibars at a depth of 30 cm) did not adversely affect the crop since yields were not significantly reduced.

2.6.6. Role of irrigation on different growth stages

Excessive irrigation during the flowering period may cause an increase of flower drop and reduce fruit set as well as delay ripening due to excessive vegetative growth. For preventing stimulation of new growth at the expense of fruit development, water supply during and after fruit set should be limited to certain rate. It must be kept in mind that for a crop grown for paste production, a more extensive irrigation may be applied prior to flowering. But light irrigations improve the size, shape, juiciness and color of the fruit. But total solids and acid content will be reduced. The fruit quality for processing may be lower due to lower solids in the fruit. The yield formation stage is very sensitive to water and any heterogeneous distribution of irrigation leads to fruit cracking. Highest demand for water is during flowering (Doorenbos and Kassam, 1979).

Helyes et al. (1999) conducted an experiment between 1977-1997, using two tomato varieties to observe the effect of irrigation and environmental factors on yield and found that regular irrigation has a vital role for optimum yield. They found that approximately 55-66% regular irrigation is required but in some years 20-25% irrigation can be effective.

Colla et al. (1999) conducted an experiment at three fertilizer levels under drip irrigation treatments. Water deficits were imposed by reducing irrigation volume by 50% or 75% of ET_c (crop evapotranspiration) in two growth periods: before or after fruit set. Water deficit in the first growth period led to a decrease in the number of flowers as well as that of fruit number and ultimately to less marketable yield. However, fruit quality in terms of soluble solids and acidity was improved. Rudich et al. (1977) reported that the quality of tomato can be improved and water can be saved by using well managed drip irrigation systems.

Rudich et al. (1977) found that irrigation during the period of fruit set and fruit development increased yield by 53 t/ha compared with non irrigated plants. They also observed that irrigation during the fruit development had a favorable influence and had an unfavorable influence on fruit quality characteristics like vitamin C, viscosity, acidity and total soluble solids.

More than 90% of the processing tomatoes are drip irrigated in Israel. Recommended irrigation scheduling begins irrigation at fruit set in the second and third inflorescences (15 days after the start of flowering in sown tomatoes), and the end of irrigation when about 50% of the fruits were red (Rudich et al., 1979).

Lowengeart-Aycicegi et al. (1999) conducted a series of trials for these growing seasons in order to observe the optimum timing of the beginning and end of drip irrigation of processing tomatoes and found that delay in beginning of irrigation resulted decrease in fresh yield significantly due to decrease in the number of fruits. However, the soluble solids content was unchanged for different cultivars.

2.6.7. Tomato yields and water stress

Karim et al. (1996) conducted an experiment for the determination of optimum soil moisture regimes and water requirements for maximum yield potential of tomato on clayey soil in Bangladesh. A maximum yield of 37.0 Mg/ha was obtained with total water use of 187.8 mm. A reduction of water depletion from 40% to 30% of SAW did not change tomato yield. But the application of 13.7% greater irrigation water resulted in a 30.7% greater yield. They found that a soil water regime at 40% depletion of SAW produced the highest yield with maximum WUE for tomato. Kalloo (1991) that the optimum moisture regime for tomato cultivation ranged from field capacity (FC) to 50% of SAW.

Rudich et al. (1977) found that irrigation during the period of fruit set and fruit development increased yields by 53 t/ha compared to non-irrigated plants. The application of irrigation water during the period of fruit development had a favorable influence on yield as well as on the efficiency of water utilization. However, they also found that irrigation at this stage had an unfavorable effect on fruit quality characteristics, namely, total soluble solids, acidity, viscosity, and Vitamin C. Losada and Rincon (1994) observed that fruit set of tomato was highly sensitive to water stress.

Rahman et al. (1999) found that water stress decreased yield, flower number, fruit set percentage and dry matter production in all varieties tested. Photosynthetic rate (P_r), transpiration rate (T_r), and leaf water potential (ψ_w) and WUE were reduced, and leaf temperature (T_l) and stomatal resistance (r_s) were increased by water stress in all cultivars.

2.6.8. Tomato quality and water stress

With the consumer's increasing preference for mature and sweet tomato fruit, high sugar content tomato production has increased (Mochizuki et al., 1987). Limitation of irrigation during culture is generally adopted in order to increase the sugar content (Imada et al., 1989). But this treatment affects many physiological processes and the growth and yield apt to decrease along with extended the stress extent (Aloni et al., 1991).

Adams (1990) conducted an experiment with two tomato crops, grown in bags of peat for12 weeks after planting, were supplied with 60, 80, 100 and 120% of the water requirement estimated from solar radiation integrals. Restricting water to 60% and 80%

of the requirements controlled vegetative vigor but reduced final yield by about 20% and 4%, respectively. These decreases were mainly because of a reduction in fruit size rather number. He also suggested that watering should be restricted to 80% or less of the estimated requirements in order to achieve a significant improvement in the flavor components of the fruit.

Veit-Kohler et al. (1999) investigated whether even a small reduction in water supply (without visible symptoms of water stress) results in high fruit quality together with high marketable fruit productions. In the treatment with lower water supply plant growth, and in particular the number of fruit were decreased and the sugar and vitamin C concentrations of the fruits were significantly increased, especially during fruit ripening. The higher levels of sugars, titrable acids, aroma volatiles and vitamin C were responsible for the higher fruit quality under the lower water supply.

Zushi and Matsuzoe (1998) observed the effects of soil water deficit on vitamin C content (fresh weight) varied depending on the cultivar. They that found vitamin C content increased in some cultivars whereas it remained unchanged in others.

In almost all cultivars under water-stressed plants, glucose and fructose were found in higher proportions than in plants receiving full irrigation. But, on a dry weight basis there was no difference. This indicates that the soil water deficit merely reduced water accumulation by the fruits. The amount of organic acid and free amino acids both increased on fresh and dry weight basis under water stress.

Franco et al. (1999) showed that at higher irrigation levels there was a high yield potential and less blossom-end rot (BER) affected fruit. Naotaka et al. (1998) observed the effect of soil water content on fruit coloring and carotene formation using four cherry tomato varieties. It was found that the soil water deficit effect on the fruit coloring was more evident during the fall cropping season than in the spring season and that the amount of ß-carotene increased in case of cv. Yellow carol.

Water stress severely affected fruit set as well as significantly decreased the number of red fruits (Losada and Rincon, 1994). May (1993) observed that low water stress resulted in maximum yield of tomato raw product and best viscosity with low soluble solids. High water stress caused lower yield, highest soluble solids and poorer viscosity. Chiaranda and Zerbi (1981) conducted an experiment with lysimeter-grown greenhouse tomatoes and observed a remarkable sensitivity of the crop to water stress during the vegetative and the flowering periods, with respect to early and late harvesting records. Shinohara et al. (1995) observed that water stress caused decreasing yield but increasing ^{0}Brix. Photosynthesis and transpiration were markedly inhibited immediately after the water stress was imposed, but plants gradually recovered under continuous stress treatment. Water stress improved the fruit quality, whereas, it inhibited photosynthesis and transpiration of the plant.

Perniola et al. (1994) carried out an experiment to study the influence of different irrigation regimes on different cultivars of tomato. They observed that crop water status was strongly influenced by the water regime, the dry matter accumulation was gradually reduced with the increase of water deficit. Lapushner et al. (1986) observed that fruit weight was reduced by water stress but marketable yield, fruit color and contents of total soluble solids and reducing sugar were improved. Differences in response between cultivars were greater after early planting (15 September) than after late transplanting (22 September). YoungHah et al. (1999) found that total and marketable yields were increased by increasing soil water tension and by varying night temperature (14 ± 1^{0}C to 10 ± 1^{0}C). Fruit cracking decreased with increasing soil water tensions. They also found that total yield was positively correlated to soil water. Soluble solids content, total acidity and citric acid content were higher in cracked fruits than in normal fruits. HuiLian (1997) carried out an experiment with greenhouse tomato cv. Capello in a peatmoss-based substrate (70% sphagnun peat + 30% perlite, (v/v)) subjected to a salinity stress and a low substrate water content (SWC) to observe the effects of salt accumulation and a prolonged substrate water deficit on photosynthesis and plant water relations. Net photosynthetic rate (P_n) decreased by 24% compared with the control one day after SWC was depleted to 55%. They found that the plants acclimatized to substrate water deficit. Leaf turgor potential decreased substantially as leaf water potential (Ψ_w) declined. However, when SWC was kept constant, Ψ_p recovered to a large extent even at the same Ψ_w. This turgor recovery was based on osmotic adjustment shown by the decrease in osmotic potential at fully hydrated status.

Matsuzoe et al. (1998) investigated the effects of soil water content on fruit color and carotene content in cherry tomato cultivars: Mini Carol (red), Cherry Pink (pink), Yellow Carol (yellow), and Orange Carol (yellow–tangerine), in Japan. They observed that soil water deficit accelerated fruit coloring in spring and autumn crops of Mini Carol, and in autumn crops of Cherry Pink. Soil water deficit increased the amount of beta-carotene in Yellow Carol, but had no effect on the beta-carotene content of Orange Carol in spring or autumn crops.

Reid et al. (1996) carried out an experiment to test whether internal blackening was caused by water deficit. They found that a greater incidence of internal blackening and blossom-end-rot, and lower Ca concentrations, in the fruit of non-irrigated plants than in those of fully irrigated plants. Root growth and root death was accelerated in these plants around the time that internally-blackened fruit were set. They suggested that internal blackening could have resulted from increased root competition for photosynthate, leading to abnormal seed development.

Pascual et al. (1998) carried out a trial between 1991 and 1994 on cherry tomatoes of different cultivars to observe the influence of irrigation and soil matric potential on yield and cracking of tomatoes and they found that increasing the amount of irrigation water increased yields in 2 of 3 trials. Radial cracking was the most frequently observed type of cracking. Fruit cracking was considerable following high fluctuations of soil water matric potential with furrow irrigation and the degree of cracking also varied from cultivar to cultivar.

2.6 8.1. Tomato color

Reflection of flesh represents the external color of tomatoes. Different varieties have different pigmentations and the main pigments are □-carotene (yellow) and lycopene (red). The main function for fruit ripeness is tomato color (Hobson et al., 1983). For consumer, color is a very important quality estimator. It indicates the suitability of the product for consumption. Several color charts have been developed for classifying ripeness degree of tomatoes subjectively. US Standards (USDA, 1975) divides tomato ripeness in six categories as described in Table 2.1.

Table 2.1. Tomato color classes (USDA, 1975).

Stage	Class	Definition
1	Green	Completely light to dark green surface
2	Breaker	Break in color from green to tannish- yellow, pink, or red color; not more than 10%
3	Turning	Over 10% but not more than 30% red, pink or tannish-yellow or a combination thereof
4	Pink	Over 30% but not more than 60% pinkish or red color
5	Light-red	Over 60% but not more than 90% red color
6	Red	Over 90% of the surface is red color

2.6.8.2. Tomato flavor

This is another important quality. Consumer acceptance and repeat sales are dependent on flavor quality. Tomato flavor depends on the scents of different chemical compounds. The level of sugar and acid and their interactions determine the tomato flavor. The more intense flavor is associated with higher levels of those chemicals. The pericarp of tomato fruit contains less organic acids than locules. Hence, cultivars with large locules and with high accumulation of acids and sugars have better flavor than those with a small locular portions (Stevens et al., 1977).

Considerable attempts have been made to improve the fruit quality through genetic alteration. For example, attempts have been made to increase fruit solids content to develop the fruit and to change fruit acid content, both of which are important quality parameters. Along with improving color of tomato, intensive efforts have been made to develop fruits with firm flesh and tough skin for machine harvesting.

2.6.8.3. Tomato sweetness and sourness

The most pronounced flavor characteristics of tomato are the taste characters sweetness and sourness (Stevens, 1985). There is some evidence that tomato breeders, in an attempt to improve sweetness, have selected for low acidity, and this has resulted in cultivars that lack of flavor because the acids are primary determinants of the potency of the flavor (Stevens et al., 1977). It is virtually impossible to develop a high yielding tomato with sweet fruits since, at best, tomato fruits contain less than 5% sugar, and this is far short of the amount required for real sweetness. There have been few attempts to quantify the impact of sugar and acids on tomato flavor. A statistical evaluation of the relationships between composition and flavor characteristics showed that sweetness is very highly correlated to reducing sugar content.

Sourness is very highly related to titrable acidity and pH. The overall flavor intensity of these hybrids is highly related to pH, acid level, and soluble solids content. It was observed that cultivars that have low-sugar and low-acid content are insipid and tasteless. Cultivars that have a high–acid content and a relatively low sugar content tend to be tart, which some consumers find objectionable. High acids and high sugar promote the desired flavor in the proper balance. Sugar/acid ratio is a much overused term because it is possible to have a desired sugar /acid ratio and still have poor flavor if both sugar and acid levels are low. For quantifying flavor, information on sugar content, acid content, and the ratio between these components is very essential (Stevens, 1985).

2.7. Water stress and blossom-end rot of tomatoes

Blossom-end rot of tomatoes is a common problem. It occurs under conditions of high plant water stress and heavy fruit load (Hodges and Steinegger, 1991). It appears as brown to black lathery spots on the underside (blossom-end) of the fruit of tomatoes. This disorder is also appeared in peppers. Squash are often afflicted with this problem when they reach two to two and one-half inches long. Affected areas are typically the size of the of quarter (or larger), sunken, and gray to black in color. As this problem progresses, one-half or more of the fruit may be affected. The fruits ripen earlier and are usually worthless. This disorder results in the decay of tomato fruits on their blossom end (Sanders, 1994).

Blossom end rot may appear on some of the first fruit clusters on a plant. This is attributed to the combination of rapid plant growth with a large leaf area for water transpiration, water stress, and fruit enlargement. Even a temporary water stress during early fruit enlargement can cause BER because the fruits are the last to receive adequate calcium (Hodges and Steinegger, 1991).

A number of environmental factors contribute to this problem. Planting in poorly drained soil, improper soil preparation and planting, inadequate or excessive watering, using excessive amounts of pesticide, soil pH levels below 5.5, inadequate calcium in the soil, applying too much nitrogen, excessive pruning, the use of plastic mulch instead of an organic mulch, and high soil temperatures. Some plant diseases such as curly-top virus are said to increase BER problems. High temperatures and low humidity also contribute to this problem. Blossom-end rot is a symptom of calcium deficiency in the plant. Even with an abundance of calcium in the soil, inadequate calcium levels in the fruit can occur.

Movement of calcium in soil and its uptake by roots is controlled by soil moisture content. Calcium will not move to the roots without sufficient soil moisture. Only young root tips in which the cell walls of the epidermis are unsuberized absorb calcium. Once the suberin layer develops in these cells, water and calcium can no longer be absorbed. Suberin is waxy substance through which water and nutrients cannot move. Excess soil moisture and a lack of oxygen results in the development of this suberin layer.

Dry soil and hot, dry, windy days create a water and calcium deficiency in the plant. This type of environment can cause high transpiration rates ideal for inducing blossom end rot. Fluctuations in soil moisture during periods of rapid plant growth create moisture stress and limits calcium distribution to the fruit. Even a brief soil water deficit can disrupt water and nutrient flow in the plant. If this occurs while fruits are developing, BER will likely develop. Blossom-end rot is usually more severe on tomato plants gardeners have pruned or placed in cages. The pruned, uncaged plants act as mulch over the soil, restricting water loss by evaporation (Hodges and Steinegger, 1991).

Blossom-end rot of tomato fruit results from low humidity and low soil moisture stress felt by the plant. These stresses result in a water deficit in the blossom end cells of young tomato fruit within the first few days after fruit set. These stressed cells in the fruit die from dehydration. Tiny, newly set tomato fruit will suffer damage when water escapes from the tip cells faster than from nearby leaves. These stressed blossom end cells will also be deficient in calcium even in tomatoes grown naturally calcium-rich soils like Texas High plains (Roberts, 1996).

2.8. Water stress and physiological response

Leaves are the main providers of carbon for fruit development. Consequently, most studies seeking to relate the effects of different cultivation practices or varying environmental conditions on fruit development have focused on the photosynthetic metabolism of leaves. The tomato plant is no exception to this generalization. Numerous papers published on source/sink interactions between leaves and fruit and their effect on crop yields have studied leaf photosynthetic activity by altering photon flux density, temperature, CO_2 concentration, nutrient and water supplies (Ho and Hewitt, 1986).

Hetherington et al. (1998) assessed the photosynthetic activities of different chlorophyll containing parts of tomato plants (Lycopersicon esculentum Mill. cv Saporo) by using chlorophyll fluorescence techniques. They concluded that the non-leaf green tissues of tomato are quite active photosynthetically and therefore potentially contribute significantly to plant growth.

This plant is very sensitive to salinity during germination and early plant development. Therefore salt, where present, needs to be removed during pre-irrigation or by over watering during initial irrigation. HuiLian et al. (1999) subjected tomatoes to salinity stress (Electrical conductivity 4.5 mS/cm) and a low (55%±8%) on gravimetric basis) SWC to evaluate the effects of salt accumulation and a prolonged substrate water deficit on photosynthesis and plant water relations. Net photosynthetic rate decreased by 24% compared with the control one day after SWC was depleted to 55%. The combined treatment of salinity and water deficit imposed an additive negative effect on net photosynthetic rate, leaf water potential and leaf turgor potential, which did not allow net photosynthetic rate to recover despite the osmotic adjustment.

Shinohara et al. (1995) evaluated the effects of water stress on the yield, quality, photosynthesis, transpiration, and photosynthate translocation of tomato. Water stress treatments were carried out using tomato cv "Momotaro" plants grown in porous volcanic gravel culture with different amount of solutions supplied. Fruit yield was decreased and photosynthesis and transpiration were markedly inhibited immediately after receiving the water stress, but gradually recovered under continuous stress treatment. Finally, they reported that water stress promoted the photosynthate translocation into fruit and improved the fruit quality, whereas it inhibited the photosynthesis and transpiration. Samuel and Paliwal (1994) observed that water-stressed plants (tomato cv.PKM-1) showed a drastic reduction in tissue water content compared with controls. The midday water potential of the leaves was reduced from -1.0 MPa to -2.6 MPa as a result of the imposed water stress. Photosynthetic rate and stomatal conductance decreased by 50% as a result of water stress. Transpiration rate decreased and diffusion resistance increased after five days of water stress.

2.8.1. Stomatal response to soil water deficits

The classical view of the response of stomata to water stress is that stomatal aperture is regulated according to the plant water stress. At the cellular level of the stomatal apparatus, it has been demonstrated that such feedback control does not occur during responses to VPD. The response of stomata may be regarded as a feed forward response, in which a signal from roots under dry soil continuous is transmitted to the leaf so that water loss is reduced before the plant experiences internal water stress (Schulze, 1986).

From very early on it had been proposed that the stress hormone abscisic acid was produced at the root tips and transported to the leaf via the xylem stream. It appears that the root tip in the actual stress sensor, and there is evidence that the root tip experiences a loss in turgor earlier than the root because it is partially disconnected from the main xylem flow. The abscisic acid response was independent of pot size (Zhang and Davies, 1987).

2.8.2. Chlorophyll flourescence

Krause and Weis (1984) reported that chlorophyll fluorescence indirectly measures photosynthesis efficiency. If a leaf is placed in the dark for a couple of minutes and then is returned to the light, fluorescence quickly rises to an initial level (F_0). Fluorescence increases from F_0 to its maximum (F_m) due to the rapid decrease of electron accepting QA (quinone-type acceptor) molecules. The variable florescences (F_v) is the difference between F_m and F_0, and is extremely sensitive to changes in the ultrastructure of membranes and rates of electron transfer. Hence, F_v/F_m can be presented as the potential yield of photochemical reactions (Krause and Weis, 1984).

2.9. Mycorrhizal interaction with water stress

Arbuscular mycorrhizal (AM) fungi are known to stimulate plant growth and nutrient absorption, especially of phosphorus and have been suggested as a factor in increasing tolerance to drastic environmental conditions such as drought (McArthur & Knowles, 1993; Sylvia et al., 1993). Under drought conditions mycorrhizal colonization improves water relations of host plants (Fitter, 1985; Nelsen, 1987). According to Fitter

(1988), the influence of vesicular arbuscular-mycorrhizae on plant relations may be a secondary consequence of enhanced host P nutrition, although these effects are inconsistent. Recent evidence supports the view that enhanced water use in mycorrhizal plants was due to the indirect effects of hypal transport of N and P, with the root signals being mediated by changes in root turgor or plant hormone levels (Auge & Duan, 1991). Allen (1982) suggested that AM fungal hyphae absorb and translocate water directly to their hosts, thus acting as a bridge between the dry zone around the root.

2.10. Soil moisture measurement

The simplest, most widely used, and probably the best method for determining soil moisture is the collection of soil samples from various depths and locations in the field. But these approaches are time consuming and laborious. Nowadays there exists equipment to reduce the drudgery of soil sampling. These types of instruments have advantages of instantaneous and immediate readings but also have some limitations. (Doneen and Westcot, 1984.)

2.10.1. Gravimetric Techniques

The most widely used technique for soil moisture measurement is to take an *in situ* sample of soil and oven-dry it at 105 ^{0}C in a forced-draft oven until a constant weight is obtained. Usually this requires 10-12 hrs of drying; however, for large samples and clayey soils, a longer drying time may be required (Scott, 2000). The amount of water in the sample can be determined and the moisture content calculated and expressed as a percentage of the dry soil weight. If the volumetric water content is required, the gravimetric value is multiplied by the bulk density of the soil (Schmugge et al., 1980):

$$\theta=100*(W_w*Y_d/W_d*Y_w) \qquad (2.4)$$

where:

θ volumetric water content, %;

W_w weight of water, g;

W_d dry weight of soil, g;

Y_w density of water, g/cm^3;

Y_d oven-dry bulk density, g/cm^3.

The advantage of this method is that sample acquisition is inexpensive and easy to calculate. Samples can be taken with an auger or tube sampler. However, there are several disadvantages: obtaining representative soil moisture values in a heterogeneous soil profile is difficult, takes a long time to monitoring soil moisture, and the procedure very destructive to the site. Detailed information about this method can be found in Brakensiek et al. (1979).

2.10.2. Nuclear techniques

Two nuclear techniques widely used for measuring soil water content involve neutron scattering and gamma-ray attenuation ((Scott, 2000). The neutron scattering method is an indirect way of determining soil moisture content This method estimates the soil moisture content of the soil by measuring the thermal or slow neutron density. Two types of neutron probes have been developed. One is a depth probe that is lowered into the soil to the depth at which the moisture content is desired through an access tube. The second part of the neutron moderation method is a rate meter, or scaler, which is usually battery powered and portable. It used to monitor the flux of slow neutrons, which is proportional to the soil water content (Schmugge et al., 1980). Scott (2000) reported the advantages of this technique: measures volumetric soil water content, is non destructive, has no lag period. The disadvantages are: it is a radiation instrument and should not be used near the surface, a calibration curve is essential, the equipment is somewhat expensive.

2.10.3. Gamma-ray attenuation technique:

It is also a radioactive method and can be used to determine the soil water content within a 1-2 cm soil layer. The assumption of this method is that scattering and absorption of gamma rays are related to the density of matter in their path and that the density of soil remains relatively constant as water content changes. This method has the same advantages and disadvantages as the neutron method. An additional advantage is that water contents can be obtained over a small horizontal or vertical distance (Scott, 2000).

2.10.4. Tensiometers

Tensiometers are used extensively in the field as well as in the laboratory. The equipment contains a porous ceramic cup filled with water. It is connected through a water-filled tube to a reliable vacuum gauge. Due to soil water tension, water moves into and out of the ceramic cup. To maintain a desired soil water range tensiometers are actually used as sensors.

The major limitation of this equipment is that it functions reliably only in wet soil, at a range of tensions of about - 0.8 atmosphere or higher (Doneen and Westcot, 1984).

2.10.5. Time domain reflectrometer (TDR) for water content measurement

Soil water content and the availability of water are fundamentally important to land activities, especially in the field of agriculture, forestry, hydrology, and engineering. The lack of reasonably straightforward methods for monitoring water content profiles in undisturbed soil samples makes existing methods for evaluating unsaturated soil water flow in soil columns difficult. Recent advances in TDR technique for measuring soil moisture (Malicki 1990; Topp and Davis, 1985) makes it possible to measure water content with an array of TDR probes. It provides a powerful tool for measuring soil water content rapidly and reliably.

2.11. Summary

At certain stages in the life cycle of the tomato plant, water must be applied at an optimum level to achieve maximum yields. Water restrictions at different growth stages have an impact on the crop's yield and quality. In order to eliminate a limiting factor, which could retard the plant's physiological growth and productivity, an appropriate approach is required. Water stress, environmental stress and the timely application of inputs need to be considered. These have a significant impact not only on yields, but also in increasing fruit quality.

Understanding the effects of deficit irrigation on physiological parameters such as photosynthesis, transpiration, stomatal conductance, leaf temperature and vapor pressure deficit could be of great help in understanding crop yield response to irrigation. This would then allow a more rational choice of irrigation regimes as well as more efficient water use. Above all, deficit irrigation provides high water use efficiency with which farmers have an option to use the water saved for another purpose.

CHAPTER III

MATERIALS & METHODS

3.1. Growing conditions

The influence of different irrigation regimes on the production and quality of greenhouse tomatoes was studied during the summer of 1999 and winter 2000. An experiment was set up in the Macdonald Campus greenhouse of McGill University at Sainte Anne-de-Bellevue, Québec. The experiment consisted of 9 irrigation treatments replicated 4 times in a randomized complete block design (RCDB), resulting in a total of 36 pot-grown plants. The experimental layout is shown in Figure 3.1.

The 24 cm-high polyethylene pots had an upper diameter of 28 cm and a diameter of 22 cm at the base. Each pot was placed in a 55 x 28.5 x 7 cm white plastic seedling tray on the concrete floor of the greenhouse, in order to trap any irrigation overflow or soil material escaping from the drainage holes at the base of the pots. Any soil material escaping from the pot was returned to the pot, thus maintaining the same total soil throughout the experiment.

In each of the four blocks, plants were staggered in two rows. Plants were spaced 60 cm (2 ft.) apart both within and between rows. Natural lighting was supplemented with overhead lighting so as to have 16 hrs of daylight. The overhead lighting consisted of 400 W (fixtures rated for 485W, 208V, 2.5 A) high-pressure sodium bulbs (P.L. Light Systems, Canada).

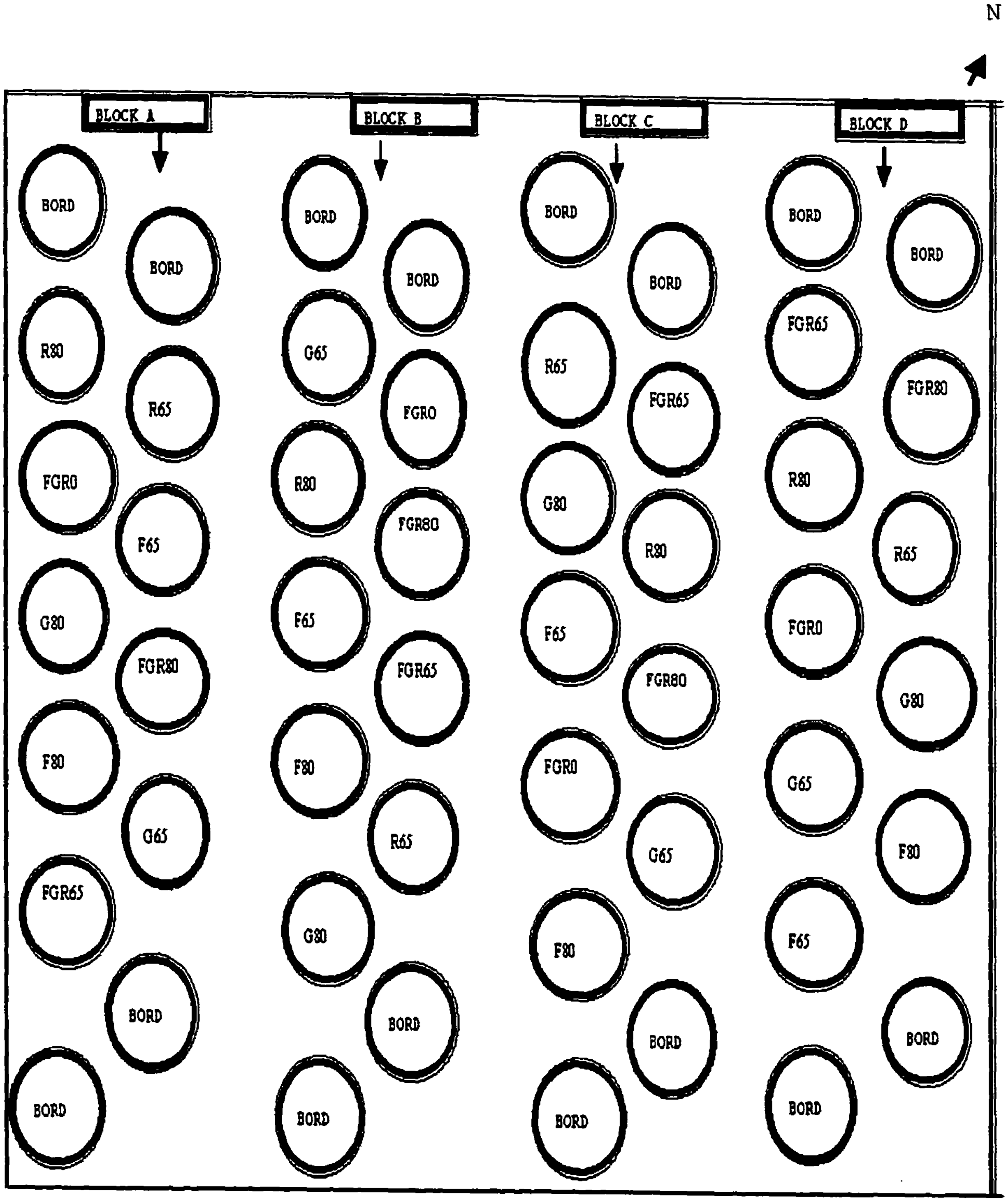

Figure 3.1. Experimental layout in greenhouse

BORD=Border plants, other abbreviation as in Figure 3.2.

The daytime temperature was maintained at 25±2°C, and the night-time temperature at 18±2°C. Relative humidity was maintained at 65%±5% throughout the growing season

3.2. Soil characteristics

The dry soil was placed in the pots and manually compacted. Dry soil was added until the surface of the compacted soil was within 0.5 cm of the rim. The soil was then wetted regularly over a period of 3 days in order for it to further compact before seeding. The soil level below the edge in each pot was measured (mean of approx. 4.0 cm). The soil consisted of a mixture of two locally available soils.

Soil organic matter and total carbon were measured by the wet oxidation-redox titration method of Tiessen and Moir (1993). Total carbon and organic matter were found to be 11.9% and 20.5% (v/v), respectively. Particle size distribution was determined by the hydrometer method. Given the high organic matter of the soil, organic matter was removed by treatment with 30% (v/v) hydrogen peroxide according to the method of Sheldric and Wang (1993). Hydrogen peroxide was only applied to a sub sample of the soil used in particle size distribution analysis, and not in the experiment itself. A standard hydrometer (ASTM No. 1 152 H) with a Boyoucos scale in g/L was used in the analysis. The proportion of sand: silt: clay of the peroxide-treated soil was 71.5%, 16.9% 11.6%, namely a sandy loam. Bulk density of the soil was measured at the end of the growing season in each treatment pot. An aluminium cylinder 4.69 cm in diameter and 3.6 cm in height was driven into undisturbed moist soil midway between the plant stem and pot edge. The sample was dried at 105°C for 36 hrs, then weighed. The average soil bulk density across all treatments and blocks was 0.80 g/cm^3.

Field capacity (θ_{fc}) was determined using the pressure plate method. A matric potential (Ψ_m) of 33 kPa was applied (James, 1988) to estimate the θ_{fc}. This was found to average 32% v/v. Due to leakage of the available pressure plate apparatus, the permanent wilting point (θ_{pwp}) was determined according to Ibarra (1997). Three tomato plants were grown to a height of 30 cm in pots identical to those used for the experimental plants. Watering was stopped and plants allowed to wilt. When the plants had remained wilted for 3 days with no overnight recovery, the soil moisture content was determined using the gravimetric method. The θ_{pwp} was found to be 11% (v/v), a value consistent with values for similar soils (James, 1988). These values were used in computing the percent depletion of plant available water (PAW) for the water stress treatments applied, based on soil moisture content values measured by TDR. Treatments under 65% soil moisture deficit level (65% depletion of plant available water from the soil field capacity), the plants received irrigation only when PAW was depleted by 65% or more, i.e. below 32-[0.65x(32-11)] = 18.3%. Similarly, treatments under 80 % soil moisture deficit level (80% depletion of plant available water from the soil field capacity), plants received irrigation only when PAW was depleted by 80% or more, i.e. below 32-[0.8x(32-11)]= 15.2% soil moisture.

3.3. Growth conditions

Plants were directly seeded in pots on DOY 131 during summer 1999 season and DOY 11 during winter 2000 season. Two seeds of cv. Sunstart, a fresh-market beefsteak variety, were planted 5 cm apart in the centre of each pot, which contained pre-soaked, pre-fertilized soil. "Sunstart" is a determinate variety. Each pot received dry granular tomato fertilizer (5-8-10; Purcell Vigoro Canada Inc., Tilsonburg, Ontario, N4G 1C8), which was mixed into the top 1.0 cm of dry soil at seeding, resulting in a roughly equivalent fertilisation rate of 110 kg N/ha, 78 kg P/ha, and 184 kg K/ha. The same amount and rate of fertilizer was applied in the winter 2000 growing season. Further fertilisations at the same rate occurred at 3 to 4 week intervals in both years.

In summer 1999, 92% emergence occurred by DOY 142, full emergence by DOY 146 and in winter 2000 by DOY 22 and DOY 25, respectively. At the 2-leaf stage, plants were thinned to one per pot and any damaged plants replaced by extras from other treatments or border pots. All plants received 500-ml irrigation twice a week and suckers were removed until plants reached the 4-leaf stage (DOY 184 and DOY 61). Subsequent suckers were allowed to grow. At this stage, just prior to the development of flower clusters, treatment plants were rearranged between blocks such that each block had plants of a similar size, i.e. one block had all the smaller plants, one all the larger plants, and the two others all the intermediate plants. Treatments were then applied.

3.4. Treatments applied

Irrigation amounts were based on soil moisture measured by TDR. In all cases, when irrigation was applied, it was sufficient to return the soil to θ_{fc} but did not lead to any drainage from the bottom of the pot. An effort was made to avoid watering directly around the pot-soil interface, and any significant drainage loss was captured by the tray underneath the pot and returned to the pot.

The following treatments were studied. Days given are for the summer 1999 season:

(FGR_0) Soil moisture returned to θ_{fc} daily - entire season (*DOY 195-314*): "Full irrigation."

(FGR_{65}) Soil moisture returned to θ_{fc} only on days when depletion of PAW $\geq$ 65% - entire season (*DOY 197-314*): "deficit irrigation."

(FGR_{80}) Soil moisture returned to θ_{fc} only on days when depletion of PAW $\geq$ 80% - entire season (*DOY 197-314*): "deficit irrigation."

(F_{65}) Soil moisture returned to θ_{fc} only on days when depletion of PAW$\geq$ 65 % - deficit irrigation during flowering/fruit set stage only (*DOY 197-215*), then full irrigation to end of season (*DOY 216-314*).

(G_{65}) Soil moisture returned to θ_{fc} only on days when depletion of PAW $\geq$ 65% - deficit irrigation during fruit growth stage only (*DOY 197-213*), then full irrigation to end of season (*DOY 214-314*).

(R_{65}) Soil moisture returned toθ_{fc} only on days when depletion of PAW $\geq$ 65% - full irrigation through flowering/fruit set stage and fruit growth stage (*DOY 198- 248*), deficit irrigation through fruit ripening stage to until end of season *(DOY 249-314)*

(F_{80}) Soil moisture returned to θ_{fc} only on days when depletion of PAW$\geq$ 80% - deficit irrigation during flowering/fruit set stage only (*DOY 197-215*), then full irrigation to end of season *(DOY 216-314)*.

(R_{80}) Soil moisture returned to θ_{fc} only on days when depletion of PAW$\geq$ 80% - full irrigation through flowering/fruit set and fruit growth stage (*DOY 196-247*), deficit irrigation through fruit ripening stage to until end of season *(DOY 248-314)*.

(G_{80}) Soil moisture returned to Θ_{fc} only on days when depletion of PAW ≥ 80% - full irrigation through flowering/fruit set stage, deficit irrigation through fruit growth stage *(DOY 212-257)*, then full irrigation until end of season *(DOY 258-314)*.

(R_{80}) Soil moisture returned to Θ_{fc} only on days when depletion of PAW ≥ 80% - full irrigation through flowering/fruit set and fruit growth stage *(DOY 196-247)*, deficit irrigation through fruit ripening stage to until end of season *(DOY 248-314)*.

A schematic diagram of developmental stages of tomatoes during the growing period for different treatments has been presented in Figure 3.2.

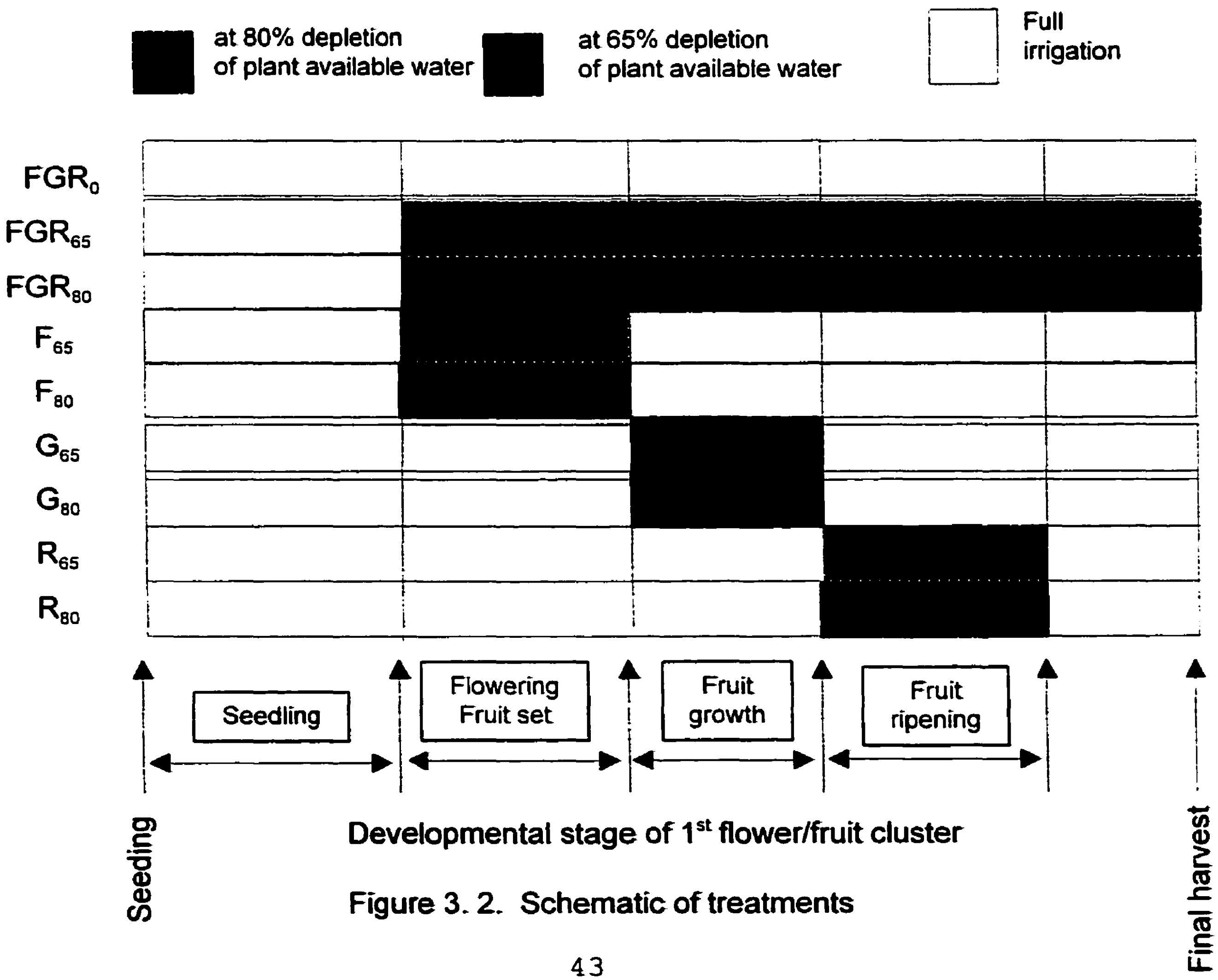

Figure 3. 2. Schematic of treatments

The description of the different developmental stages at different treatments during summer 1999 and winter 2000 are summarised in Table 3.1 and Table 3.2.

Table 3.1. The date (DOY) of different developmental stages during summer 1999.

Treatment	Flowering	Fruit growth	Ripening	Final harvest
F_{65}	197	214	246	314
F_{80}	197	215	256	314
FGR_{0}	195	211	245	314
FGR_{65}	197	215	253	314
FGR_{80}	197	215	255	314
G_{65}	197	213	253	314
G_{80}	194	211	257	314
R_{65}	198	210	248	314
R_{80}	196	211	247	314

Table 3.2. The date (DOY) of different developmental stages during winter 2000.

Treatment	Flowering	Fruit growth	Ripening	Harvesting
F65	80	96	124	193
F80	81	101	124	193
FGR0	85	98	126	193
FGR65	81	97	125	193
FGR80	81	96	125	193
G65	82	95	131	193
G80	81	94	131	193
R65	86	103	133	193
R80	81	92	122	193

3.5. Irrigation scheduling

Irrigation was given to every pot based on visual judgment up to the flowering stage (flowering of first cluster). After each plant reached the flowering stage, moisture status in every pot was monitored by TDR and the amount of water for each pot was calculated according to its need based on the treatment applied. Generally, pots containing the plants on zero moisture stress had water applied daily, while for other treatments water was applied on every alternate day (or two-day intervals) based on water demand at different growth stages. Irrigation was given manually using a measuring cylinder. Careful attention was taken for homogenous application of irrigation water in the pot throughout the whole growing period of the plant.

3.6. Measurement of soil moisture

3.6.1. TDR method

TDR was used to measure the daily soil moisture for the soil of the experimental pots. In the TDR technique, a transmission line probe is inserted in to the soil, and the travel time of electromagnetic mode (TEM) through the soil surrounding the probe is measured. The connections of probes with aligator clips in experimental plot are shown in Figure 3.3a. Geometrical configuration of TEM and the dielectric constant of the material around the positive transmission line influence the characteristic impedance of the line (Lorrain and Corson, 1970). Topp et al. (1980) showed for a variety of soils that the relationship between volumetric water contents (θ_v) and a dielectric constant (K_a) is essentially independent of soil texture, porosity, and salt content.

Fig: 3.3a.Three probe connections for measuring water content by TDR

Fig3.3b. Photosynthesis measurement with Licor (L—6400)

They proposed a third degree polynomial relationship for conversion of Ka values to volumetric water content as follows:

$$\theta_V = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 \quad (3.1)$$

For this study, TDR was calibrated for establishing the relationship between Ka and θv. The relationship (Figure 3.4.) was found to be

$$y = 0.14 Ln(x) + 0.52 \quad (3.2).$$

In each pot three parallel stainless steel rods of diameter 6.5 mm held in a plywood block were used with the TDR. The probes were placed at a uniform interval of 44.25 mm and the depth of the rods was 178 mm.

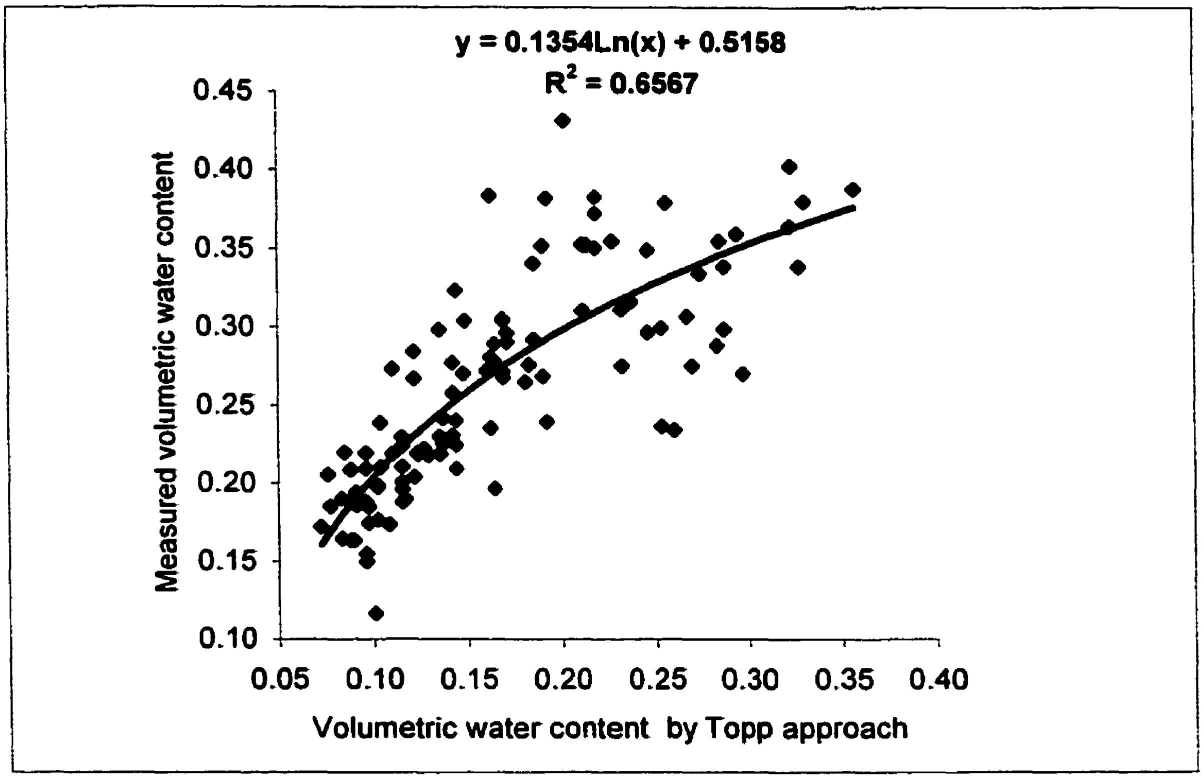

Figure 3.4. Calibration curve for measured volumetric water content and the water content by Topp method (Topp et al., 1980).

3.7. Crop physiological data collection

Only the leaves that had most recently matured, i.e. third or fourth leaves from the apex were used for measuring the physiological parameters. Photosynthetic rate (P_r), transpiration (T_r), stomatal resistance (R_s) and leaf temperature (T_l), vapor pressure deficit were also measured with a portable photosynthesis system (Model Li- 6400, Licor Inc. USA) from 12:00 to 2:00 p.m. Use of this machine is shown in Figure 3.3b.

To evaluate the effect of water stress on the morphological parameters of the plant, at the time of final harvest, stem diameter was measured with digital calipers (Marathon Management Company Ltd., Canada). The accuracy of the caliper was ± 0.02 mm (< 100mm). Stem fresh weights were also measured to evaluate biomass for summer 1999 and winter 2000.

3.8. Postharvest attributes evaluation

3.8.1. Maximum and minimum equatorial diameter and fruit height

For each fruit of every pot, maximum and minimum equatorial diameter and fruit heights were measured by the same electronic digital caliper, which was used for measuring stem diameter

3.8.2. Color

Color is one of the principal factors, which determines the degree of consumer acceptance of tomatoes. North American producers have proposed determining color by calculating color indices, which are applicable to both dehydrated and whole fresh fruit (Hobson et al., 1983; Dodds et al., 1991). Color measurements were made using a Minolta Chroma Meter (CR-300, USA). It is a compact tristimulus color analyzer for measuring reflective colors of surfaces. The equipment was calibrated to white standard plate (Y= 94.4, x = 0.3141 y = 0.3207). The equipment was set up for L (luminosity), a (red-green component), b (yellow-blue component) before taking any measurements. Measurements for individual fruit were made approximately 1 cm from the blossom scar, which permits the greatest distinction between ripening stages (Garret et al., 1960). Three readings were averaged for each tomato at sampling. A tomato color index of the whole fresh fruit (TCI_f) was calculated as reported by Hobson et al (1983) and Dodds et al. (1991):

$TCI_f = 2000 \times a/[L \times (a^2 + b^2/]^{1/2}$ ....(3.3)

The index was first used for raw tomato juice (Yeatman et al., 1960) and found to be suitable for whole tomato fruit (Hobson, 1983). The index value increases from green fruit to fully red-ripe fruit.

3.8.3. Biomass

At final harvesting, shoots were collected and their fresh weight was taken. The stems and leaves were then dried at 72 ^{0}C for 48 hours, and their dry weights were recorded.

3.8.4. pH

The pH of the tomato juice of individual replications were determined using a pH meter (Fisher Accumet pH Model 610 A). Primary filtration was done using cheese cloth and then the juice was placed into a vacuum filtration set up with Buchner funnel. The fruit from all clusters of individual treatments were mixed to give the average value. Before taking a sample reading, the equipment was standardized at pH = 4 with a reference buffer solution (catH7590-4, distributed by American Hospital Supply Canada Inc. Mississauga, Ontario).

Everyday, before starting the data recording, the pH meter was standardized with the same standard solution. After every sampling, the electrode of the pH meter was washed with distilled water and before taking another reading it was immerged with its standby mode into distilled water. For every record the electrode was dried with soft tissue paper and cheesecloth and the electrode then was inserted into the tomato juice and placed in measurement mode to obtain the pH value. For each sample the data was recorded approximately five seconds after inserting the electrode.

3.8.5. Soluble solids

The percent total soluble solids was determined using a Bausch and Lomb Abbe-3L refractrometer. This is a precision instrument that provides the index of reflection on a wide variety of liquid or solid samples in the range of 1.30-1.71 η_D. This instrument also furnishes direct readings in "percent total dissolved solids" from 0-85%. The refractrometer was adjusted manually with a wrench for a 10% standard solution. After each sample, a non-ionic detergent was used to clean the prisms and the upper prism was kept closed when not in use. For every sample, three values were recorded and were averaged for a representative value.

3.9. Data Analysis

The data was treated as 2x5 factorial combination of water stress level and timing arranged in a randomized complete block (RCBD) with 4 blocks. Statistical analysis of the data of both years was done using PROC ANOVA in the SAS system, Windows version 6.12

(SAS Institute Inc. NC, USA.). The effects of water stress on different parameters were evaluated using a protected least significant difference (LSD) test at $p< 0.05$. The full irrigation treatment (FGR_0) data was duplicated and served as a no- stress control for both the 65% and 80% moisture depletion level (MDL) treatments. The five timing of stress treatments were thus:

(i) no stress (full irrigation throughout the season),

(ii) at flowering

(iii) during fruit growth

(iv) during fruit ripening

(v) throughout the season.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Marketable yield

4.1.1. The effect of moisture depletion level

Moisture depletion level (MDL) applied on the first fruit cluster showed no statistically significant ($p>0.05$) effect on total marketable tomato yield or fruit number in the summer 1999 season. However, yield and fruit number were 5% and 10.3% greater respectively, under the 65% MDL than the 80% MDL. In the winter 2000, both yield and fruit number, while generally lower than in the summer 1999 season, were significantly greater under the 65% MDL than the 80% MDL. The increase between the 65% MDL and the 80% MDL for yield and fruit number were 12.2 % and 10.3 %, respectively (Table 4.1). Thus, generally speaking, yield by weight and by number was greater under the lesser water stress.

Table 4.1. Effect of water stress level on tomato yield during summer 1999 and winter 2000.

	Summer 1999		Winter 2000	
Water stress level (%)	Mean yield (g)	Number of fruit	Mean Yield (g)	Number of fruit
65	1301.9a	17.1a	1103.3a	11.7a
80	1239.9a	15.5a	982.8a	10.6b

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

4.1.2. Effect of stress timing

Timing of water stress had a significant ($p<0.05$) effect on yield and fruit number in both growing seasons. In both years, the plants receiving no water stress whatsoever showed significantly greater numbers of fruit than those receiving any water stress treatment (Table 4.2. & Table 4.3.). With the exception of stress at flowering in winter 2000, yield was greater under full irrigation than under any water stress treatment. Water stress applied throughout the season, reduced yield by 56% in summer 1999 and by 64% in winter 2000 compared to full irrigation.

Table 4.2. Effect of water stress timing on tomato yield during summer 1999.

Stage	Yield (g)	Number of fruit
Non stress (control)	1781.3 a	23 a
Flowering	1488.5b	14.6 b
Fruit growth	1068.9 c	14.7 b
Fruit ripening	1240.5 c	15.5 b
Stress all stages	775.8 d	11.1 c

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

In all cases stress applied throughout the season resulted in lower yields than stress applied only at flowering, during fruit growth, or during ripening. Of the partial water stress treatments, that at flowering showed the least effect on yield, while that during the fruit growth stage showed the greater reduction of yield.

Fruit number was significantly ($p<0.05$) greater under full irrigation than under any stress treatment. Similarly, fruit number was significantly less under full season stress than any partial water stress treatments. In winter 2000, fruit number was least for stress at the fruit growth stage coinciding with the partial stress treatment with the lowest yields (Table 4.3). However, in summer 1999 no significant difference in the fruit number was seen between the partial stress treatments. Still generally, in terms of both yield and fruit number, the fruit growth stage appeared to be the least tolerant to water stress.

The explanation for this reduction is that as the soil dries, the rate of absorption by roots falls short of transpiration rate by the plant, thus creating an internal water deficit which affects photosynthesis and results in reduced leaf area, cell size and intercellular volume which reduces soil moisture accumulation. This internal water deficit had a greater effect at fruit growth stage as at this time the expanding fruit tissues require a great deal of water.

Water stress at the growth stage resulted in fewer fruit being set (Table 4.2 and Table 4.3). A plausible explanation for this is that the average number of flowers per truss decreases with the decreasing water supply. Water stress at this stage also retarded fruit growth and ultimately fruit size (Table 4.5.). Water availability also affects flower formation and, later, fruit enlargement (Wuduri and Handerson, 1985).

The yield reduction was associated with increased soil moisture tension, which when allowed to continue resulted in loss of turgidity, cessation of growth, and eventual death of the plants, a finding consistent with that of Rudich et al. (1977).

Table 4.3. Effect of water stress on yield at different growth stages of tomato during winter 2000.

Stage	Yield (gm)	Fruit number
Non stress (control)	1339.3 a	14.5 a
Flowering	1401.2 a	12.5 b
Fruit growth	982.5 b	9.6 c
Fruit ripening	1004 b	11.3 b
Stress all stages	487.8 c	7.8 d

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

The results of the present study are in line with the findings by Ramalan and Nwokeocha (2000), Pill and Lambeth (1980) and Mitchell et al. (1991).

Similar to this finding that water stress during flowering reduced flower number, Losada and Rincon (1994) found that water stress severely affected fruit setting as well as decreased significantly the number of red fruits.

4.2. Fruit size

4.2.1. Effect of moisture depletion level

In both seasons, MDL had no significant ($p>0.05$) effect on fruit size, the dimensions under the 65% MDL being only about 2% greater than under the 80% MDL treatment (Table 4.4). However, fruit size in terms of maximum and minimum diameter, and fruit height tended to be higher under the lesser water stress.

Table 4.4. Effect of water stress level on tomato size during summer 1999 and winter 2000.

	Summer 1999			Winter 2000		
Water stress level (%)	Max diameter (mm)	Min Diameter (mm)	Max height (mm)	Max diameter (mm)	Min Diameter (mm)	Max height (mm)
65	53.4a	49.4a	46.3a	52.1a	48.3a	42.8a
80	52.4a	48.5a	45.5a	50.8a	47.3a	42.4a

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

4.2.2. Effect of stress timing

Timing of water stress had a significant ($p<0.05$) effect on fruit size parameters in both growing seasons. The fruit size was significantly greater for plants receiving no stress than any other stressed plant, except plants stressed at the flowering stage. In both years stress at the flowering stage tended to provide greater size. The percent increase in maximum diameter, minimum diameter and fruit height between stress at flowering and no stress were 15%, 7% and 13% respectively during the summer season and 4%, 15% and 1% greater, respectively in the winter season. Maximum and minimum diameter, and fruit height were 24%, 17% and 23% greater, respectively under stress at flowering than under the stress throughout the season. Thus the fruit size was greatest for plants stressed at flowering or no receiving stress.

Stress at fruit growth and ripening stage yielded no significant difference in tomato size between themselves, but size was generally less than plants stressed at flowering. At this stress, fruit number was also significantly lowered and as a result tomato size increased. During both years, both fruit growth and ripening were influenced by partial water stress (Table 4.5).

Table 4.5. Effect of water stress on tomato size at different stages during summer 1999 and winter 2000.

	Summer1999			Winter 2000		
Crop stages	Max diameter (mm)	Min diameter (mm)	Max height (mm)	Max diameter (mm)	Min diameter (mm)	Max height (mm)
Non stress all stages (control)	53.3b	50.5ab	46.4b	54.6ab	50.6a	44.9a
Flowering	61.5a	54.0a	52.3a	56.7a	51.4a	45.1a
Fruit growth	49.7bc	46.2bc	42.4c	53.0.ab	49.5a	44.7a
Fruit ripening	51.7bc	48.4bc	45.5bc	50.6b	46.8a	41.3ab
Stress in all stages	48.1c	45.7c	42.8bc	42.4c	40.3b	37.1b

Means within columns followed by different letters are statistically different at $p < 0.05$ (LSD test)

Water stress at flowering stage, reduced the number of fruits being set. The shortest duration of stress occurred over the flowering stage. When water stress was released after fruits on first cluster were set, the plants had the opportunity to resume development upon their return to non-stress condition. Due to fewer fruit growing on these plants, each fruit received sufficient or a luxury consumption of nutrients. As a result, the fruit size was greater. Salter (1958) and Ho & Hewitt (1986) reported that water availability affects the fruit size.

4.2.3. Fruit cluster 1 versus subsequent (≥ 2) fruit cluster

The effect of water stress imposed during the ripening stage of first cluster fruit was compared with respect to fruit size of first cluster and subsequent (≥2) cluster. This was only done in the winter 2000. For both stress levels and for maximum and minimum equatorial diameter and fruit height, the fruit of the stressed first cluster were smaller than those of subsequent fruit clusters (Figure 4.1- 4.3).

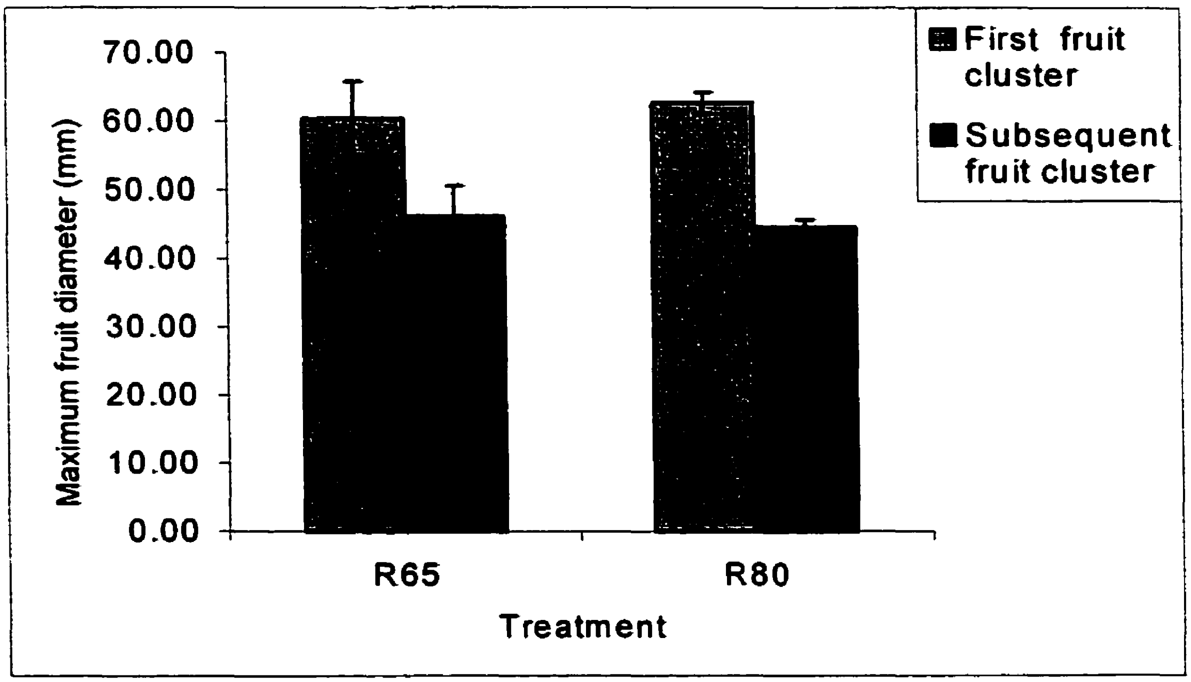

Figure 4.1. Maximum equatorial diameter of first and subsequent (≥ 2) fruit cluster with water stress imposed during the ripening of the first cluster fruit.

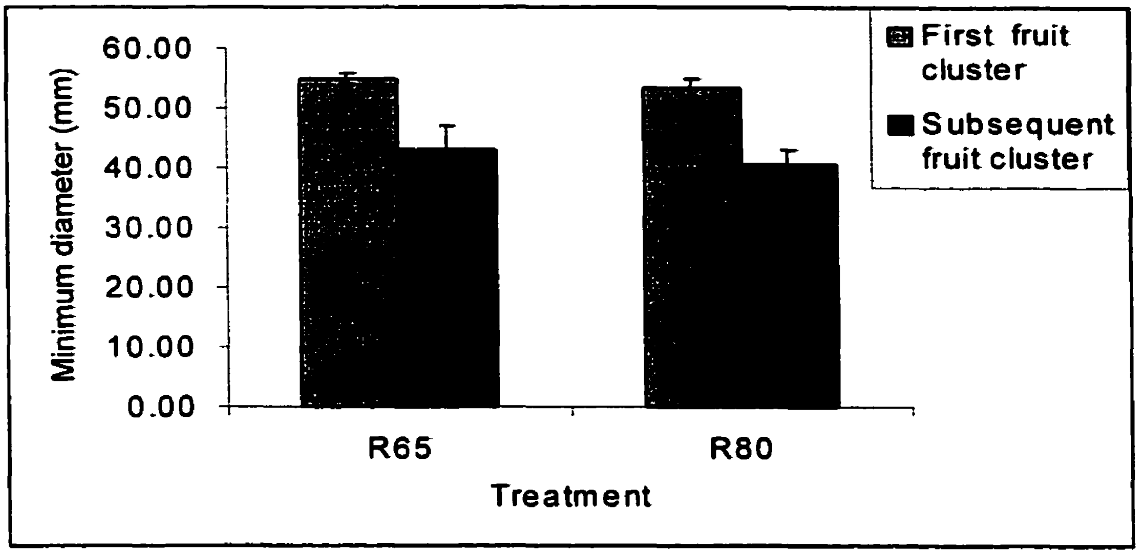

Figure 4.2. Minimum equatorial diameter of first and subsequent (≥ 2) fruit cluster with water stress imposed during the ripening of the first cluster fruit.

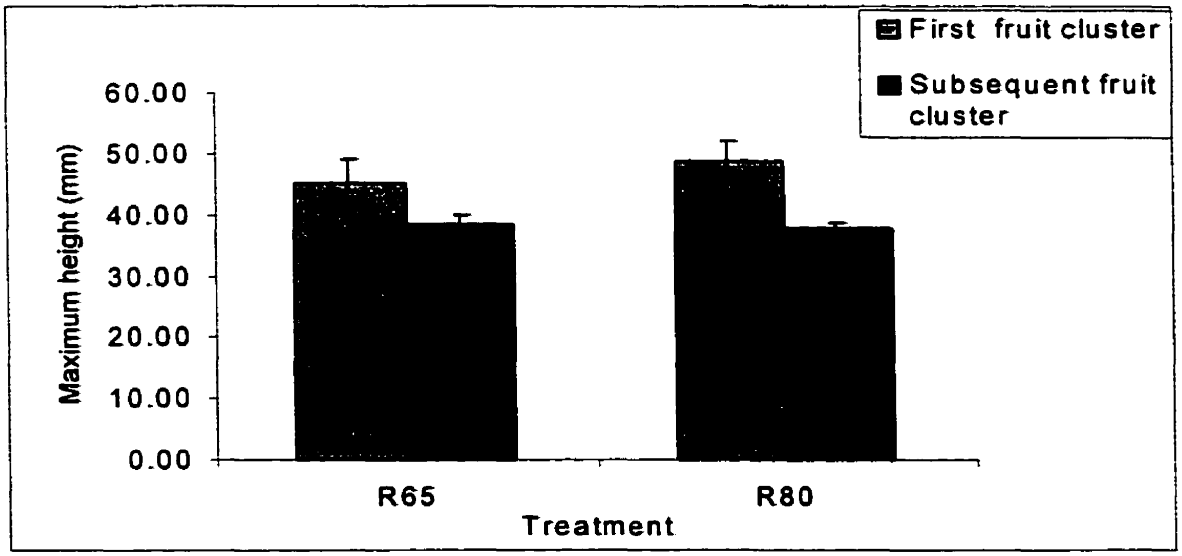

Figure 4.3. Fruit height of first and subsequent (≥ 2) fruit cluster with water stress imposed during the ripening of the first cluster fruit.

The first cluster fruit subjected to the 80% MDL during ripening stage were smaller than hose subjected to the 65% MDL, however this difference was not apparent for the fruits of subsequent clusters.

Lower soil moisture under the greater deficit criterion (80% of PAW) resulted in a reduction of fruit size. The findings of the present study are in line with the findings of Ranalan and Nwokeocha (2000).

4.3. Photosynthetic rate

Soil drought leads to water deficits in the leaf tissue, thus affecting many physiological processes with ultimate consequences on yield. In winter 2000, data were taken on three days (DOY 114, 118, 121) during the fruit growth stage of the first cluster. Consequently, only the FGR_{65}, FGR_{80}, and G_{65} and G_{80} treatments were under stress irrigation at the time of these measurements. Photosynthetic rate was drastically reduced compared to non stressed treatments (Figure 4.4).

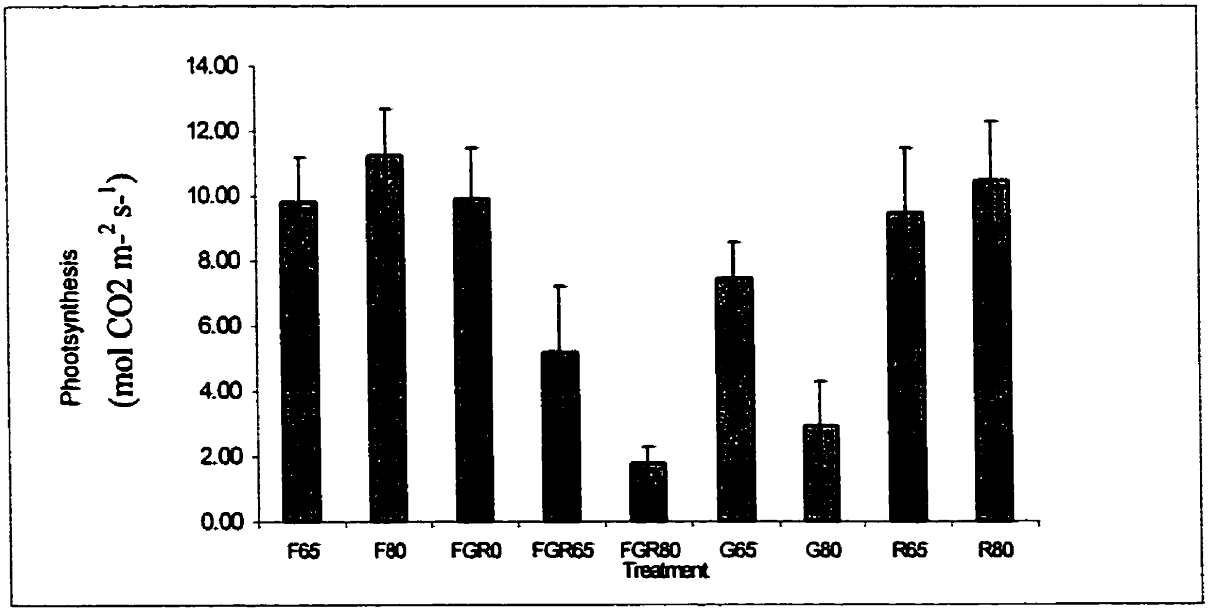

Figure 4.4. Effect of water stress imposed during the fruit stage on photosynthetic rate of tomato plants, Winter 2000 [Treatments as in Figure 3.2. Mean ± Std. Err. (n =3 dates × 4 blocks = 12)].

This decline in photosynthetic rate was possibly due to a reduction in tissue water content. Plants with no stress at that stages of development showed almost the same photosynthetic rate. The photosynthetic rate decreased by 82% at 80% MDL throughout the growing season whereas at 65% MDL throughout the growing season, the decrease in photosynthetic rate was 48%, in comparison to no stress throughout the season. Eighty percent MDL during the fruit growth stage showed 70% decrease and 65% MDL showed a 25% decrease compared to full irrigation. While 65% MDL and 80% MDL imposed during the fruit growth stage showed a significant reduction in photosynthetic rate, the decrease in rate seen with full season 65% or 80% MDL stress was much greater, showing that the water stress prior to the growth stage had a holdover effect of its own during the fruit growth period. Samuel and Paliwal (1993) showed that there was a 50% reduction in the photosynthetic rate (Pr) and stomatal conductance under water stress. When they compared to the control, rate of transpiration decreased and the diffusion resistance and leaf temperature increased in the water stressed plant. This likely was the cause of the lowered P_r rate and would also potentially have effects on other physiological processes in particular those related to fruit set, fruit growth and so on. In another study, Rahman et al. (1999) found a pronounced decrease in P_r under a water stress treatment but after re-watering a more rapid increase in P_r. The findings of the present study are in line with the findings of these authors.

4.3.1. Relationship between soil moisture and photosynthetic rate

There was relationship ($p<0.05$) between available soil moisture and P_r of tomato plants. The correlation coefficient r, was 0.52 (Figure 4.5). There were some values that could have been considered outliers and hence the correlation coefficient would possibly be higher.

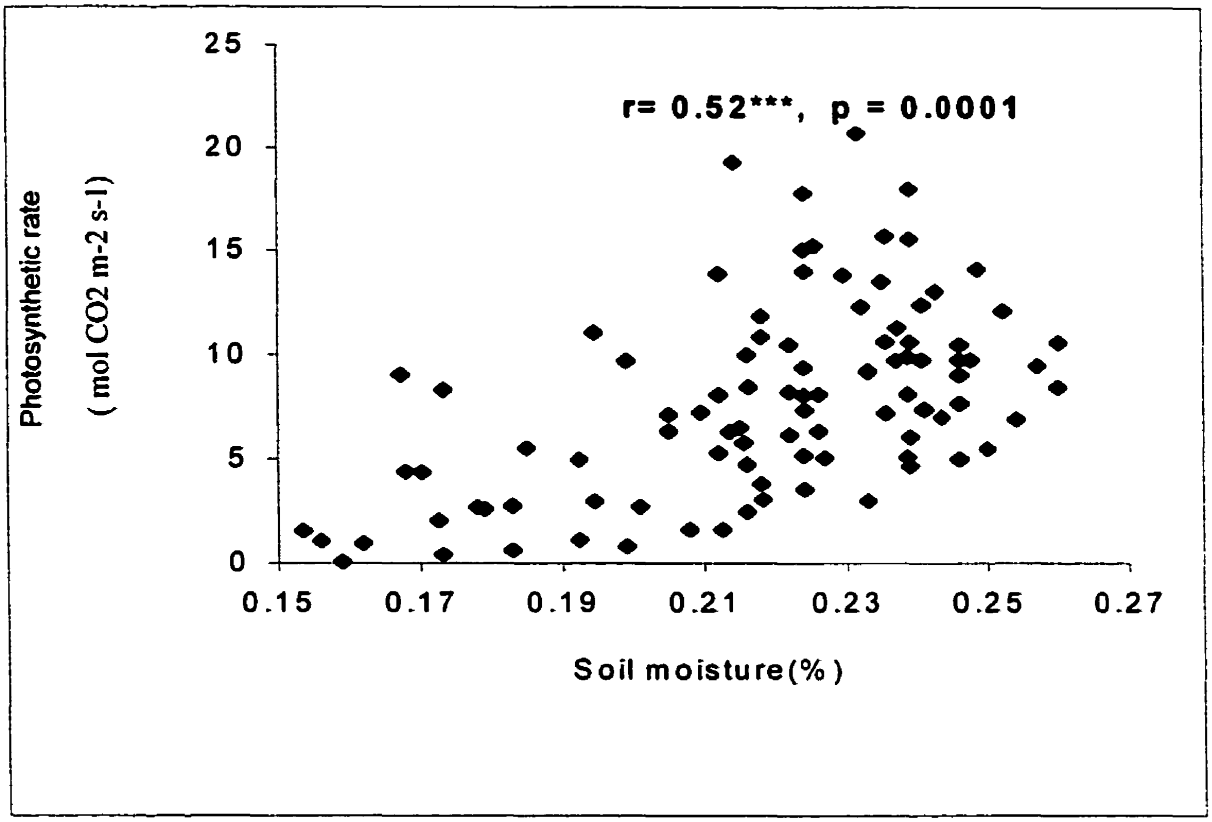

Figure 4.5. Relationship between soil moisture and tomato plant photosynthetic rate at three dates during winter 2000 .

Shinohara et al. (1995) observed that water stress caused decreasing yield but increasing ^{0}Brix. Photosynthesis and transpiration were markedly inhibited immediately after the water stress was imposed, but plants gradually recovered under continuous stress treatment. Water stress improved the fruit quality, whereas, it inhibited photosynthesis and transpiration of the plant.

Rahman et al. (1999) found that water stress decreased yield, flower number, fruit set percentage and dry matter production in all varieties tested. Photosynthetic rate, transpiration rate, and leaf water potential and WUE were reduced, and leaf temperature and stomatal resistance were increased by water stress in all cultivars.

4.4. Biomass

Fruit weight and stem weight were taken separately to evaluate above ground biomass. The stems were dried for 72 hrs at 70 ^{0}C. Stem dry weight was much less than fruit weight. The variability of total above-ground biomass among the treatments was almost exclusively due to the variability of fruit weight. Hence these two parameters are analyzed and discussed separately.

4.4.1. Effect of moisture depletion

Water stress level showed no significant effect on the fresh and dry weight of stems during the summer 1999 (Table 4. 6).

Table 4.6. Effects of water stress level on stem weight of tomato at harvest, during summer 1999 and winter 2000.

	Summer 1999		Winter 2000	
Water stress level (%)	Fresh weight	Dry weight	Fresh weight	Dry weight
65	418.1a	152.6a	333.9a	129.2a
80	406.8a	142.1a	313.1b	126.3a

Means within columns followed by different letters are statistically different at $p < 0.05$ (LSD test)

However, stem fresh and dry weights were 3% and 7% greater respectively under 65% MDL than 80% MDL. In winter 2000, stress level had a significant effect only on the fresh weight but not on the dry weight.

The mean fresh and dry weights in the winter 2000 season were generally lower than in summer 1999. Thus fresh stem weight and dry stem weight were marginally greater (7% and 2%, respectively but not significantly) under the lesser water stress.

4.4.2. Timing of water stress

Timing of water stress had a significant ($p<0.05$) effect on the fresh and dry weight in both growing seasons (Table 4.7).

Table 4.7. Effects of water stress timing on stem weight of tomato at harvest, summer 1999 and winter 2000.

	Summer 1999		Winter 2000	
Crop stages	Fresh weight (g)	Dry weight (g)	Fresh weight (g)	Dry weight (g)
Non stress all stages (control)	470.6a	164.7a	401.8a	142.5a
Flowering	442.8a	166.9a	336.09b	140.6a
Fruit growth	445.1a	157.8a	326.7b	128.3b
Fruit ripening	374.8b	130.8b	272.9c	114.7c
Stress in all stages	328.9b	116.7b	280.1c	112.6c

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

In both years, plants not subjected to any water stress showed a significant higher weight than those stressed at the ripening stage or continuously stressed throughout the growing season

In summer 1999, the stem weight was greater than in the winter season. Stem weight associated with stress at fruit ripening or under continuous stress was significantly less than that under full irrigation. The probable reason is that in these two stages the plants did not get a large enough window of opportunity to recover before harvestings of fruit occurred, whereas stress at earlier growth stages had no such effect and the plants were able to recover after their release from water stress. Furthermore, the shortest stress duration occurred over the flowering stage, and those plants had the opportunity to resume development upon their return to non-stress conditions. Fewer fruits were obtained from those plants stressed at flowering stage and upon recovery in non-stress conditions the individual fruits were bigger. The percent increment in stem weight for stress received at the fruit growth stage, compared to stress over all stages was 35% in summer 1999 and 17% in winter 2000, respectively.

4.5. Fruit Quality

4.5.1. Effect of moisture depletion level on soluble solids

4.5.1.1. Soluble solids

Moisture depletion level showed no significant effect ($p>0.05$) on the soluble solids (^{0} Brix) of tomato fruit during summer 1999 (Table 4.8). But soluble solids were 1.30% greater under 80% MDL than under 65% MDL. In winter 2000, there were no significant differences between 65% and 80% MDL.

May (1993) observed that low water stress resulted in maximum yield of tomato raw product, best viscosity and low soluble solids. High water stress caused lower yield, highest soluble solids and poorer viscosity.

Table 4.8. Effects of water stress level on fruit quality of tomato during summer 1999 and winter 2000.

	Summer 1999			Winter 2000		
Water stress level (%)	Soluble solids (^{0} Brix)	pH	Color index	Soluble solids (^{0} Brix)	pH	Color index
65	7.6a	4.5a	38.5a	8.3a	4.3a	36.3a
80	7.7a	4.5a	38.7a	8.3a	4.2b	35.7b

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

4.5.1.2. pH

Water stress level had no significant effect on pH of the fruit during summer 1999. In the winter 2000 season, the pH was significantly greater at 65% MDL than at the 80% MDL (Table 4.8). Similarly, Tan (1995) showed that pH decreased with no irrigation treatment while irrigation treatment increased pH. Giardini et al. (1988) also found that acidity decreased with higher irrigation rates, although other researchers found the opposite (Sanders et al. 1989) or found no effect (Alvino et al., 1988).

As the overall flavor intensity of tomato fruits are highly related to pH, acid level and soluble solids content. High sugars and high acids in the proper balance promote the desired flavor. Sugar: acid ratio is a much overused term because it is possible to have a desired sugar: acid ratio and still have very poor flavor if both sugar and acid levels are low. To accurately quantify flavor, information on sugar content, and the ratio between these components is needed.

4.5.1.3. Color index

The 65% MDL and 80% MDL treatments did not show any significant difference in color index during summer 1999 (Table 4.8). The 80% MDL treatment showed a marginally more red-ripe color value than under the 65% MDL treatment. In the winter 2000, water stress level showed a significant effect on the color index. Color index was 1.61% greater under 65% MDL than at 80% MDL.

Naotaka et al. (1998) observed the effect of soil water content on fruit coloring and carotene formation using four cherry tomatoes. They found that the effect of soil water deficit on the fruit coloring was greater in the fall cropping season than that in the spring and that the amount of ß- carotene increased under stress in case of the "Yellow carol" variety.

4.5.2. Effect of water stress timing

4.5.2.1. Soluble solids

Timing of water stress showed a significant effect on the soluble solids for both years (Table 4.9). Plants under no water stress yielded the lowest soluble solids in both years. There was no significant difference between no water stress and stress at the flowering stage in either year. Continuous stress throughout the season provided significantly higher soluble solids than no stress, in both years. Soluble solids were 27 % greater under continuous stress than in the absence of stress for the summer 1999 season. Soluble solids were higher with stress application during fruit ripening than with the fully irrigated control in the summer season, but were not different than under continuous stress. The increase for stress during ripening was (33%) compared to the unstressed control.

Table 4.9. Effect of water stress timing on fruit quality of tomato, during summer 1999 and winter 2000.

	Summer 1999			Winter 2000		
Crop stages	Soluble solids (^{0} Brix)	pH	Color index	Soluble solids (^{0} Brix)	pH	Color index
Non stress all stages (control)	6.7 c	4.5a	37.4b	7.1b	4.34a	33.4b
Flowering	6.8c	4.4a	37.6b	7.7b	4.28ab	32.7b
Fruit growth	7.7b	4.5a	39.4a	8.9a	4.24ab	38.7a
Fruit ripening	8.9a	4.6a	39.1a	8.8a	4.29ab	37.4a
Stress in all stages	8.5a	4.5a	39.3a	9.1a	4.19b	37.8a

Means within columns followed by different letters are statistically different at $p< 0.05$ (LSD test)

Stress at flowering and full irrigation treatment control did not show any difference of soluble solids. Soluble solids significantly differed between the flowering and no stress treatments.

It seems soluble solids increase when water stress applied at fruit growth and fruit ripening stages and overall it increased when plant is under stress. When applied in ripening or as a continuous stress soluble solids were highest, perhaps because of the longer stress duration.

In winter 2000, soluble solids followed the same trend as in summer 1999, the only difference being that continuous stress resulted in the highest soluble solids. The soluble solid was 28% greater under continuous stress than in the control. Partial stress at fruit growth and fruit ripening did not show any significant difference when compared to continuous water stress. Soluble solids were higher in winter than in summer. So, fruit would tend to have been sweeter in the winter than summer.

4.5.2.2. pH

Timing of stress had no significant effect on pH of tomato fruit in summer 1999, whereas in winter 2000 it showed a significant difference when control were compared with full stress or partial stress treatments (Table 4.9). The highest pH was found to be in the treatments with no stress throughout the growing season. The pH was 4% greater under no water stress than under continuous stress throughout the season. The lowest pH was found to be at continuous stress in compared no water stress.

pH did not appear to be influenced systematically by reduced irrigation at different growth stages, but owing to the limited range of irrigation schemes used in this study, this question needs further study.

4.5.2.3. Color index

Timing of water stress had a significant effect on the color index during both the summer 1999 and winter 2000 (Table 4.9). In both years, fruits from plants under either full-season water stress (65% or 80% AW) showed a significantly greater color index than those from plants under no water stress throughout the season or exposed to partial water stress at flowering, fruit growth or ripening stages. Percent increase in color index of the fruits from the plants stressed throughout the season was 5% in summer 1999 and was 16% in winter 2000 compared to full irrigation.

Of the partial stress treatments, that at flowering showed the least effect on color index, while that during the fruit growth and fruit ripening stages showed the greater increase in color index. Stress at fruit growth and fruit ripening and stress throughout the season had the same effect on color index in both seasons. Color index was lower in the winter 2000 season than in summer 1999.

Lapushner (1986) observed that the fruit weight was reduced by water stress but the fruit colors were improved.

Matsuzoe et al (1998) investigated the effects of soil water content on fruit color and carotene content in cherry tomato cultivars. They observed that soil water deficit accelerated fruit coloring of the red-ripening cultivars, 'Mini Carol', and the pink-ripening cultivars 'Cherry Pink'. Soil water deficit increased the amount of beta-carotene in yellow ripening cultivars 'Yellow Carol', but had no effect on the beta-carotene content of orange- ripening cultivars 'Orange Carol'.

However, the current work did not study rate of ripening, but only final ripe fruit color. The color index does not measure level of specific pigments but the overall color of the fruit. However, as other have shown stress increased final fruit color in this study.

4.5.3 Blossom end rot

The effect of water stress on the development of blossom end rot was evaluated for the summer 1999 and winter 2000 seasons. It is a physiological disorder characterized by the appearance of dead and dying tissue at the blossom end of the developing fruit, reducing their commercial quality. This disorder is associated with many environmental, genetic, anatomical and cultural factors. It may happen due to irregular watering, high temperature, high light conditions, cultivar susceptibility and high differentials between day and night temperature.

Water stress had a significant effect on the number of blossom end rot affected fruit. This effect was seen within couple of days after fruit set. These stressed cell in the fruit die from dehydration. Blossom end rot occurs as a lack of co-ordination between the transport of assimilates by the phloem and of calcium by the xylem during rapid cell enlargement in the distal placenta tissue, i.e. an interaction between the rates of fruit growth and of calcium acquisition at the distal end of the fruit. Water availability is a factor affecting BER. Since calcium is transported only in the water-conducting tissues (xylem), when water uptake is reduced, calcium uptake is reduced proportionally. Hence, water stress causes calcium deficiency in the plant. Therefore, it seems that water stress disrupted water and nutrient flow in the plant.

In the present study, only the effect of different irrigation levels at different growth stages were taken into consideration. There was a significant effect of level of moisture depletion on the number of blossom end rot affected fruits during summer 1999 and winter 2000. The higher number was observed for 80% depletion than 65% depletion, for both years (Table 4.10).

Table 4.10. Effect of water stress level on blossom end rot in tomato plant during summer 1999 and winter 2000.

	Summer1999	Winter 2000
Water depletion level	No. of affected fruits/plant	No. of affected fruits/plant
65%	2.6b	2.5b
80%	4.5a	3.8 a

Different letters within the same column indicate significant difference at $p<0.05$ (LSD test)

It seems this physiological disorder was more frequent with increasing moisture depletion levels. Allowing of higher depletion will increase the soil temperature. No appreciable difference was observed for BER affected fruit under 65% depletion from one season to the next. But a larger number of blossom end rot affected fruits were obtained in summer than in winter. This for the 80% depletion treatment may be due to high variability of hot and dry condition of soil.

The highest number of affected fruit was obtained for the continuous stress throughout the growing season, and the lowest number for the full irrigation control. The high frequency of irrigation in the FGR_0 treatment would allow greater evaporation from the soil surface resulting in cooler soil. Stress at fruit growth stages also had a significant number of affected fruit. Overall we may confirm that irregular irrigation, especially going from very dry to wet conditions is important in the development of this type of physiological disorder.

Franco et al. (1990) showed that at higher irrigation levels fewer fruit were affected by blossom-end rot.

Reid et al. (1996) carried out an experiment to test whether internal blackening was caused by water deficit. They found that a greater incidence of internal blackening and blossom-end-rot, and lower Ca concentrations occurred, in the fruit of non-irrigated plants compared to fully irrigated plants. Similarly, in this study, greater BER were found under higher water stress levels.

4.6. Water use efficiency (WUE)

While assessing water use efficiency by the irrigated crops, water applied and water taken up by the plants is important. WUE is defined as the marketable yield (kg) produced per unit amount of water (m^3) applied, and reflects the characteristics of the irrigation method adopted and the volume of irrigation water applied. The level of water depletion had no significant effect on the WUE during either year (Table 4.11)

Table 4.11. Effect of water stress level on water use efficiency (kg/m^3) of tomato plant during summer 1999 and winter 2000.

	Summer1999	Winter 2000
Water depletion level	WUE (kg/m^3)	WUE (kg/m^3)
65%	20.3a	25.2a
80%	19.7a	24.9a

Different letters within the same column indicate significant difference at $p<0.05$ (LSD test)

But in winter 2000, WUE was comparatively higher than in the summer 1999 season due to more water use in summer 1999. Though the experiment was conducted in greenhouse conditions, it seems that still there exists an impact of outside environmental impact on the greenhouse environment. For 65% moisture depletion level the mean WUE was 20.27 (kg/m^3) and 25.22 (kg/m^3) during summer 1999 and winter 2000, respectively.

In terms of timing of stress, there was a significant difference in WUE for both years. The highest WUE was obtained for the fully irrigated control during summer 1999 whereas it was marginally higher for stress at the flowering stage during winter 2000. WUE was higher in winter 2000 in all the stages due to less water applied (Table 4.12).

Table 4.12. Effects of water stress on water use efficiency (kg/m^3) at different stages of tomato during summer 1999 and winter 2000

Stage	Summer 1999	Winter 2000
	WUE (kg/m^3)	WUE (kg/m^3)
Non stress (control)	27.5a	26.4a
Flowering	20.9b	28.9a
Fruit growth	16.71c	26.1a
Fruit ripening	20.8b	26.0a
Stress all stages	13.8c	18.4b

Different letters within the same column indicate significant difference at $p<0.05$ (LSD test)

The lowest WUE was found at the stress throughout the growing season. It may be concluded that deficit irrigation practices as described in this study did not increase the WUE.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1. Summary

An experiment involving deficit irrigation practices was conducted at the Macdonald Campus greenhouse, McGill University, during summer 1999 and winter 2000. The Sunstart variety of tomato was used in this experiment to observe water stress influence at different developmental stages under different moisture regimes. Nine treatments with four replications were setup in RCBD.

Throughout the growing season, moisture contents were assessed with a portable TDR. Irrigation was given manually on the basis of moisture available in the soil of the different pots with a preset threshold moisture level fixed in the treatments. Photosynthesis was measured to observe the relationship with different soil moisture regimes.

At harvest, tomato yield, maximum and minimum widths and height of fruit and fresh weights of plants were measured. Analysis was done to evaluate the soluble solids and pH of harvested fruit for both years, and color index was also measured. The dry weights of plants at 70 ^{0}C were recorded. WUE were also calculated as a marketable yield (kg) per unit of amount of water (m^3).

5.2. Conclusions

The first objective of the present study was to:

1. Observe the effect of water stress at different phenological stages of tomato plant development. From the present study, it was observed that

a) Water stress at the flowering stage reduced the fruit number but increased the fruit size, resulting in a higher yield.

b) Water stress at the growth stage resulted in fewer fruit being set. The average number of flowers per truss decreased with the decreasing water supply. Water stress at this stage also retarded fruit growth and ultimately fruit size.

c) Stress at fruit growth and ripening stage yielded no significant difference in tomato fruit size between themselves, but size was generally less than for plants stressed at flowering.

d) Water stress at the fruit growth stage and fruit ripening stage significantly increased the fruit quality.

e) Blossom end rot increased dramatically under high water stress imposed on fruit growth stage or stress applied throughout the season.

f) There exists a significant relationship between soil moisture available in the soil and the photosynthetic rate. This is probably, in part, because under water stress, stomates close, and CO_2 exchange is reduced, while when the plant receives sufficient soil moisture stomates are generally open and CO_2 exchange occurs more frequently.

The second objective was to:

2. Observe the influences of water stress on yield, biomass and quality of tomato.

The following effects were observed in the present study:

a) The effect of water stress proved to be significant for tomato quality, fruit size, biomass and blossom-end rot occurrence. With increased water deficit either throughout the season or during the early stage of ripening, and at fruit growth stages, one could expect an increase in soluble solids of the fruits and an improvement in the color index of tomatoes. For tomato products that are sold on solids content basis, the higher the solids of the raw products, the greater the value of the crop. Color of fruit is used as a key quality parameter in grading raw fruit for determination of price for delivered fruit. Hence, a processor may select this irrigation strategy. However, it seems that the range of water deficit levels studied in the present study did not increase the WUE.

b) Tomato yield appeared to increase with the increase of use of water although the size of the fruit may be smaller. This is due to the higher fruit number in non-stress plants.

c) There was no systematic effect of water stress on pH in this study. Increasing the moisture deficit level, could possibly allow one to evaluate this question. Although it seems that water stress decreased the pH of the fruit juice which influences the storability of processed tomato products.

d) A non-stress strategy throughout the growing season is a good choice for the growers that might provide a good yield, but would not necessarily be best for the processor.

e) The present study might serve as a guideline for irrigation management under greenhouse conditions and could provide insight to produce the most economical and best quality tomato product.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE RESEARCH

1. In the present study data from only 36 plants was collected and analyzed. To have more representative results, field trials could provide better and more extensive yield and fruit quality data.

2. Crop water requirements changed according to the different developmental stages. Changing the different irrigation regimes to meet the demand of each stage could prove more useful.

3. Studies with various tomato varieties known to respond differentially to irrigation could determine which variety is the best for a particular moisture level.

4. Studies of deficit irrigation practices with tomatoes in the field could be more effective in identification and evaluation of some field problems and the development of practices which the farmer can implement to improve the yield could in turn improve their socio-economic status.

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Appendix

(Sample input file for LSD test in SAS

& Selected pictures to show water stress effects)

Table A.1. Sample of input file of quality data analysis in SAS during winter 2000.

```
Data molla;
Input awater stage block sols ph colind;
cards;
65      1       1       7.52      4.17          36.36
65      1       2       8.42      4.15          37.91
65      1       3       7.23      4.32          21.22
65      1       4       8.38      4.26          32.67
80      1       1       7.41      4.18          31.60
80      1       2       7.67      4.18          31.18
80      1       3       8.13      4.32          34.92
80      1       4       6.93      4.08          35.90
65      0       1       7.92      4.37          33.47
65      0       2       7.83      4.34          36.43
65      0       3       6.08      4.29          31.02
65      0       4       7.37      4.38          36.01
80      0       1       6.92      4.37          32.47
80      0       2       7.83      4.34          34.43
80      0       3       7.08      4.29          31.02
80      0       4       6.37      4.38          33.01
65      4       1       8.82      4.41          38.89
65      4       2       8.90      4.17          31.09
65      4       3       9.35      4.24          38.32
65      4       4       10.13     4.14          36.10
80      4       1       8.37      4.07          40.64
80      4       2       8.70      4.17          39.68
80      4       3       10.10     3.92          39.19
80      4       4       9.11      4.42          38.99
65      2       1       8.61      4.49          39.89
65      2       2       8.21      4.22          37.03
65      2       3       9.27      4.27          39.65
65      2       4       8.57      4.46          40.02
80      2       1       10.13     4.19          39.24
80      2       2       9.62      4.12          36.87
80      2       3       8.35      4.16          38.82
80      2       4       8.79      4.04          38.32
65      3       1       9.00      4.63          40.31
65      3       2       9.17      4.45          41.29
65      3       3       8.58      4.31          38.70
65      3       4       8.52      4.13          40.10
80      3       1       8.45      4.27          41.50
80      3       2       8.63      4.27          39.38
80      3       3       8.92      4.19          24.91
80      3       4       9.52      4.13          33.09
;
proc anova;
class awater stage block;
model sols ph colind= awater stage block;
means awater stage/LSD;
Run;
```

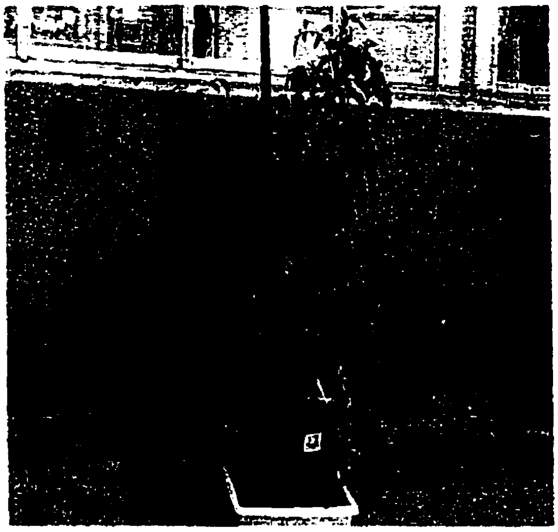
Table A.2.Calculation procedure of irrigation water requirement during greenhouse tomato production

Date	pot no	Treatment	x1	x2	Prob length (m)	x2-x1	eb	0.99	theta	theta-adj	Threshhold moisture level 0,320 deficit1	0,183 deficit2	0,152 deficit3	IRRIG 1	IRRIG 2	IRRIG 3
12-Apr-00	1	R_{80}	2,83	3,22	0,18	0,39	4,898		0,077	0,170	0,150	0,150	0,000	1,41	1,41	0,00
	2	FGR_0	2,83	3,24	0,18	0,41	5,600		0,094	0,197	0,123	0,000	0,000	1,16	0,00	0,00
	3	G_{80}	2,83	3,22	0,18	0,39	4,954		0,079	0,173	0,147	0,147	0,000	1,39	1,39	0,00
	4	F_{80}	2,83	3,26	0,17	0,43	6,528		0,115	0,224	0,096	0,000	0,000	0.90	0.00	0,00
	5	FGR_{65}	2,83	3,24	0,18	0,41	5,475		0,091	0,192	0,128	0,000	0,000	1,20	0,00	0,00
	6	R_{65}	2,83	3,25	0,18	0,42	5,681		0,096	0,199	0,121	0,000	0,000	1,14	0,00	0,00
	7	F_{65}	2,83	3,25	0,18	0,42	5,681		0,096	0,199	0,121	0,000	0,000	1,14	0,00	0,00
	8	FGR_{80}	2,83	3,21	0,18	0,38	4,703		0,073	0,162	0,158	0,158	0,000	1,49	1,49	0,00
	9	G_{65}	2,83	3,2	0,18	0,37	4,458		0,067	0,150	0,170	0,170	0,170	1,60	1,60	1,60
	10	G_{65}	2,83	3,25	0,18	0,42	5,617		0,094	0,197	0,123	0,000	0,000	1,16	0,00	0,00
	11	R_{80}	2,83	3,24	0,18	0,41	5,475		0,091	0,192	0,128	0,000	0,000	1,20	0,00	0,00
	12	F_{65}	2,83	3,23	0,18	0,4	5,152		0,083	0,181	0,139	0,139	0,000	1,31	1,31	0,00
	13	F_{80}	2,83	3,23	0,18	0,4	5,152		0,083	0,181	0,139	0,139	0,000	1,31	1,31	0,00
	14	G_{80}	2,83	3,21	0,18	0,38	4,650		0,071	0,159	0,161	0,161	0,000	1,51	1,51	0,00
	15	FGR_0	2,83	3,24	0,18	0,41	5,475		0,091	0,192	0,128	0,000	0,000	1,20	0,00	0,00
	16	FGR_{80}	2,83	3,19	0,18	0,36	4,173		0,060	0,135	0,185	0,185	0,185	1,74	1,74	1,74
	17	FGR_{65}	2,83	3,21	0,18	0,38	4,598		0,070	0,157	0,163	0,163	0,000	1,54	1,54	0,00
	18	R_{65}	2,83	3,24	0,18	0,41	5,413		0,090	0,190	0,130	0,000	0,000	1,22	0,00	0,00
	19	R_{65}	2,83	3,24	0,18	0,41	5,413		0,090	0,190	0,130	0,000	0,000	1,22	0,00	0,00
	20	G_{80}	2,83	3,24	0,18	0,41	5,413		0,090	0,190	0,130	0,000	0,000	1,22	0,00	0,00
	21	F_{65}	2,83	3,26	0,18	0,43	5,954		0,102	0,208	0,112	0,000	0,000	1,06	0,00	0,00
	22	FGR_0	2,83	3,27	0,18	0,44	6,165		0,107	0,214	0,106	0,000	0,000	1,00	0,00	0,00
	23	F_{80}	2,83	3,25	0,18	0,42	5,681		0,096	0,199	0,121	0,000	0,000	1,14	0,00	0,00
	24	FGR_{65}	2,83	3,24	0,18	0,41	5,413		0,090	0,190	0,130	0,000	0,000	1,22	0,00	0,00
	25	R_{80}	2,83	3,26	0,18	0,43	5,954		0,102	0,208	0,112	0,000	0,000	1,06	0,00	0,00
	26	FGR_{80}	2,83	3,24	0,18	0,41	5,413		0,090	0,190	0,130	0,000	0,000	1,22	0,00	0,00
	27	G_{65}	2,83	3,22	0,18	0,39	4,898		0,077	0,170	0,150	0,150	0,000	1,41	1,41	0,00
	28	FGR_{65}	2,83	3,23	0,18	0,4	5,211		0,085	0,183	0,137	0,137	0,000	1,29	1,29	0,00
	29	R_{80}	2,83	3,27	0,18	0,44	6,234		0,109	0,216	0,104	0,000	0,000	0,98	0,00	0,00
	30	FGR_0	2,83	3,25	0,18	0,42	5,745		0,097	0,201	0,119	0,000	0,000	1,12	0,00	0,00
	31	G_{65}	2,83	3,23	0,18	0,4	5,152		0,083	0,181	0,139	0,139	0,000	1,31	1,31	0,00
	32	F_{65}	2,83	3,22	0,18	0,39	4,954		0,079	0,173	0,147	0,147	0,000	1,39	1,39	0,00
	33	FGR_{80}	2,83	3,29	0,18	0,46	6,891		0,124	0,233	0,087	0,000	0,000	0,82	0,00	0,00
	34	R_{65}	2,83	3,26	0,18	0,43	5,954		0,102	0,208	0,112	0,000	0,000	1,06	0,00	0,00
	35	G_{80}	2,83	3,24	0,18	0,41	5,475		0,091	0,192	0,128	0,000	0,000	1,20	0,00	0,00
	36	F_{80}	2,83	3,28	0,18	0,45	6,595		0,117	0,226	0,094	0,000	0,000	0,89	0,00	0,00

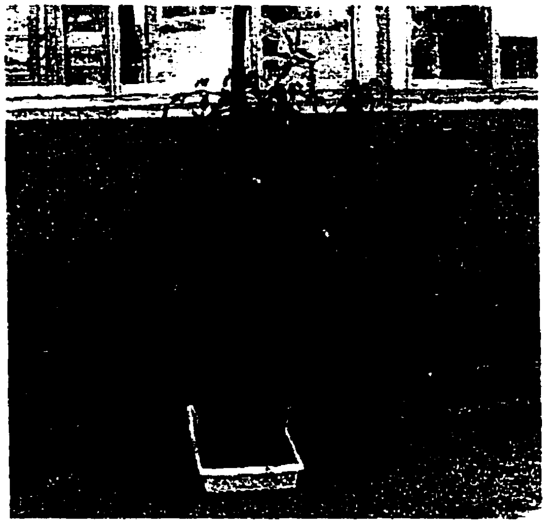
Deficit 1= Field capacity-avalable soil moisture
Deficit 2= 2nd threshold moisture level (0,183) -avalable soil moisture
Deficit 3= 3rd threshhold moisture level (0,152) - avalable soil moisture

Theta and theta adjusted was calculation according to equation 3,1 and equation 3,2,
Calculation procedure; Average area of the soil surface in the pot = 471,3 cm^2 and depth of the root zone =20 cm.

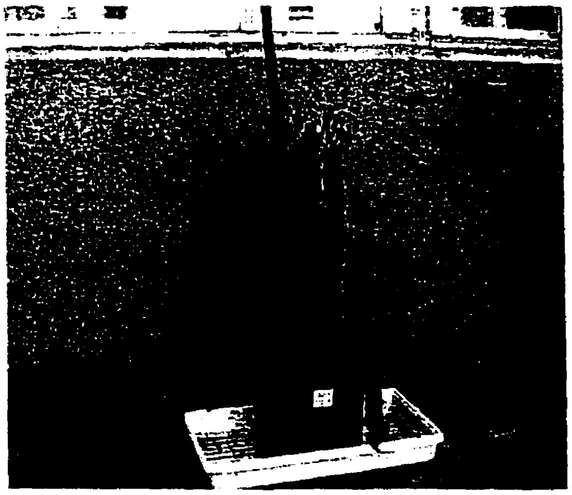
Hence, irrigation requirement (litres) = deficit*depth of root zone(cm)*surface area(cm^2)/1000,



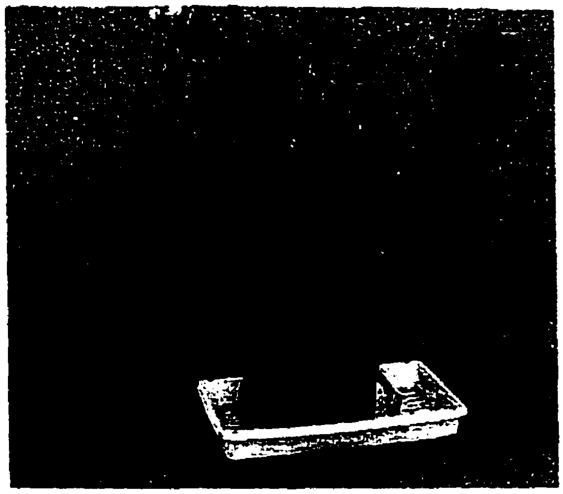
A non-stressed plant



A non-stressed plant



A severely stressed plant



Moderately stressed plant

Figure A.1. Effect of water stress on tomato

Figure.A.2. A picture of the whole experiment in greenhouse.