Water and nitrogen use efficiency of corn (*Zea mays* L.) under water table management

Ajay Kumar Singh

Department of Bioresource Engineering

Macdonald Campus of McGill University

Montreal, Canada

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Doctor of Philosophy

Submitted: February 2013

Abstract

Drainage and water table management are essential for crop production in humid regions. Water table management not only increases crop yield, but also reduces nitrate leaching to water bodies. This study investigated the water and nitrogen use efficiency of corn under two water management conditions and three nitrogen fertilizer levels. The sap flow heat balance method was used to measure the daily water uptake of corn, over an extended period of the growing season. The impacts of climate change on grain corn and biomass yield in eastern Canada under tile drained conditions was also evaluated over a 30 year future period (2040 to 2069).

The study was conducted at a field scale in 2008 and 2009 at St. Emmanuel, Quebec. The two water management conditions were: conventional drainage (FD), and controlled drainage with subirrigation (CD-SI). The three nitrogen (N) fertilizer treatments (low, medium, and high N) were applied in a strip across three blocks.

The seasonal water balance indicated that the plants in the CD-SI plots had more water than required in the wet periods, despite the system automation, while the FD plots exhibited deficit water conditions. Water could be saved in the wet periods by better regulating water supplied by subirrigation. However, in dry years, the CD-SI system increased yield. The grain corn water use efficiency (WUE) for FD plots was 2.49 and 2.46 kg m^{-3}, in 2008 and 2009, respectively. In these years, the grain WUE for CD-

SI plots was 2.43 and 2.26 kg m^{-3}. Water management treatments demonstrated significant difference ($p < 0.05$) in grain yields in 2009, at low and high nitrogen levels. However, at the medium nitrogen level, water management demonstrated no significant effect ($p > 0.05$) on grain yields. The two water treatments had no effect on the above-ground dry biomass yields in both years. Mean nitrogen use efficiency (NUE) of grain corn and biomass varied from 27 to 99 kg kg^{-1}. Highest NUE (99 kg kg^{-1}) was observed under low N (~120 kg N ha^{-1}) and lowest NUE (41 kg kg^{-1}) occurred in the high N (~260 kg N ha^{-1}). This might be due to higher nitrogen losses due to leaching, residual nitrogen in the soil, and more denitrification in high N plots.

The rate of plant water uptake measured by the sap flow method, varied from 3.55 to 5.11 mm d^{-1} from silking to full dent stage of corn growth. These rates were consistent with ET_c calculated by the FAO-56 Penman-Monteith method (3.70 to 5.93 mm d^{-1}) for both years. Although, silking is considered as a critical stage for corn growth, water demand was highest at the milk stage (45.63 to 59.80 mm). Transpiration during this stage constituted 10 to12% of the total water requirement of the corn for the season. The silking to full dent stage accounted for approximately 40% of the total water requirement of the crop.

The STICS (JavaStics v1.0) crop model was used to examine the impacts of climate change, under the B1 emissions scenario, on corn yield from 2040-2069. The model was calibrated using 2008 field measured data, and then validated using the 2009 data set. Corn grain yield was underestimated by 1.5 to 2.6 Mg ha^{-1} for the two years of measurement. Total dry biomass was also underestimated by 0.9 to 2.6 Mg ha^{-1}. Simulations for the B1 emissions scenario using synthetic weather data was run under the same crop conditions as in 2008. Tukey's studentized range (HSD) test of corn grain yield indicated that yields at high and low N, and high and medium N were different at the 95% confidence level. Grain and biomass production from 2040-2069 under B1 emissions scenario responded differently ($p < 0.05$) for the three N treatments. However, the Mann–Kendall test showed neither increasing nor decreasing trend (MK-stat > - 1.96) at a 95% confidence level.

Résumé

Le drainage et la gestion de la nappe phréatique des parcelles agricoles permet non seulement d'augmenter la production des récoltes, mais aussi de réduire les pertes de nitrates par lessivage, qui contribue à leurs transferts vers les étendues d'eau. Cette étude a examiné l'efficacité d'utilisation de l'eau et de l'azote du maïs grain sous deux conditions de gestion de l'eau et trois niveaux d'application d'azote. Les facteurs climatiques jouent un rôle important dans la production du maïs-grain. Les impacts des changements climatiques sur les projections de maïs-grain et de la production de biomasse en sol drainé ont aussi été évalués pour l'est du Canada pour une période futur de 30 ans (2040 à 2069).

L'étude a été accomplie à l'échelle du champ en 2008 et en 2009 à Saint Emmanuel au Québec. Les deux scénarios de gestion de l'eau étaient (a) le drainage conventionnel (FD) et (b) le drainage contrôlé combiné à l'irrigation souterraine (CD-SI). Les trois traitements d'azote (N) (dose faible, moyenne et élevée) ont été appliqués en bande sur trois blocs. La méthode du bilan thermique relatif à l'écoulement de la sève a été utilisée pour mesurer la consommation d'eau quotidienne du maïs-grain.

Le bilan hydrique saisonnier a indiqué un surplus d'eau pour les blocs en CD-SI alors que les blocs en FD étaient en déficit d'eau. Lors des périodes pluvieuses, l'eau pourrait être économisée pour les champs en système CD-SI en contrôlant l'eau provenant de l'irrigation souterraine. En contrepartie, le système CD-SI augmente la production des années

sèches. L'efficacité d'utilisation de l'eau du maïs (WUE) pour les blocs en FD était de 2.49 kg m^{-3} et 2.46 kg m^{-3} en 2008 et 2009 respectivement. Pour ces années, L'WUE du maïs-grain pour les blocs en CD-SI était de 2.43 kg m^{-3} et de 2.26 kg m^{-3}. Les traitements relatifs à la gestion de l'eau ont permis d'améliorer la production de rendement du maïs-grain significativement ($p < 0.05$) en 2009, que cela soit avec des doses d'azotes basses ou élevées. Cependant, pour des doses intermédiaires, la gestion de l'eau n'a démontré aucun effet significatif ($p > 0.05$) sur les productions de maïs-grain. Les deux traitements relatifs à la gestion de l'eau n'ont eu aucun effet sur la production de biomasse sèche au-dessus du sol pour les deux années. L'efficacité moyenne de l'utilisation de l'azote (NUE) du maïs grain et de sa biomasse variait de 27 kg kg^{-1} à 99 kg kg^{-1}. La plus haute NUE (99 kg kg^{-1}) a été observée pour une dose de N faible (~120 kg N ha^{-1}). La plus basse NUE (41 kg kg^{-1}) s'est produite pour une dose de N élevée (~260 kg N ha^{-1}).

La consommation des plantes en eau mesurée par la méthode d'écoulement de la sève, vari de 3.55 mm d^{-1} à 5.11 mm d^{-1} pour la période de l'apparition des soies jusqu'à la croissance complète du maïs-grain. Ces taux sont en accord avec l'ET_c calculée (3.70 mm d^{-1} à 5.93 mm d^{-1}) pour les deux ans. Bien que, le développement de la soie soit considéré comme le stade critique pour le maïs-grain, la demande en eau fut la plus élevée lors du stade laiteux du développement du maïs (45.63 mm à 59.80 mm). À ce stade, 10 à 12% des besoins totaux de la plante en eau pour la saison furent transpirés. Du stade de la soie jusqu'au développement complet de l'épi de maïs les besoins en eau de la plante ont représenté environ 40 % de son besoin total.

Le modèle de récolte STICS (JavaStics v1.0) a été utilisé pour examiner les effets du changement climatique sur la production de maïs-grain, de 2040 à 2069 et sous le scénario d'émissions de gaz à effet de serre B1. Le modèle a d'abord été calibré en utilisant les données mesurées au champ en 2008 et, a ensuite été validé avec l'ensemble des données de 2009. La production de maïs-grain est sous-estimée de 1.5 Mg ha^{-1} à 2.6 Mg ha^{-1} pour les deux ans de mesure. La biomasse sèche totale est aussi sous-estimée de 0.9 Mg ha^{-1} à 2.6 Mg ha^{-1}. Les simulations pour le scénario d'émissions B1 en utilisant des données météorologiques synthétiques font été utilisées dans les mêmes conditions de récolte que 2008. Le test : studentized de Tukey (HSD) appliqué au rendement de maïs-grain a indiqué que les rendements étaient différents avec un niveau de confiance de 95%, pour des doses faibles et élevées ainsi que pour des doses élevées et intermédiaires de N. Les prédictions de la production de maïs-grain et de sa biomasse pour la période 2040-2069 sous le scénario d'émissions B1 sont différentes ($p < 0.05$) selon les trois traitements de N. Cependant, l'épreuve de Mann-Kendall n'a montré aucune tendance à la hausse ou à la baisse (MK-stat> - 1.96) pour un niveau de confiance de 95%.

Acknowledgements

My sincere thanks to thesis supervisor, Dr. Chandra A Madramootoo, for his guidance, understanding, and patience throughout this study. I am very thankful for the confidence he showed in me for my research work. I would also like to thank my thesis committee adviser Dr. Donald L. Smith, for his knowledgeable guidance, and reviewing the manuscripts very patiently.

I am grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC) for providing funding for this project. I acknowledge Dr Samuel B. Gameda, Eastern Cereal and Oilseed Research Centre (ECORC), Agriculture and Agri-Food Canada, Ottawa, Canada, for providing us with synthetic weather data used for this research. I appreciate the support of Dr. Ian Strachan, Associate Professor of Micrometeorology in the Department of Natural Resource Sciences, McGill University, for providing the weather data (2008-2009) used in this study. Thank you to Mr. Guy Vincent for accommodating our experiment design on his field where the experiments were carried out.

Additional thanks are extended to Dr. Shiv Prasher, Professor and Chairman of the Department of Bioresource Engineering, for his valuable support during the period of my research. I also appreciate the support of Ms. Susan Gregus, Ms. Trish Singleton and Ms. Abida Subhan for administrative and office support. Thank you to Wendy Ouellette, for your

help, professionalism, support, advice and above all, a friend, with whom I shared my happiness and disappointments.

Thank you to Dr Marcia Knutt, who was my TA supervisor. It was fun and learning experience to work with her in Physics freshmen laboratory. Special thanks to Dr. Xiaomin Zhou, and Dr. Caroline Begg, who helped me in the experiment design. If I had questions on nitrogen and plant response, I would go to them without appointment; they answered my questions and/or guided my thinking to find the solutions. Thank you to Mr Peter Kirby, who helped in grain and biomass sampling, and also reviewing my first manuscript. Thank you to Ms Helene Lalande, for her assistance in the laboratory for soil analysis. Thanks to Sam and Scott for their help in the workshop. Thank you to my friends, Apurva, Simone, Mark, Colline, Rufa, Olanike, Felix, Emily, Eddy, Heidi, Bano, Candice, Kenton, Satya, Rakesh, Katie, and many others who helped me in my field work and daily life. Their listening ears and encouraging smiles had made this experience to remember for a long time.

Special thanks to my friend Dr. Bijaya Adhikhari for his encouragement, and constructive feedback. He has gone through all my manuscripts and helped me improve it considerably. Special thanks to Dr. Manish Goyal, who provided help in calibration and validation of the STICS model, climate change impacts assessment, and statistical analysis. And special thanks to my friends at Macdonald Athletics Department, Silvia

Cristofaro, Don Moffat, Bill Ellyett, Andrew Leroux, and Lee Beiber, who made my stay in Montreal, as pleasant as it can be.

I would like to express my deep gratitude to my wife, Archana, understanding, love, and support; and my dear sons Priyanshu and Sudhanshu for their patience to wait for the right time to play with me. Finally, I would also like to acknowledge my parents, my brother, and sisters for their help and support to let my dreams come true.

I would like to dedicate this thesis to my PhD supervisor Dr C.A. Madramootoo. I could not have finished this program unless I would have received continuous support, encouragement, and guidance from him.

Contribution of authors

This thesis has been written in Manuscript - based format. Ajay K. Singh, Dr. Chandra A. Madramootoo and Dr. Donald L Smith are co-authors of all manuscripts in this thesis (Chapter 3, 4, and 5). All the experimental works, analysis of data, and preparation of manuscripts were completed by the candidate, Ajay Kumar Singh, under the supervision of Dr. Madramootoo and Dr. Smith. Both gave the guidance, technical information, reviewed, and edited the manuscripts. Dr. Madramootoo provided the necessary funds to carry out this research. Dr Manish K Goyal is co-author in Chapter 5, provided assistance in calibration, validation, and climate change impact assessment with the STICS crop model.

List of manuscripts based on the thesis:

1. Ajay K. Singh, Chandra A. Madramootoo, Donald L. Smith. (Chapter 3). Water and nitrogen use efficiency of corn under different water and nitrogen management scenarios. Transactions of the ASABE (under review).
2. Ajay K. Singh, Chandra A. Madramootoo, Donald L. Smith. (Chapter 4). Determination of corn water uptake using sap flow method. Agricultural and Forest Meteorology (under review)
3. Ajay K. Singh, Chandra A. Madramootoo, Manish K. Goyal, Donald L. Smith. (Chapter 5). Corn yield simulation using the STICS model

under varying nitrogen management and climate change scenarios. Agricultural and Forest Meteorology. (under review).

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Nomenclature

The most commonly used symbols, abbreviations and acronyms are listed below. The specific symbols that are used in a particular equation or section are described at their place of appearance in the text.

ANOVA	analysis of variance
CD-SI	controlled drainage with subirrigation
CHU	crop heat unit
d	index of agreement
DAP	days after planting
ET	evapotranspiration, mm
ET_c	crop evapotranspiration, mm
ET_r	reference evapotranspiration, mm
FD	conventional or free drainage
GCM	general circulation model
GDD	growing degree days, ^oC
GLM	general linear model
K_{cb}	basal crop coefficient
K_{sh}	stem gage constant
LAI	leaf area index
MBE	mean bias error

MK	Mann-Kendall
N	nitrogen
NUE	nitrogen use efficiency
R^2	coefficient of determination
RH	relative humidity, %
RMSE	root mean square error
R_s	solar radiation, MJ m^{-2}
RUE	radiation use efficiency, g dry matter MJ^{-1}
S	Kendall score
SI	subirrigation
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard
T	transpiration, mm
u_2	wind speed at 2 m height above the ground surface, ms^{-1}
VPD	vapour pressure deficit, kPa
WUE	water use efficiency, %

Chapter 1

Introduction

Subsurface drainage is necessary to increase agricultural production in humid regions of the world. Tile drains have been installed extensively in United States and Canada to remove excess soil water. Subsurface tile drainage has been implemented in over 735,000 ha of farmland in Quebec, Canada (Gollamudi, 2006).

Although conventional drainage improves machine trafficability and increases crop yields (Madramootoo et al., 2007), it can also lead to soil water stress in during dry periods.Controlled drainage systems help farmers to better manage the soil moisture by removing excess water in wet periods of the season. During dry periods, farmers can close the drain outlets to retain moisture in the field. In order to have more control over the soil moisture and provide optimum conditions for growth, subirrigation can be implemented in conjunction with controlled drainage. Controlled drainage with subirrigation, removes excess water from the soil during wet periods, in addition to maintaining a desirable water table depth during dry periods. In periods of water deficit, water is provided to the crop from an external source, via the tile drainage system. This reduces drought stress and provides the crop with an optimum environment for growth. Drained lands are among the most productive lands in the world (Wright and Sands, 2001).

While, there has been research to study water and nitrogen use by plants, the two most important components affecting yield, there has been few research on the effect of different water table management scenarios over a range of nitrogen levels on water use efficiency (WUE) and nitrogen use efficiency (NUE). This study, therefore investigates the effects of three nitrogen levels under two water table management conditions on water and nitrogen use efficiency, and corn yield.

An additional concern is the impact of a changing climate on crop production, especially in light of diminishing land and water resources. Crop growth model studies can be used to predict yields under different climatic regimes, and may be used to assess the impacts of climate change on corn grain and biomass yield in eastern Canada under tiled drained conditions. The STICS crop model was used to analyze the corn grain and biomass yield trend due to the effects of climate change under three nitrogen levels from 2040 to 2069.

1.1. Objectives

This research was conducted with two main objectives:

1. To investigate the water and nitrogen use efficiency for various water management scenarios, over a range of nitrogen levels.

2. To predict crop growth response to various water table and nitrogen management scenarios using the STICS crop growth model.

These main objectives were achieved through the following specific objectives:

i. To determine water use efficiency and nitrogen use efficiency for conventional drainage and controlled drainage along with subirrigation over a range of nitrogen levels.
ii. To determine water uptake by corn at various stages of growth using the sap flow heat balance method under two water management scenarios.
iii. To evaluate the STICS model for different nitrogen application levels on a conventional drainage system, and assess the impacts of climate change on corn grain and biomass yield in eastern Canada under tile drained conditions and a B1 greenhouse gas emissions scenario.

1.2. Scope

This study was conducted in southern Quebec which is characterized by a humid climate and winter conditions such that soils remain frozen for approximately 4 to 5 months a year. The soil was a Soulanges very fine sandy loam underlaid by clay deposits, classified also as Humic Gleysol.

The field was tile drained and the topography was flat. The crop grown was corn in both study years. Hence, the results and recommendations of this research are limited to similar conditions.

1.3. Thesis outline

This thesis has been written in a ‘manuscript based’ style. Chapter 1 is general introduction, which presents the research topic, gaps in knowledge, and objectives of the research. Chapter 2 presents the literature review on topics such as drainage, water use efficiency, nitrogen use efficiency, sap flow measurement methods, crop growth models, and climate change. Chapters 3, 4, and 5 present the results of the experiments in the form of three papers with connecting text. Tables and Figures are given at the end of each chapter. The format of the three manuscripts has been changed to be consistent with the requirements of Library and Archives Canada. All the references cited in the thesis are given at the end of the thesis.

Chapter 2

Literature review

2.1 Water availability

Although three-fourth of earth's surface is covered by water, only 3% of it is fresh water (Fry, 2005), and over 2.5% is frozen, locked up in Antarctica, the Arctic and glaciers, and not available for human use. Only 0.5% of the world's total water is available for consumption (Fig. 2.1). Seventy-seven percent of surface freshwater is stored as ice and 22% as groundwater and soil moisture. The remaining freshwater, making up less than 1% of the world total, is contained in lakes, rivers and wetlands. Agriculture is the largest user of fresh water for irrigation, consuming nearly 60% (Siebert et al., 2007, USGS, 2005). Irrigation water use comprises 31% of total surface water and 68% of ground water is used for agriculture (USGS, 2005). Although fresh water is considered a renewable resource, the quantity of available fresh water is steadily decreasing. In North Gujarat, India, the water table is falling by 3 to 6 meters per year over the last 15 to 20 years due to over utilization that exceeded aquifer recharge rate (Brown, 2006). The underground water table has dropped by more than 30 meters since 1940's in parts of Texas, Oklahoma, and Kansas, the three leading grain-producing states in the United States (Brown, 2006).

The sources of freshwater are also shrinking due to pollution and injudicious use of water. Without appropriate management, irrigated agriculture can be detrimental to the environment and endanger long-term sustainability (Howell, 2001). The best ways to address this are to enhance water use efficiency (WUE) in irrigated agriculture which increases the output per unit of water utilization, reduces losses of water to unusable sinks, reduces water degradation and reallocates water to higher priority uses (Howell, 2001).

2.2 Corn production and nitrogen utilization

North America is a major corn producer representing more than one-third of the corn production worldwide (Table 2.1). In 2011, close to 170 million ha of corn was harvested worldwide, with a production of 884 million Mg (FAOSTAT, 2013). Corn is the third largest grain crop in Canada (after wheat and canola), and the most important crop in Eastern Canada (Pattey and Jégo, 2010). Canada produced 11 million Mg of corn in 2011 on an area of over 1.2 million ha (Table 2.1) (FAOSTAT, 2013).

Nitrogen (N) is one of the major components of crop fertilizers; it improves the crop yield and aids in feeding billions of people worldwide. High-yielding varieties of rice, wheat, and corn were released during the Green Revolution; these respond to high N inputs (Earl and Ausubel, 1983) and this, along with low cost of chemical fertilizer, easy availability, lack of awareness (Tabi et al., 1990) led to over fertilization. Global fertilizer consumption was 169 million Mg in 2007-2008 (Heffer, 2009). Nitrogenous fertilizer accounted for 98 million Mg or 60% of total fertilizer use (Heffer, 2009). Cereals account for 50% of the total fertilizer consumption (Fig. 2.2) with maize accounting for 16% of the total fertilizer use and 17% of the world total nitrogenous fertilizer use (Fig. 2.3). Thus, 16 million Mg of nitrogenous fertilizer is applied annually to corn cultivation. Canada applied a total of 1.8 million Mg of nitrogenous fertilizer with 156,000 Mg (8.9%) to corn fields in 2006-07. Higher nitrogen application increases corn yield but it also creates health and environmental hazards when nitrogen leaches out to rivers and lakes (Madramootoo et al., 1992). High concentration of nitrates in drinking water may cause methemoglobinemia, also known as blue-baby syndrome, and other health disorders (Gelberg et al., 1999). Water table management is a tool that has been demonstrated to mitigate the problem, as well as increase the crop yield (Elmi et al., 2002, Madramootoo, C.A., 1990).

2.3 Tools for conservation of water resources

2.3.1 Water table management

In many regions of the world, subsurface drainage is necessary to increase agricultural production. Tile drains have been installed extensively in United States and Canada to drain excess water from the agricultural fields. In Quebec alone, subsurface drainage has been implemented in over 735,000 ha of farmland (Gollamudi, 2006). The benefits of water table management include an increase in water storage capacity in the soil profile, reduces damage to soil structure, improves physical properties, decreases tile drainage peak flow rates and outflow volumes under certain conditions, a strong reduction of nitrate concentrations in tile drainage outflows, and increased crop yield (Hundal et al., 1976, Amatya et al., 1998, Madramootoo, 1990, Madramootoo et al.,1992, Mejia and Madramootoo, 1998, Skaggs et al., 1995, Busman and Sands, 2002, Stampfli and Madramootoo, 2006, Zhao et al., 2000). Drained lands are some of the most productive in the world (Wright and Sands, 2001).

2.3.2 Types of water table management systems

There are three kinds of water table management systems: (i) conventional drainage (FD), (ii) controlled drainage (CD), and (iii) controlled drainage with subirrigation (CD-SI). In a conventional drainage system, drains are laid out at certain depth to remove excess water from the field (Fig. 2.4). The farmer has no control on the flow of water leaving the field in this system. While drainage improves trafficability and crop yields, it can also cause soil water deficit stress in drought seasons. However, with controlled drainage systems, farmers can open the drains to remove excess water in wet periods and close the drains to retain moisture in the field when drought is forecasted. This reduces the need for water from external sources during subsequent dry periods (Amatya et al., 1998). In order to have more control over soil moisture conditions and provide optimum conditions for growth, subirrigation can be done in conjunction with controlled drainage. Controlled drainage with subirrigation, removes excess water from the soil at the beginning of the season, and also maintains a desirable water table depth later in the season. During periods of water deficit, subirrigation provides adequate water to the crop from an external source, via the tile drains (Fig. 2.5). When precipitation exceeds the amount of water required by the crop, subirrigation is stopped and the system acts like a conventional drainage system and excess water is drained from the field (Fig. 2.6).

2.3.3 Water use efficiency

Water use efficiency (WUE) does not have a single precise definition (Bacon, 2004). In its simplest terms, it is characterized as crop yield per unit of water use. At a more biological level, it is the carbohydrate formed through photosynthesis from CO_2, sunlight, and water per unit of transpiration (Howell, 2001; Bacon, 2004). Jones (2004) defines WUE as the ratio of the rate of mass production to the rate of plant transpiration also known as transpiration efficiency. At a crop or vegetation scale, she further defines water use efficiency as the ratio of production of total biomass, shoot biomass or harvested yield against total evapotranspiration or plant transpiration. Howell (2001) stated that in agronomic perspective, WUE is the ratio of crop yield (usually the economic yield) to the water used to produce the yield. The WUE is expressed in units of kg of plant material per unit water volume (m^{-3}) or g plant material kg^{-1} per unit water volume (m^{-3}). WUE of corn ranged from 1.1 to 2.7 kg m^{-3} globally (Zwart and Bastiaanssen, 2004).

2.4 Nitrogen use efficiency

Nitrogen use efficiency (NUE) can be defined as grain yield per unit N fertilizer applied (G_w/N_f) (Sowers et al., 1994). Campbell et al. (1993) estimated N supply as the sum of (i) soil nitrate measured in spring, and (ii) N fertilizer applied. Moll et al. (1982) defined NUE as grain yield per unit N supplied (G_w/N_s); both variables are expressed in the same units. NUE was measured using Campbell et al. (1993) procedure in this study.

NUE for cereal production is 33% worldwide (Raun and Johnson, 1999). In Quebec, NUE can vary from 9 to 58% for nitrogen application rate of 400 and 170 kg N ha^{-1}, respectively (Liang and Mackenzie, 1994). Wienhold et al. (1995) studied fertilizer use efficiency under irrigated conditions. They found that above ground dry matter production exhibited greater response to N fertility than the grain. They also found that grain utilized 35% and stover an additional 15% of the applied fertilizer, while 30% remained in the upper 0.6 m of the soil profile at the end of the growing season. Twenty percent of the applied fertilizer could not be accounted for, presumably being lost to leaching or denitrification.

In 1999, the world population reached six billion (USCB, 2007). The UN estimates that by 2050 there will be an additional three billion people with most of the growth occurring in developing countries (USCB, 2007). There will be increased demand for water and food to sustain the needs of an increased population. Corn requires 2.5 m^3 of water to yield 1 kg grain (; C.A. Madramootoo, personal communication, 2007). This emphasizes the need for efficient utilization of water and fertilizer to increase crop productivity of agricultural lands.

2.5 Crop water uptake

2.5.1 Role of water

Every plant process is affected directly or indirectly by the water supply (Kramer, 1959). Plant growth is controlled by the supply of organic and inorganic compounds required for synthesis of new protoplasm and cell walls, rates of cell division and enlargement of cells with water. Water is essential to maintain all of these processes. Water constitutes 80 to 90% of most plant cells and tissues in which there is active metabolism. It forms a continuous liquid phase through the plant from root hairs to the leaf epidermis (Kramer, 1959). Water in plants acts as a reagent or reactant in various physiological processes, including photosynthesis, and hydrolytic processes such as the digestion of starch and sugar. It’s role in these processes is just as essential as that of carbon dioxide and nitrogen. Water also acts as a solvent in which minerals, gases and other solutes enter plants and move from cell to cell within the plant. Another essential role of water is in maintenance of turgidity of plant tissues. The most evident and important overall effect of an internal water deficit is reduction in vegetative growth, because maintenance of water content, and therefore turgor, is essential for cell enlargement (Kramer, 1959). In view of these facts, water is among the most important environmental factors for plant growth and development, and also other biochemical processes as photosynthesis and respiration.

2.5.2 Soil water pressure

Soil water is subject to a number of forces, which cause its potential to differ from that of pure free water. Accordingly, the total soil water potential is the sum of the separate contribution of these factors, as shown in Eq. 2.1 (Michael, 1995):

$$\Phi_t = \Phi_g + \Phi_p + \Phi_o + \ldots\ldots\ldots\ldots \tag{2.1}$$

where Φ_t is the total soil water potential, Φ_g the gravitational potential, Φ_p the pressure (or matric) potential and Φ_o the osmotic potential. The gravitational potential (Φ_g) arises from the gravitational forces acting on the water in the soil. The matric potential (Φ_t) arises from capillary and adsorptive forces associated with the soil matrix. The osmotic potential (Φ_o) or osmotic pressure arises from the presence of dissolved solutes. The turgor potential (Φ_p) arises from the forces exerted on the cell walls, by the water drawn into the cell by the solutes and solids in the protoplast. It is also termed as turgor pressure, wall pressure, hydrostatic pressure or pressure potential (Michael, 1995).

The complete path of water from the soil through the plant to the atmosphere forms a continuous system that may be analysed by evaluating the potential difference between soil and atmosphere in contact with roots and leaves, respectively. The path of water may be divided into four sequential processes as follows:

soil → roots → stems → leaves → atmosphere

The rate of water movement is proportional to the potential gradient and inversely proportional to the resistance to flow. The magnitudes of these potentials are given below (Michael, 1995):

Soil	-10 to -2,000 kPa
Leaf	-500 to -5,000 kPa
Atmosphere	-100,000 to -200,000 kPa

The properties of both soil and roots determine the degree of water uptake by the roots. Water absorption by roots is dependent on the supply of water at the root surface. As the soil dries out from the saturated state, the rate of movement of water in the soil decreases rapidly. Water movement in a soil drier than field capacity, controls the distance in the soil, from which roots can extract water.

Plant cells lose water when solute concentrations are higher outside than inside, or when evaporation occurs faster than the water can enter the cells. In either case, the cells shrink as the volume of water decreases inside, turgor pressure declines, and as a result, plants will eventually begin to wilt. As water is lost to the atmosphere from the mesophyll and inner surfaces of the epidermal cells of the leaf, the water potential of these cells falls and a gradient in water potential is then established between plant leaves and the soil. This gradient is proportional to the rate of transpiration and to the resistances to water flow in the soil and plant.

2.5.3 Atmospheric demand: Evapotranspiration

Transpiration is the loss of liquid water contained in the plant tissues and the vapour removal to atmosphere. Evaporation is the process whereby liquid water is converted to water vapour and lost to the atmosphere. Evaporation and transpiration occurs simultaneously, and these two processes are together known as evapotranspiration (ET). At sowing, nearly 100% of ET comes from evaporation, while at full crop cover more than 90% of ET comes from transpiration.

The ET is affected by weather parameters, crop characteristics, crop management practices, and environmental aspects (Allen et al., 1998). The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity, and wind speed. The crop type, variety and developmental stage impact the evapotranspiration from crops. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels among various crops under identical environmental conditions. Factors such as soil salinity, poor land fertility, limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration (Allen et al., 1998).

There are different terms for evapotranspiration, such as reference evapotranspiration (ET_r), crop evapotranspiration under standard conditions (ET_c), and evapotranspiration under non-standard conditions (ET_{adj}). The reference surface is a hypothetical grass crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen et al., 1998). The reference surface closely resembles a uniform surface, consisting of the same or similar vegetation, having specified height, not lacking in water, and should stretch 100 m in every direction. The ET rate measured from such surface is called ET_r. The ET_r values measured or calculated at different locations or in different seasons are comparable as they refer to the ET from the same reference surface (Zotarelli et al., 2010). It obviates the need to define a separate ET level for each crop and stage of growth. The only factors affecting ET_r are climatic parameters. The ET_c for a given location can be determined from ET_r using a crop specific coefficient (K_c).

$$ET_c = K_c * ET_r \tag{2.2}$$

2.5.4 FAO-56 Penman-Monteith evapotranspiration method

ET can be determined by many different methods but estimated results are inconsistent (Grismer, 2002). Different ET methods were evaluated with lysimeter data, and it was found that FAO-56 Penman-Monteith method is relatively accurate and consistent in both arid and humid climates (Allen et al., 1998, Itenfisu et al., 2003). The FAO-56 Penman-Monteith method has a root mean square difference of 0.8%, lowest of all ET methods when hourly and daily weather data from 49 geographically diverse sites in the United States were compared (Itenfisu et al., 2003). Hence, the FAO-56 Penman-Monteith method was used in this study and is discussed below.

Penman equation (Eq. 2.3) which is based on a combination of energy balance and aerodynamic formulas, and Monteith (1965) bulk surface resistance term are combined together to give the Penman-Monteith equation (Eq. 2.4).

$$\lambda E = \frac{[\Delta(R_n - G] + (\gamma \lambda E_a)}{(\Delta + \lambda)} \qquad (2.3)$$

and

$$\lambda ET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad (2.4)$$

where λET is the latent heat flux (evapotranspiration) (mm d^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s-e_a is saturation vapour pressure deficit (kPa), Δ is slope of vapour pressure curve (kPa °C^{-1}), γ is psychrometric constant (kPa °C^{-1}), r_s and r_a are the (bulk) surface and aerodynamic resistance, and E_a is vapour transport flux (mm d^{-1}).

2.5.4.1 Aerodynamic resistance

Aerodynamic resistance (r_a) is the transfer of heat and water vapour from the evaporating surface to the air above the canopy (Allen et al., 1998). For neutral stability conditions, r_a is defined as:

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right]\ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \tag{2.5}$$

where r_a is aerodynamic resistance (s m^{-1}), z_m is height of wind measurements (m), z_h is height of humidity measurements (m), d is zero plane displacement height (m), z_{om} is roughness length governing momentum transfer (m), z_{oh} is roughness length governing transfer of heat and vapour (m), k is von Karman's constant, 0.41 u_z is wind speed at height z (m s^{-1})

2.5.4.2 (Bulk) surface resistance (r_s)

The 'bulk' surface resistance describes the resistance of vapour flow through the transpiring crop and evaporating soil surface (Allen et al., 1998) and is defined as:

$$r_s = r_1 / LAI_{active} \tag{2.6}$$

where r_s is (bulk) surface resistance (s m^{-1}), r_1 is bulk stomatal resistance of the well-illuminated leaf (s m^{-1}), and LAI_{active} is active (sunlit) leaf area index [m^2 (leaf area) m^{-2} (soil surface)].

The FAO-56 Penman-Monteith (Eq. 2.7) is derived from the Penman-Monteith equation (Eq. 2.4), and the equations of the aerodynamic (Eq. 2.5) and surface resistance (Eq. 2.6):

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2.7)$$

2.5.5 Sap flow method

Sap flow methods are direct ways of measuring transpiration rate or water uptake by herbaceous plants and trees. Sap flow methods are becoming increasingly popular for determining water needs of crops. They have been used on a range of herbaceous plants such as corn, cotton, grapes olive, orange, papaya, plum, potato, soybean, sunflower, rose, and sugarcane, and trees such as apples, apricot, beech, birch, cottonwood, date palm, fir, hardwood, oak, and pine, (Assouline et al., 2002, Bethenod et al., 2000, Cohen and Li, 1996, Bovard et al., 2005, Brooks et al., 2003; Chabot et al.,2005, de Oliveira et al., 2006, Dugas et al., 1994, Fernandez et al., 2001, Fernandez et al., 2006, Gazal et al., 2006, Gessler et al., 2005, Gong et al., 2006, Gordon et al., 1997, Granier et al., 1996, Granier et al., 2000, Heilman et al., 1994, Jara et al., 1998, Johnson et al., 2004, Katul et al., 1997, Matinez-cob et al., 2008, Moreno et al., 1996, Rose et al.,1994, Sellami and Sifaoui, 2003, Steppe and Lemur, 2004, Steinberg and Henninger, 1997, Simpson, 2000, Tan and Buttery, 1995, Vandegehuchte et al., 2012, Weibel and Devos, 1994). Sap flow has been used for a range of applications. Sap flow provides an alternative to lysimeters in the measurement of crop transpiration rate (Cohen and Li, 1996). Sap flow methods have been used to quantify water uptake of various crops, effect of environmental controls on transpiration, tree conductance of shelter belts, to study drought avoidance mechanism, stress, diagnosing water deficit, gas exchange relationship to transpiration, stomatal conductance, xylem anatomy, modeling xylem and phloem water flows, pest infestation, evapotranspiration components, and sprinkler irrigation application efficiency (Nicolas et al., 2006, Assouline et al., 2002, Bovard et al., 2005, Chang et al, 2006, Chirino et al., 2011, Conejero et al., 2007, Ma et al., 2007, Ortuno et al., 2005, Dragoni et al., 2005, de Oliveiro et al,. 2006, Fernandez et al., 1997, Holtta et al., 2006, Fernandez et al., 2006, Gavloski et al., 1992, Zhang et al., 2011, Merta et al., 2006, Williams et al., 2004, Martinez-Cob et al., 2008).

There are basically four types of sap flow methods, stem heat-balance method, truck sector heat balance method, heat pulse technique, and heat-dissipation technique (Baker and Nieber, 1987, Cermak et al., 1973, Green et al., 2003, Granier, 1985). These methods use heat as a tracer for sap movement (Smith and Allen, 1996). Each of the four methods of measuring sap flow is reported to be accurate to within 10% (Smith and Allen, 1996). However, when using any of these sap flow measurement methods, there are potential sources of error, and users should take suitable precautions against these, otherwise errors in sap flow rates can become much larger

(Smith and Allen, 1996). The three common sap flow methods, heat balance, heat pulse, and heat dissipation methods are described below:

2.5.5.1 Sap flow heat pulse method

In the heat pulse method, sap flow rate is determined by measuring the velocity of a short pulse of heat carried by the moving sap stream rather than by the heat balance (Smith and Allen, 1996). The heat pulse method uses the temperature difference between two thermocouples radially inserted into the stem to estimate sap velocity. Heater and sensor probes are installed by drilling holes into the sap wood. Each heat pulse sensor (ICT International Pty Ltd., Armidale, Australia) must be calibrated for each sensor configuration (Swanson, 1994). The probes are usually 1.3 - 2.0 mm in diameter and are implanted in parallel holes drilled radially into the stem, with one sensor probe (the upstream probe) placed 5 mm below the heater and the other (the downstream probe) placed 10 mm above the heater (Smith and Allen, 1996). Short pulses of heat are periodically released from the heater probe and the sensor probes are monitored continuously to measure the velocity of each pulse as it moves with the sap stream. It is generally used for woody stems (Dugas et al., 1993, Smith and Allen, 1996) but it has also been used for herbaceous plants such as corn and sunflower (Cohen and Li, 1996). Heat pulse sensors needs to be validated for new species especially if the thermal homogeneity of the wood is in doubt

(Smith and Allen, 1996). A knowledge of plant physiology is required to correctly position the sensors in sap-conducting elements.

2.5.5.2 Thermal dissipation technique

Thermal dissipation technique is an empirical method of measuring sap flow in trees developed by Granier in 1985. This method is also known as the Grainier method (Smith and Allen, 1996); it is popular among tree physiologists and forest hydrologists owing to its simplicity, high degree of accuracy, reliability and relatively low cost (Lu et al, 2004). Two cylindrical probes of 2 mm in diameter are radially inserted into the stem, 10 to 15 cm apart (Smith and Allen, 1996). The downstream (upper) probe is continuously heated at constant power (0.2W) while the upstream (lower) probe is left unheated to measure the ambient temperature of the wood tissue and acts as a reference probe (Lu et al, 2004). Sap flow rate is determined by balancing the heat input and the quantity of heat dissipated by convection and conduction at the wall of the probe under conditions of thermal equilibrium. Being an empirical method, it may not be possible to utilize this method without calibration for each plant species (Smith and Allen, 1996).

2.5.5.3 Sap flow heat balance method

This sap flow method is based on heat balance and uses constant heat supplied to a section of stem, and the mass flow of sap obtained from the balance of the fluxes of heat into and out of the heated section of stem (Smith and Allen, 1996, Baker and Nieber, 1989). A uniform and known amount of heat (Q_h) is applied to the entire circumference of the stem or a small segment of stem through a heater as shown in Fig. 2.7 (Swanson, 1994). The Q_h is the equivalent to the power input to the stem from the heater, P_{in}. One pair of thermocouples (A and B) is placed above the heater and a second pair (H_a and H_b) is placed below the heater to measure the vertical or axial heat loss (Q_v) as shown in Fig. 2.7. A third pair of thermocouples is placed at the inner and outer layers of the gage material to measure the radial heat conducted through the gage to the ambient air (Q_r). By measuring P_{in}, Q_v, and Q_r, the remaining heat, Q_f (heat convection carried by sap) can be calculated as shown in Eq. 2.8. After dividing Q_f by the specific heat of water and the increase in sap temperature, the heat flux is converted directly to mass flow rate (Eq. 2.9).

$$Q_f = P_{in} – Q_r – Q_v \tag{2.8}$$

and

$$\text{Sap flow, } F\ (g\ s^{-1}) = Q_f / (C_p \times \Delta T) \tag{2.9}$$

where C_p is specific of water (4.186 J $g^{-1}\ {}^{o}C^{-1}$), and ΔT is the temperature increase of the sap (^{o}C). Q_f, P_{in}, Q_r and Q_v are measured in Watt.

Heat balance gages are available from stem diameter sizes of 2.1 to 165 mm. It is recommended to start with minimum power settings. Sap flow errors have been reported at high sap flow rates and solar heating. It is recommended to insulate the stem gage section with thick foam and weather shield to minimize external thermal gradients or solar heating (Smith and Allen, 1996). Additional foam, fiber glass or aluminium foil is wrapped below and above the sensor to reduce heat gain or loss from the stem section, and therefore the errors (Dynamax, 2005). Sap flow error due to heat storage is zero when transpiration rate is determined over a day (Wiebel and Boersma, 1995). Several studies have reported accuracy of sap flow heat balance methods from 88 to 96 % (Weibel and Boersma, 1995, Jara et al., 1998, Bethenod et al., 2000). The sap flow heat balance method was selected for this study because it is more quantitative than heat pulse velocity method (Swanson, 1994). No heating elements are inserted into the plant in the heat balance method while both heat pulse and Grainer methods require needles to be inserted into the stem (Köstner et al., 1998). It is also not easy to calculate actual values of water flow in a plant stem or trunk by the heat pulse techniques (Swanson, 1994). This is related to the difficulty in determining the cross sectional area of the water conducting system. Heat balance methods require more power than the other two methods (Köstner et al., 1998, Swanson, 1994). A sap flow heat balance method was evaluated with reference to the FAO-56 Penman-Monteith evapotranspiration method under humid and subsurface drainage conditions. Daily water uptake of corn was investigated from silking stage to full dent stage of the crop under FD and CD-SI water treatments at medium nitrogen level (~180 kg N ha^{-1}).

2.5.5.4 Sampling and scaling from plant to canopy

Since the sap flow method involves measurement of a single plant, it is essential to extrapolate the water use of sampled plants to that of the field transpiration. In uniform stands, such as monoculture crops or forest plantations with closed canopies, this is done by multiplying the unit sap flow by plant density because most plants in the stand are of similar size and the supply of radiant energy and soil water is uniform (Cohen and Li, 1996, Smith and Allen, 1996, Ham et al., 1990, Dugas and Mayeux, 1991).

2.6. Crop growth models

There are three categories of crop models: physical models, mathematical models and computer models (Singh, 2009). These types are further defined as static and dynamic models. Crop models are dynamic mathematical models which describe the growth and development of a crop interacting with soil (Wallach, 2006). Crop models are based on equations which describe the processes involved in crop growth and development (Makowski et al., 2006). A major problem with crop models is obtaining the values of the variables (Wallach, 2006). Although all the variables can be measured, some of the variables cannot be determined accurately. There are continuous interactions among these variables. Some of the measurements are of a destructive nature. Hence, it is important to calibrate and validate the models before use. The crop models provide an inexpensive tool to evaluate the impact of scientific management and climate scenarios on crop yield and the environment (Tsuji et al., 1998). The three most used crop models (DSSAT, RZWQM, and STICS) are described below.

2.6.1 DSSAT crop model

The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) is a process oriented crop model that simulates growth, development and yield of a crop growing on a uniform area of land over time (Jones et al., 2003). These simulations are conducted at a daily time steps and, in some cases, at hourly intervals depending on the process and the crop module. Since, this research deals with corn; I have limited the discussion to CERES-Maize module.

Minimum data required to run the CERES-Maize model includes field management, daily weather, soil profile characteristics, initial soil condition, and cultivar characteristics (Liu et al., 2011). Crop genetic information is defined in a crop species file that is provided by DSSAT and cultivar information should be provided by the user.

The soil water balance in the model is one-dimensional and computes the daily changes in soil water content by soil layer due to infiltration of rainfall and irrigation, vertical drainage, unsaturated flow, soil evaporation, and root water uptake processes (Jones et al., 2003). The model uses a 'tipping bucket' approach for computing soil water drainage when a layer's water content is above a drained upper limit parameter. The modified Soil Conservation Services (SCS) method is used to partition rainfall into runoff and infiltration, based on a 'curve number' that attempts to account for texture, slope, and tillage; it considers layered soils and soil water content at the time when rainfall occurs (Jones et al., 2003).

The soil is also represented as a one-dimensional profile; it is homogenous horizontally and consists of a number of vertical soil layers (Jones et al., 2003). DSSAT-CSM simulates the soil organic matter and nitrogen balance either via the CERES soil model or the Century soil model. The CERES soil model is insensitive to soil type, depth to clay, and soil nitrogen (Sadler et al., 2000).

The minimum weather input required to run the model includes latitude and longitude of the weather station, daily solar radiation (MJ m^{-2}), daily maximum and minimum temperature (^{o}C), and daily precipitation (mm). Management data includes information on planting date, dates when soil conditions were measured prior to planting, planting density, row spacing, planting depth, crop variety, irrigation, and fertilizer practices.

CERES-Maize calculates plant biomass growth based on thermal time, or growing degree-days (GDD), which is computed based on the daily maximum and minimum temperatures. Only temperature and, in some cases, day length, drive the accumulation of GDD; drought and nutrient stresses have no effect. The model predicts seed number as a linear function of plant growth rate (Kiniry and Knievel, 1995). The model simulates seed mass production from a potential seed growth rate, flowering based on the cultivar's genetic potential, canopy height, average rate of carbohydrate accumulation during flowering, and temperature, water and nitrogen stresses (Kiniry et al., 1997).

2.6.2 RZWQM crop model

The RZWQM (Root Zone Water Quality Model) is a one-dimensional process-based, integrated model for simulating the soil water- plant-atmosphere system (Singh and Kanwar, 1995). The model was developed primarily for water quality research with a generic plant growth module (Ma et al., 2006). The generic plant growth model simulates crop yield, biomass, leaf area index, root biomass, and rooting depth (Hanson et al., 1999). However, it does not simulate leaf number, phenological development, and other yield components. The RZWQM model is now coupled with DSSAT crop models and can simulate detailed yield components, leaf numbers, and phenological development. RZWQM provides CERES-Maize with the daily soil water and nitrogen (N) contents, daily potential evapotranspiration (PET), and daily soil temperature, in addition to daily weather data. The CERES-Maize model supplied RZWQM with daily plant water uptake, N uptake, and plant growth variables (Ma et al., 2006). The plant N uptake, snow pack dynamics, solute, water, and heat transport processes are calculated hourly (Hanson et al., 1999).

The strengths of RZWQM include macropore flow, tile drainage simulation, water table fluctuation, soil microbial population simulation, plant population development, and management effects (Ahuja et al., 2000). The model uses the Green-Ampt equation for infiltration into the soil, Richard’s equation for soil matrix flow, Poisueille’s law for macropore flow, and the extended Shuttle-Wallace equation for evapotranspiration (Ahmed et al., 2007).

The RZWQM simulates major physical, chemical, and biological processes in an agricultural crop production system through six major processes (Ma et al., 2001), namely (1) physical processes including hydrologic processes, infiltration, chemical transport during infiltration; (2) plant growth processes which predict the relative response of plants to changes in environment; (3) soil chemical processes consist of the soil inorganic environment in support of nutrient processes, chemical transport, and pesticide processes; (4) nutrient processes define carbon and nitrogen transformation in the soil profile; (5) pesticide processes include the transformations and degradation of pesticides on plant surfaces, plant residue, the soil surface, and in soil profile; and (6) management processes consist of descriptions of management activities influencing the state of the root zone, including tillage practices, soil bulk density, and macroporosity; fertilizer, pesticide, and manure applications. All these processes require a detailed set of theoretical parameters. Some of these parameters cannot be easily measured or determined. The natural soil-plant-atmosphere conditions are highly complex and variable, and very difficult to characterize in terms of effective variables (Hanson et al., 1999). Also, frozen soil dynamics are not considered in RZWQM (USDA-ARS, 2013).

2.6.3 STICS crop model

STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) is a process-based crop model with a daily time step (Brisson et al., 1998). The model simulates crop growth, soil water and nitrogen balances. Climate, soil, and crop management data are required to run the model. STICS can simulate the soil/crop system over one crop cycle or several crop cycles, to simulate rotations. The upper boundary of the system is the atmosphere, characterised by standard climatic variables (radiation, minimum and maximum temperatures, rainfall, reference evapotranspiration and possibly wind and humidity); the lower boundary corresponds to the soil/subsoil interface (Brisson et al., 2008).

The STICS model is organised into nine modules (Fig. 2.8). A first set of three modules (phasic development, shoot growth, yield formation) deals with the ecophysiology of aboveground plant parts (Brisson et al., 2003). A second set of four modules (root growth, water balance, nitrogen balance, soil transfer) deals with how the soil responds in interaction with underground plant parts. The crop management module deals with the interactions between the applied techniques and the soil-crop system. The microclimate module simulates the combined effects of climate and water balance on the temperature and air humidity within the canopy (Brisson et al., 2003). Brief descriptions of each module are given below (STICS modules are referenced from Brisson et al., 2003, 2008). The model input parameters are described in Chapter 5.

2.6.3.1 Phasic Development

STICS calculates biomass as a function of radiation use efficiency (RUE). Crop growth is driven by the plant's carbon accumulation; solar radiation intercepted by the foliage and then transformed into aboveground biomass that is directed to the harvested organs during the final phase of the crop cycle. The sum of degree-days is the development unit, and is calculated on the basis of air temperature or crop temperature.

2.6.3.2 Shoot growth

Shoot growth is a function of the intercepted radiation according to a parabolic relationship involving the maximal RUE. For homogeneous crops, a Beer's law analogy is used as a function of leaf area index (LAI). For row crops, radiation interception method that takes crop geometry into account is used. The LAI is calculated from leaves gross growth and leaves senescence as a result of the natural ageing of the foliage plus stress-induced senescence. The stress indices are values between 0 and 1 that reduce the vital plant functions.

2.6.3.3 Yield component

For determinate species, including cereals, the number of grains (or other harvested organs) depends on the mean growth rate of the crop during a grain-number determination phase. The relationship is linear and introduces the maximal number of grains, a typically genetic quality. The dry matter and nitrogen accumulated in the grains are calculated by applying linearly increasing 'harvest indices' to the shoot biomass and nitrogen.

For indeterminate plants, the fruits (or other harvested organs) become established between the onset of filling and the end of fruit setting. On each day, during this period, the number of set fruits is the product of a genetic parameter (the potential number of set fruits per plant and per degree-day), the effective temperature and the source-sink ratio.

2.6.3.4 Root front

In STICS, root growth is separated from above ground growth. Roots act only as water and mineral nitrogen absorbers. Root growth stops if it reaches a soil depth that poses an obstacle (physical or chemical) or, finally, when net leaf growth ceases.

2.6.3.5 Crop management

The model has a provision for irrigation application either over-the-crop, under the crop or in the soil (drip irrigation). Water retained on the foliage, directly subjected to the evaporative demand of the surrounding atmosphere, can evaporate, thereby significantly reducing the saturation deficit within the canopy and crop water requirements. Mineral nitrogen originates from fertilisers, irrigation water and rainwater (0.02 kg N ha^{-1} mm^{-1}). Fertiliser losses through volatilisation and immobilisation are parameterised according to the type of fertiliser.

2.6.3.6 Microclimate

The daily crop temperature is assumed to be the arithmetic mean of the maximal crop temperature and the minimal crop temperature. The model uses one of the two methods to determine the crop temperature, either by using the simplified relationship from Seguin and Itier (1983) or by solving the energy balance. The simplified approach to calculating the crop temperature is based on a relationship between surface temperature in the middle of the day and daily evaporation. In this approach, it is hypothesised that the minimal crop temperature coincides with that of the air.

The energy balance approach is based on two calculations made at the time of the maximum and minimum temperature. Atmospheric radiation is assumed to be constant throughout the day, whereas soil radiation is calculated with the maximal and minimal temperatures.

2.6.3.7 Water balance

Water balance is used in the calculation of water status of the soil and the plant, the water stress indices that reduce leaf growth, and net photosynthesis. STICS uses crop coefficient or resistive approach to calculate evapotranspiration. The crop coefficient approach used either the Penman-FAO 24 or Priestly-Taylor methods together with a crop coefficient based on LAI, height and roughness (Brisson et al., 2006). The energy balance (or resistive) approach is based on an adaptation of the model of Shuttleworth and Wallace at a daily time-step. The resistive method requires data concerning wind and air humidity and is based on two parameters: minimal resistance of the leaves and maximal height of the canopy. Pattey and Jégo (2010) have reported that the resistive approach provided better results than the crop coefficient approach, which strongly overestimated predictions of ET.

On a daily time scale, root uptake is considered to be equal to leaf transpiration. Calculated root uptake is then distributed between the soil layers. Relative transpiration, i.e. relationship between actual transpiration (EP) and maximal transpiration (EOP) is assumed to be bilinear function of the available water content in the root zone. The EP/EOP ratio is considered to be the stomatal water stress.

2.6.3.8 Nitrogen balance

Net nitrogen mineralisation in the soil is the sum of humus mineralisation and the mineralisation of organic residues (crop residues or organic wastes). Only the nitrate concentration is considered in the leaching calculations. Nitrogen uptake by the plants is calculated on the basis of the total amount of mineral nitrogen in the soil. In the case of fertilisation, it is necessary to give the proportion of ammonium in the fertiliser.

2.6.3.9 Transfers in the soil

The dynamics of soil temperatures in the soil depend on the surface conditions. Daily crop temperature and its amplitude are used as upper limits for the calculations of soil temperatures. The soil is divided into five horizons but calculations on microporosity are done per 1 cm layer, which is the resolution required to derive nitrate concentration. Water transport in soil micropores is calculated for each 1 cm layer using a tipping bucket approach. The tipping bucket model assumes that each layer of soil has a capacity to hold water to the field capacity or the drained upper limit of the soil (Emerman, 1995). No water drains from a layer if its volumetric water content is less than its field capacity. If the water content exceeds field capacity then either all of the water in excess of field capacity or some fraction of the water between field capacity and the saturated water content drains into the underlying layer in a given time step (Emerman, 1995). The Hooghoudt equation is used for subsurface drainage flows and water table heights.

2.6.4 Model selection

The STICS model was selected because of it’s simplicity and adaptability to various crops. The input parameters required to run the model are fewer than other models (Webber, 2008). However, this affects its accuracy which ranged from 80 to 90% (Brisson et al., 2002, Flénet et al., 2004).The modular structure of the model facilitates new development and easy addition of new crops or cultivars (Jego et al., 2011). STICS has an open architecture, which provides easy access to all parameters for cultivar calibration (Jego et al., 2011). The model is robust and has ability to simulate various soil-climate conditions without excessive error. STICS was first calibrated using 2008 soil, climate, and crop management data for conventional drainage at three nitrogen levels and validated using 2009 data. Further, the impact of climate change on corn biomass and grain yield, using synthetic weather data from 2040 to 2069 under a B1 emissions scenario, was investigated.

2.7 Conclusions

Increasing world population, decreasing water and arable land resources, and the impact of changing climate pattern demand for better management of water and land resources to feed the growing world population. With the higher application rate of nitrogenous fertilizer, crop yield has been successfully increased. However, that affects the environment due to nitrogen leaching into the water bodies. Managing the ground water table by subsurface drainage has increased the crop productivity and conserved the environment (Madramootoo et al., 1992). Water and nitrogen use efficiencies are the benchmark of efficient utilization of these resources. There have been a few studies to quantify water and nitrogen use efficiency of subsurface irrigation practices in humid regions. In this context, the following chapters describe water and nitrogen use efficiencies of corn under subsurface drainage conditions was measured over a range of nitrogen application and interaction between water table depths and nitrogen applications. In consideration of changing climate pattern, corn yield was simulated using the STICS crop model under a B1 emissions scenario for subsurface drainage conditions. The study provides technological tools to agronomists, policy makers, and other stakeholders for better management of nitrogen application and water demand of corn under these conditions.

Table 2.1

Corn production in USA, Canada and World (FAOSTAT, 2013).

	Area harvested (ha)	Production (Mg)	Productivity (Mg ha^{-1})
World	170,398,070	883,460,240	5.2
USA	33,986,300	313,918,000	9.2
Canada	1,201,700	10,688,700	8.9

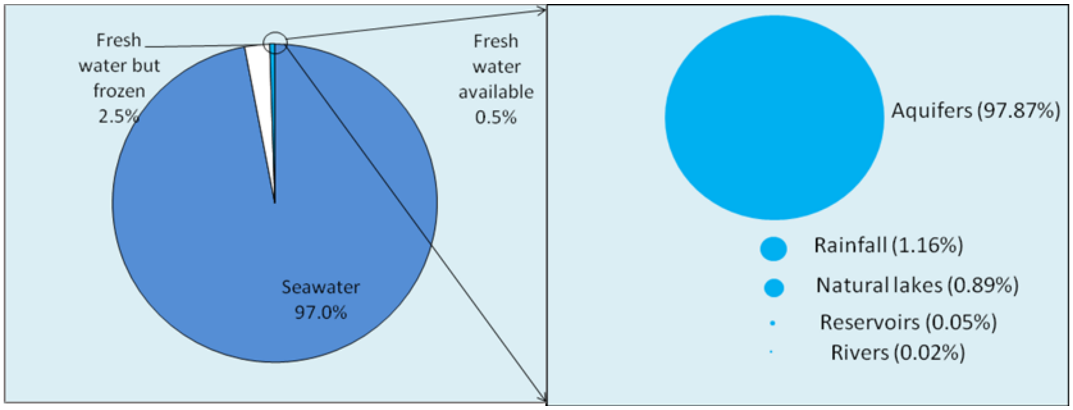


Fig. 2.1 Distribution of water on the earth's surface (Al Fry, 2005).

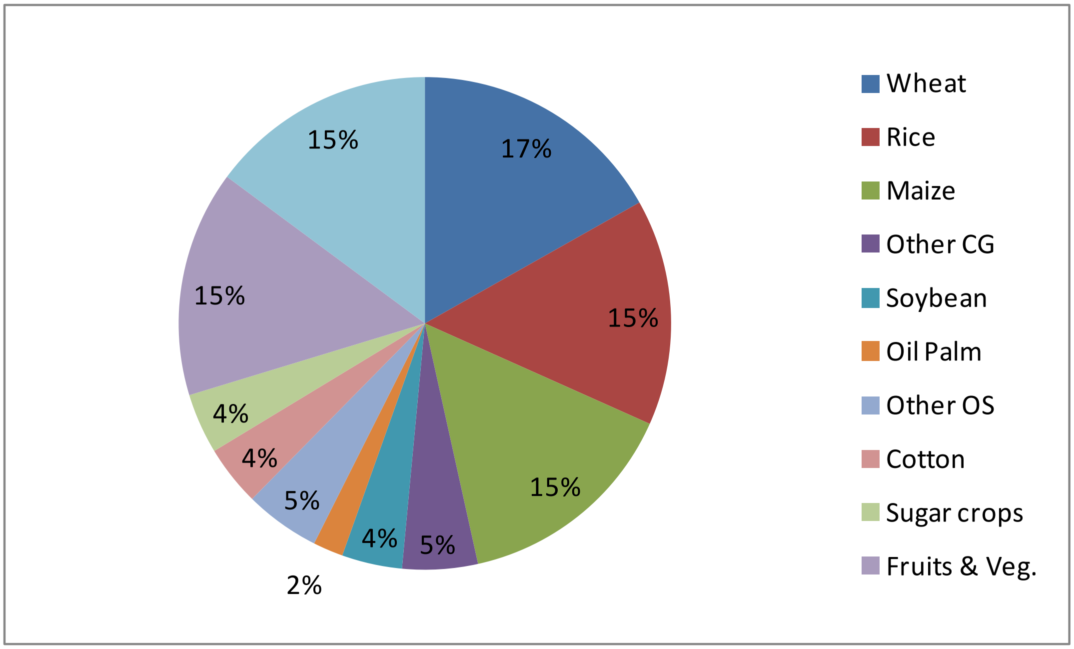


Fig. 2.2 Total global fertilizer use by crop in 2006-2007 (Heffer, 2008).

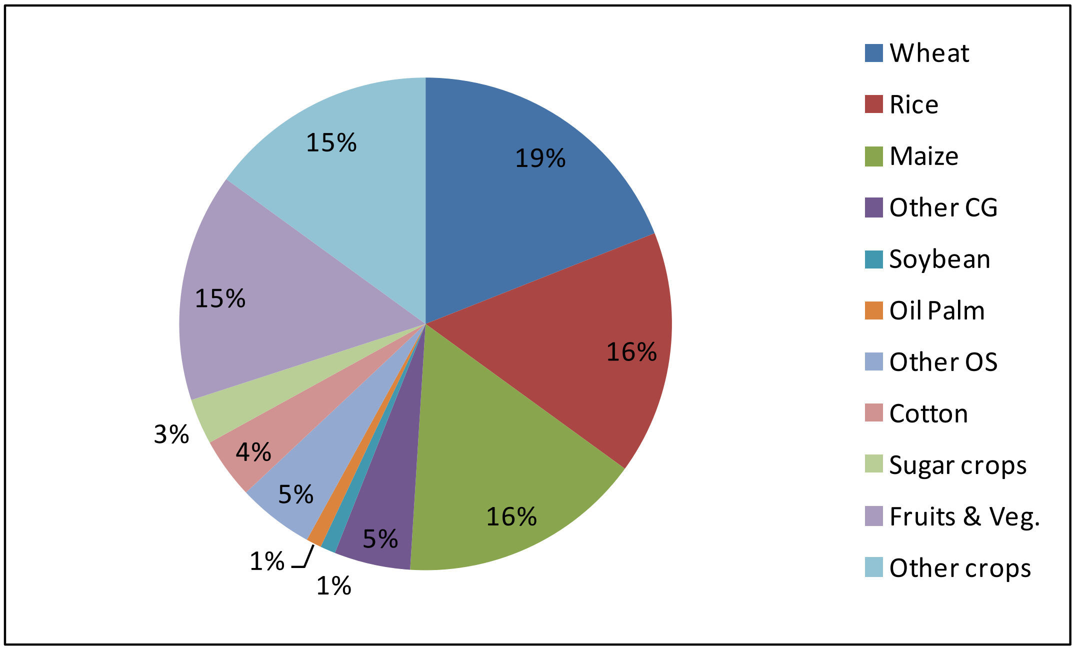


Fig. 2.3 Global nitrogen fertilizer use by crop in 2006-2007 (Heffer, 2008).

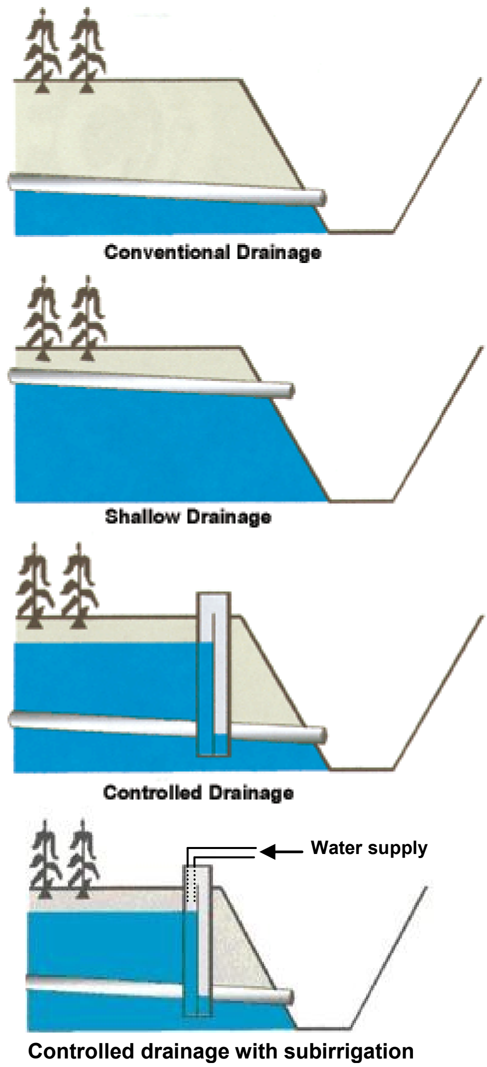


Fig. 2.4 Types of drainage system (Busman and Sands, 2002).

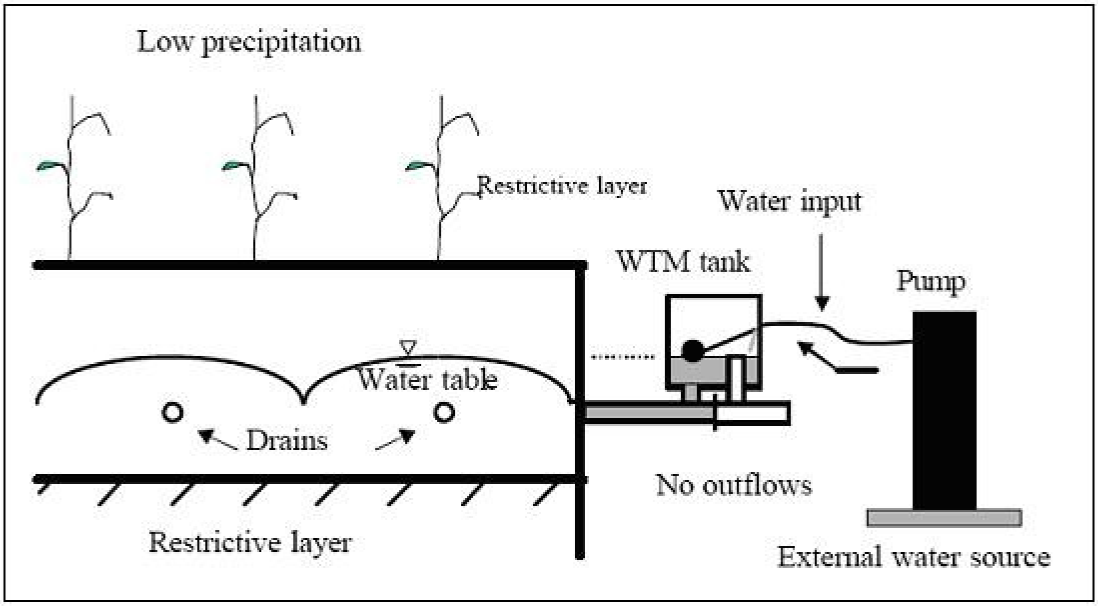


Fig. 2.5 Water table management system in subirrigation mode (Stampfli, 2003).

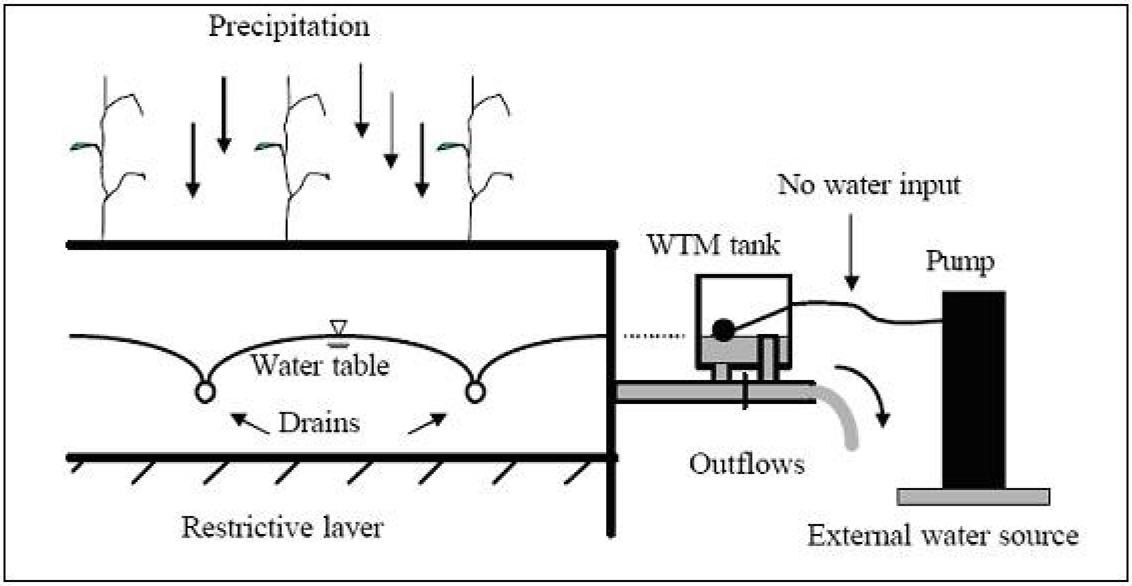


Fig. 2.6 Water table management system in drainage mode (Stampfli, 2003).

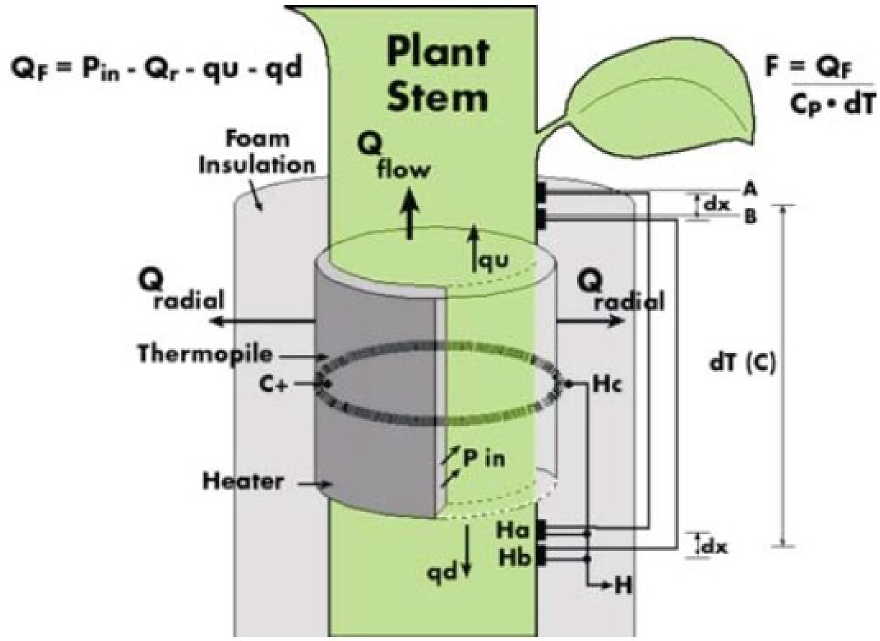


Fig 2.7 Configuration of the sap flow heat balance method (Dynamax, 2005) F = sap flow (g s^{-1}), Q_f = sap flow (W), Q_r = radial heat loss (W), q_u and q_d = components of vertical heat loss (Q_v) (W), C_p = specific heat capacity of water, dT = increase in temperature (^oC)

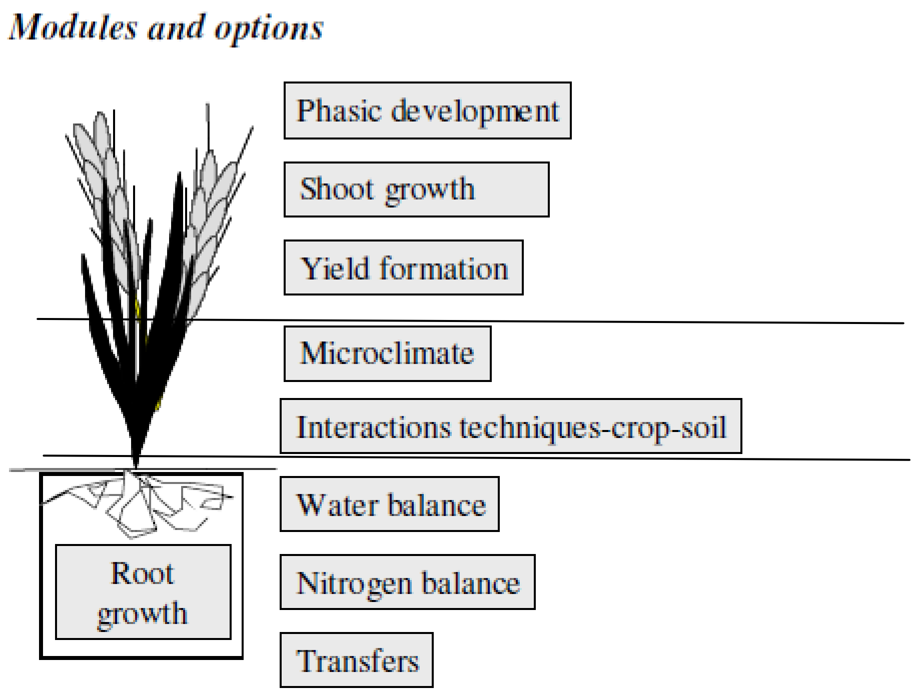


Fig. 2.8 The main modules of the STICS crop model (Brisson et al., 2008).

Connecting text to Chapter 3

This chapter addresses the first objective of the thesis, investigating the water and nitrogen use efficiency of corn under conventional drainage and controlled drainage/subirrigation at three nitrogen levels. Interaction effect of the two water treatments and three nitrogen levels on corn grain and biomass yield is also investigated. Experiment design and field description is presented in this chapter. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Research paper based on the chapter:

Singh, A. K., Madramootoo, C.A. Smith, D.L., 2013. Water and nitrogen use efficiency of corn under different water and nitrogen management scenarios. Transaction of the ASABE (under review).

Chapter 3

Water and nitrogen use efficiency of corn under different water and nitrogen management scenarios

Ajay K. Singh, Chandra A. Madramootoo, Donald L. Smith

Abstract

This study investigated the water balance, crop yield, water use efficiency (WUE), and nitrogen use efficiency (NUE) of a water table management system compared to conventional drainage system at three nitrogen levels (low, medium and high). A two year field study was conducted using three blocks; each block was composed of two water management treatments – controlled drainage with subirrigation (CD-SI) and conventional or free drainage (FD).. Three nitrogen treatments – low, medium, and high N, were applied in strips across all blocks. The results found that the seasonal water balance indicated surplus water conditions in CD-SI plots while the FD plots had deficit conditions. In 2008 and 2009, the corn grain WUE for FD plots was 2.49 and 2.46 kg m^{-3}, respectively. In these years, the grain WUE for CD-SI plots was 2.43 and 2.26 kg m^{-3}. WUE of corn grain responded to the water treatments ($p < 0.05$) in 2009, but not in 2008. In 2009, at low and high nitrogen levels, water management treatments demonstrated significant difference ($p < 0.05$) on grain yields. However, water management demonstrated no significant effect ($p > 0.05$) on grain yields at the medium nitrogen level. Furthermore, the two water treatments had no effect on the above-ground dry biomass yields in both years. Highest NUE

(99 kg kg^{-1}) and lowest NUE (41 kg kg^{-1}) for grain corn were observed for low N (130 N kg ha^{-1}) and high N (277 N kg ha^{-1}), respectively. It appears advantageous to implement a CD-SI system in dry years and FD subsurface drainage system in wet years to obtain optimum corn yields.

Keywords: Water use efficiency; nitrogen use efficiency, corn (Zea mays); water table management; controlled drainage; subirrigation.

3.1 Introduction

Irrigated agriculture accounts for about 70% of total world fresh water use worldwide representing as a largest user (Siebert et al., 2007). In the US alone, irrigated agriculture consumes 58 and 42% of total surface and groundwater abstractions, respectively (USGS, 2005). Although fresh water is considered a renewable resource, fresh water availability for irrigation is steadily decreasing globally. In North Gujarat, India, water tables are falling by 6 meters per year due to higher groundwater utilization compared to lower aquifer recharge rate (Brown, 2006). In three major grain-producing areas in the United States namely Texas, Oklahoma, and Kansas, the water table has dropped by more than 30 meters (Brown, 2006). One way to address this decline in irrigation water availability is to enhance water use efficiency (WUE) in irrigated agriculture, i.e. increasing the crop output per unit of water, reducing loss of water to unusable sinks (e.g., in the unsaturated vadose zone, the ocean, or salt sink), reducing water quality degradation, and reallocating water to higher priority uses (Howell, 2001).

Corn is one of the world's most important cereal crops. North America produces approximately 44% of the world's production of corn (FAOSTAT, 2009). In 2009, corn was harvested from 158 million ha of land that produced about 819 million Mg grain worldwide. In the same year, Canada harvested 1.14 million ha of corn with a production of 9.56 million Mg (FAOSTAT, 2009). Grain corn is the second most widely grown crop in the province of Québec, Canada with a peak cropped area of 450,000 hectares in 2007-2008 (Statistics Canada, 2011).

Nitrogen fertilizer is universally accepted as a key component to high corn grain yield and optimum economic return (Gehl et al., 2005). Nitrogen is the one of the major components of fertilizer. Globally, 169 million Mg of fertilizer were applied in 2007-2008 for corn production, with 60% nitrogenous fertilizer (Heffer, 2009). Corn accounts for 16% of the total fertilizer use and 17% of the world total nitrogenous fertilizer use. Higher nitrogen application increases corn yield, but decreases NUE (Liang and Mackenzie, 1994). Also, it creates health and environmental hazards when nitrogen leaches to rivers and lakes (Madramootoo et al., 1992). Madramootoo et al. (2001) found that total seasonal nitrate–N leaching losses in 1998 and 1999 were reduced by 80 and 58%, respectively in CD-SI plots compared to free drainage. Judicious use of water and fertilizer would increase the yield and land productivity associated with corn production.

In humid regions, surface and subsurface drainage is necessary to increase agricultural production. Approximately, 8 million ha of land in Canada are drained, mainly as surface drainage (ICID, 2009). Tile drains have been installed extensively in the US and Canada to drain excess soil water from agricultural lands, to mitigate water logging problems. Subsurface drainage has been implemented on over 2.5 million ha of agricultural land in the provinces of Ontario and Quebec (ICID, 2011). In Quebec alone, over 735,000 ha of farmland are drained by implementing subsurface drainage system (Gollamudi, 2006). A large proportion of this subsurface drained land is used for grain corn production.

Subsurface drainage improves field trafficability and crop yields (Madramootoo et al., 2007). However, it can also increase the frequency of soil water stress during drought periods. In the case of controlled drainage systems, farmers can open the drains to remove excess water, and then close them during dry periods to retain the moisture in the field. This decreases the need for water from external sources for irrigation (Amatya et al., 1998). Subirrigation in conjunction with controlled drainage (CD-SI), achieved by maintaining a desirable water table depth, allows more control over soil moisture conditions and provides optimum conditions for crop. During periods of water deficit, water is provided to the crop from an external source, via the tile drains. This decreases drought stress and provides the crop with an optimum environment for growth. Conversely, when precipitation exceeds the amount of water required by the crop, subirrigation is stopped and excess water is drained from the field.

Drained lands are one of the most productive in the world (Wright and Sands, 2001). Madramootoo (1990) reported increased soil water storage capacity and less damage to soil structure with CD-SI systems. Hundal et al. (1976) reported that CD-SI systems improved soil physical properties. The other benefits of controlled drainage with subirrigation include decreased conventional-drainage peak-flow rates and outflow volumes under certain conditions, a substantial reduction of nitrate concentrations, as compared to conventional drainage outflows (Mejia and Madramootoo, 1998; Skaggs et al., 1995; Madramootoo et al., 1992), and increased crop yield (Stampfli and Madramootoo, 2006; Busman and Sands, 2002; Zhao et al., 2000).

Although Canada is a water rich country, the future provision of this resource should not be taken for granted (Mehdi et al., 2006). July temperature below normal and May precipitation above normal have negative effects on corn yield in south-western Quebec (Almaraz et al., 2008). Although climate change projections may be fraught with uncertainties, adaptation is necessary to ensure sufficient supply for economic development, the environment, and recreation, and more importantly to preserve peace between user groups (Mehdi et al., 2006). By the 2090s, regions such as Canada’s southern prairies would experience serious summer deficiencies in soil moisture (Hengeveld, 2000). There have been a few studies on water and nitrogen use efficiency of subsurface irrigation practices in humid regions. Therefore, the main objective of this study was to determine the water use efficiency (WUE) and nitrogen use efficiency (NUE) for various water management scenarios over a range of nitrogen levels. The second objective was to calculate the daily field water balance under these scenarios.

3.2 Materials and methods

3.2.1 Description of the study area

The experimental field work was conducted on a 4.2-ha field (latitude 45.32, longitude -74.17) in Coteau-du-Lac, Quebec, Canada in 2008 and 2009. The study area lies in the St. Lawrence lowlands, approximately 60 km west of Montréal, in Soulanges County. The soil at the site was a Soulanges very fine sandy loam (Lajoie and Stobbes, 1951). It had a mean depth of 50-90 cm and overlays clay deposits from the Champlain Sea. The field has a flat topography, with an average slope of less than 0.5% (Kaluli, 1999).

3.2.2 Experimental design and agronomic practices

The experimental field was divided into three blocks (Fig. 3.1). A strip split-plot design was used to study the effects of water-table management and nitrogen treatments on corn. The two water management treatments (main plots) were contained in each block and ran along the direction of the drainage pipes (north-south). The three nitrogen treatments were applied orthogonally in strips over the main plots across the entire field. Each strip was 18 m wide. The two water management treatments compared in this study were: 1) conventional or free subsurface drainage system (FD) and 2) controlled drainage with subirrigation (CD-SI) also referred to as subirrigation plots. The three nitrogen treatments were: 1) Low N, 2) Medium N and 3) High N. Thus each block was comprised of 6 plots of 18 by 30 m. Tables 3.1 and 3.2 list the water and nitrogen treatments, respectively.

The water treatment plots were isolated from each other by vertical plastic curtains installed to a depth of 1.5 m, to prevent lateral seepage (Tait et al., 1995). The water table depth was set at 0.60 and 0.75 m below the ground for CD-SI plots in 2008 and 2009, respectively (Table 3.1). Buffer plots separated the water treatment plots. The drains were installed at a depth of 1.0 m below the ground surface, in the center of each main plot. The drains spacing was 15 m. The drains discharged into two buildings located on the north side of the field (Fig. 3.1).

In 2008, corn cultivar ‘Mycogen 2R426’ was planted on 4 May with a seeding rate of 89000 plants ha^{-1}. In 2009, the producer planted corn variety “Pioneer 38N8T” with a seeding rate of 85000 plants ha^{-1} on 7 May. In 2008, the desired nitrogen rates was attained (Table 3.2) by applying nitrogen in three applications. In 2009, the desired nitrogen rates were achieved through two applications. Residual nitrogen in the soil was measured prior to sowing of seeds and was included in final nitrogen application rates.

3.2.3 Monitoring of water table depth

Water table depth was monitored every 7 to10 days using observation pipes installed in each plot. The pipes were 2.54 cm diameter PVC pipes with 2 mm holes along their whole length, approximately 5 cm apart and wrapped in geo-textile to prevent clogging with fine soil particles. There were two observation wells in each plot. In the “medium N” plots, an extra pipe (5 cm diameter) was installed. These pipes were fitted with a levelogger (Solinist Canada Ltd.; Model 3001) which recorded water table depth at 15 min intervals. A pressure logger was also installed in each block along with another levelogger to allow compensation for changes in measured water table depth due to atmospheric pressure.

3.2.4 Soil water balance

The soil water balance is the sum of the total water entering the soil profile compared to the sum of the total water leaving. It was calculated for the top 60 cm of soil as:

$$I + P = ET_c + RO + DP + D +/- \Delta SW \tag{3.1}$$

where I is irrigation, P is precipitation, ET_c is crop evapotranspiration, RO is run-off, DP is deep percolation, D is drainage, ΔSW is change in the soil water storage. All units are in mm.

There was no surface run-off observed, hence it was assumed to be negligible (Stampfli, 2006). Based on work by Kaluli (1999) on the same site, it was assumed that deep percolation was also negligible, and assumed to be zero in the above equation. Therefore, equation 3.1 is simplified as follow:

$$I + P = ET_c + D +/- \Delta\ SW \tag{3.2}$$

To provide subsurface irrigation, water was pumped from a well into the drainage pipes through water control structures (Fig. 3.1). A flow meter in building 1, measured the irrigation water supplied to block A, while another flow meter located in building 2 measured the irrigation water supplied to plots in blocks B and C. The total water supplied to each block was equally distributed to each plot. Subirrigation for the CD-SI plots commenced on 25 June and 23 June in 2008 and 2009, respectively. For each subirrigation plot, there was a water table control chamber which regulated the flow of water into and out of the plots (Tait et al., 1995). During the times of high precipitation, drain valves were open to drain surplus water, and to lower the water table to the desired depth for CD-SI plots. Once the water table had reached the desired depth, the drainage valves were closed and the irrigation pump was restarted. At the end of the 2008 growing season, the subirrigation was stopped on 9 September and the drainage pipes were opened on 15 September. In 2009, the irrigation pump was turned off and drainage pipes were opened on 20 September to enable crop harvesting.

Crop evapotranspiration (ET_c) was calculated by adjusting the FAO Penman-Monteith equation with crop coefficients (Allen et al., 1998).

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.3}$$

and

$$ET_c = k*ET_r \tag{3.4}$$

where ET_r is reference evapotranspiration (mm d^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s-e_a is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa $°C^{-1}$), γ is psychrometric constant (kPa $°C^{-1}$), k is crop coefficient, and ET_c is actual evapotranspiration.

A single crop coefficient was used in equation 3.4 and adjusted for the site (Allen et al., 1998). An on-site weather station provided data on temperature, humidity, wind-speed, long-wave radiation and short wave radiation for equation 3.3. Weather data were recorded hourly, and were comparable to data available from the Environment Canada weather station at Coteau-du-Lac (Station ID – 7011947) located 500 m from the experimental site. Precipitation data were taken from the Environment Canada weather station at Coteau-du-Lac, due to its better availability.

Drainage data were measured using tipping buckets in the two instrument control buildings. The tipping buckets were calibrated and connected to a datalogger which recorded the data continuously (Tait et al., 1995). Changes in soil profile moisture were measured with two sets of sensors. Watermark soil moisture sensors (Model No. 6450; Spectrum technologies, Inc., Plainfield, Ill, USA) and Theta probes (Model ML2x; Delta-T Devices Ltd., Cambridge, UK) were installed at depths of 15 and 45 cm, respectively, below the surface of each sub plot. Data obtained from the watermark sensors were in kPa, and were converted into percentage moisture content using soil moisture characteristic curves. Soil moisture characteristic curves were obtained for various soil layers in a pressure plate apparatus (Model No. 1500 and Model No. 1600 Pressure Extractors; Soilmoisture Equipment Corp., Santa Barbara, Cal., USA).

3.2.5 Water use efficiency (WUE) and nitrogen use efficiency (NUE)

In this study, WUE was determined using two methods. It was defined as the ratio of grain yield (kg) to ET_c (m^3) known as crop water use efficiency (WUE_{ET}). ET_c determined by Eq. 3.1 when multiplied by the area (m^2) gives volume of water used by the plant.

$$WUE_{ET}\ (kg\ m^{-3}) = Yield\ (kg) / ET_c\ (m^3) \qquad (3.5)$$

Secondly, WUE was also defined as the ratio of grain yield (kg) to amount of water (m^3) supplied through subirrigation, known as subirrigation water use efficiency and denoted as $SWUE_{SI}$ (Eq. 3.6). There is no $SWUE_{SI}$ calculation for FD plots, since subirrigation water was not applied to these plots.

$$SWUE_{SI}\ (kg\ m^{-3}) = Yield\ (kg) / Volume\ of\ irrigation\ water\ supplied\ (m^3) \qquad (3.6)$$

In this study NUE was defined as grain yield per unit N fertilizer applied (Campbell et al., 1993).They estimated N supply as the sum of (i) soil nitrate measured in the spring (soil N), and (ii) N fertilizer applied.

3.2.6 Crop yield and above-ground biomass sampling

The mature corn grain and above-ground biomass were sampled at the time of harvest. Each plot was divided into four sections. Leaving rows at the plot edges as a buffer, five consecutive plants in each section were randomly selected in a row. Thus, 20 plants were collected from each plot.

In 2008 and 2009, the samples were collected on 12 and 14 October, respectively. Cobs were separated in the field and placed in paper bags. Stalks were weighed and chopped at an off-site location the following day. Biomass subsamples for each plot were collected, weighed again and oven dried at 70^oC for 48 h. Harvested cobs were similarly oven dried. The dried biomass and the mass of dry grain were converted to Mg ha^{-1}, to allow for comparison with other published data.

3.2.7 Statistical analyses

The model for a strip split-plot design used is shown below (Montgomery, 2009)

$$Y_{ijk} = \mu + \rho_i + \alpha_j + (\rho\alpha)_{ij} + \beta_k + (\rho\beta)_{ik} + (\alpha\beta)_{jk} + \epsilon_{ijk} \qquad (3.7)$$

where Y_{ijk} is the observation corresponding to k^{th} level of factor A (water treatment), j^{th} level of factor B (nitrogen treatment) and i^{th} replication, μ is the population mean, ρ_i is the i^{th} block effect, α_j is the effect of j^{th} level of factor A, β_k is the effect of k^{th} level of factor B, $(\alpha\beta)_{jk}$ is the interaction between j^{th} level of factor A and k^{th} level of factor B. The error components $(\rho\alpha)_{ij}$, $(\rho\beta)_{ik}$ and ε_{ijk} were independently and normally distributed with a mean of zero and respective variances $\sigma^2{}_a$, $\sigma^2{}_b$ and $\sigma^2{}_\varepsilon$.

Analyses of variance were performed with the Statistical Analysis System (SAS, 2010) using a 95% confidence level. The effects of the water (factor A) and nitrogen (factor B) treatments, block differences (Block), interaction between the block and the water treatments (Block* A), and interaction between the water and the nitrogen treatments (A*B) were investigated. The MIXED procedure in SAS was used to determine the random effect of block. When it was determined that blocks had no significant effect, the GLM procedure was used for the analysis of variance. The mean square of the strip-plot error MS (StPE), was subtracted from the subplot error (MSE_{AB}) which resulted in a smaller MSE_{AB}, and the error term was used to test the interaction A*B. This gave an improved precision in the tests for interaction effects (Steel & Torie, 1980).

3.3 Results and discussion

3.3.1 Climatic data

The monthly average temperatures were 17.1^{o}C in 2008 and 16.7^{o}C in 2009, which were similar to the 30 year average (17.0^{o}C) during the growing season (May - September). The distribution of rainfall over the season was similar between the two years. The total precipitation for the growing season (May – September) was 432 and 462 mm in 2008 and 2009, respectively, compared to last 30 yr average rainfall of 474 mm during the same period.

3.3.2 Drainage and subirrigation

The amount of water drained from the CD-SI plots was more than twice that of the conventionally drained plots in each block and each year (Table 3.3). The greater volume of drainage water in CD-SI plots was observed due to extra water supplied through subirrigation which resulted in more water being stored in the soil profile, and being released when the drainage valves were opened. The amount of water supplied through subirrigation is presented in Table 3.3. The supplied water was highest in the month of August for both years. This represented 34-36% of the total water supplied (Table 3.3). Approximately, 64-68% of total subirrigation water was supplied in the two months of August and September in both 2008 and 2009 when the corn had reached the reproductive stage of growth.

3.3.3 Water balance

The water balance for the two water treatments differ as depicted in Fig. 2. Crop evapotranspiration (ET_c) exceeded precipitation for all months of the growing season except in September 2008 and in July and September 2009 (Table 3.4). In September, precipitation is greater than ET_c by 14 to 18% for 2008 and 2009, respectively. Seasonal rainfall was 20 and 10%deficit (ET_c > rain) of the total crop water demand (ET_c) in 2008 and 2009, respectively. The water balance was found to be significantly higher ($p < 0.05$) for CD-SI plots compared to FD plots. Water surplus in CD-SI plots was a result of extra water supplied by subirrigation than measured by ET_c. Water surplus ranged from 83 to154 mm in CD-SI plots in 2009 compared to 20 to 91 mm in 2008. This led to total drainage of 256 mm in 2008 in CD-SI plots which was 47% higher than 2009. Precipitation was 30 mm higher, and ET_c was 33 mm less in 2009 than in 2008. Surplus water in CD-SI plots might be the deep percolation losses which requires further investigation as deep percolation was assumed to be zero.

3.3.4 Dry grain and above-ground dry biomass yields

Corn grain yields in FD plots were 2 and 8% higher than CD-SI plots in 2008 and 2009, respectively. However, corn grain yields were not significantly different ($p > 0.05$) for FD and CD-SI treatments in 2008 (Table 3.5). Favourable weather conditions and the fact that the producer had planted peas in 2007 after 7 years of continuous corn which has an overall beneficial effect on soil structure and reduced pest levels, might have contributed to good yields in 2008. In 2009, corn yields were significantly different between the two water treatments ($p < 0.05$).

Corn grain yields responded differently to the two water treatments at different nitrogen levels in 2009 (Table 3.6). Grain yields were significantly higher ($p < 0.05$) for FD treatments at low and high nitrogen levels. . The yields in FD plots were higher than CD-SI plots by 1.84 and 0.49 Mg ha^{-1} in low N and high N treatments respectively. However, at medium nitrogen level, grain yields did not respond to the two water treatments ($p = 0.3177$). This may be due to minimal nitrogen stress at medium nitrogen levels of 180 kg ha^{-1}, and no water stress for the two treatments, since there was precipitation occurring every other day during the growing season.

The two water treatments have no effect ($p > 0.05$) on the above-ground dry biomass yields in both years (Table 3.5). The biomass yield in FD plots was higher than CD-SI plots by 7 and 9% in 2008 and 2009, respectively. Subirrigation commenced 47 days after planting, approximately at 9 to10 leaf stage of plant growth. There was good precipitation (102 to158 mm) in the months of July and August, providing optimum conditions for plant biomass growth. Therefore, there was no noticeable difference in dry biomass yields for the two water treatments.

Besides the current study period of 2008 and 2009, higher yields were also reported in 1998 and 1999 for FD plots at the same site (Madramootoo et al., 2001). However, subirrigation plots demonstrated higher yields in 1993, 1994, 1995, 1996, 2001 and 2002 (Zhou et al., 2000, Mejia et al., 2000, Stampfli and Madramootoo, 2006). Table 3.7 summarizes the yield results for two water management systems. However, the yield advantage is limited to only 2 to 7%, except for the driest year i.e. 2001. In 2002, there was a normal seasonal rainfall of 475 mm. However, 63% of the total seasonal rainfall occurred in the months of May and June. August was very dry with monthly rainfall of only 25 mm. Hence, 33% higher yield was observed in CD-SI plots in 2002. FD plots produced 25% higher yield in the wet year of 1998. Hence, it can be concluded that it is advantageous to have a CD-SI system in dry years, as higher yields are achieved (Madramootoo et al., 2007). The FD system is advantageous in wet years. The use of CD-SI and the selection of crop should not be based on only economic benefits, but also on environmental benefits as CD-SI also reduces nitrogen pollution in water bodies by 17 to 80% (Madramootoo et al., 2001, Skaggs, 2010).

3.3.5 Crop water use efficiency

The crop water use efficiency (WUE_{ET}) of grain corn ranged from 2.3 to 2.5 kg m^{-3} (Table 3.5) and is comparable to a global range of 1.1 to 2.7 kg m^{-3} (Zwart and Bastiaanssen, 2004). For FD plots, WUE_{ET} was similar in both 2008 than 2009 for grain corn yield. WUE_{ET} was 7% higher in 2008 than 2009 for CD-SI plots. WUE_{ET} for biomass yield was only 6% higher in 2008 than 2009 for CD-SI plots while it was higher by only 4% for FD plots in 2008. Corn has highest WUE when compared to rice, wheat or cotton (Zwart and Bastiaanssen, 2004). However when compared to other bioenergy crops, miscanthus has a significantly higher WUE compared to corn and switchgrass, while corn and switchgrass have similar WUE (VanLoocke et al., 2004). With increased competition, sharing of water among interprovincial partners, which are already almost fully allocated in some Canadian provinces under drought conditions (Mehdi et al., 2006), WUE data will help in the selection of various cropping systems for a changing climate.

The effect of water management on WUE_{ET} of corn grain was significant ($p < 0.05$) in 2009 but not in 2008. WUE_{ET} was 11% higher for FD treatments than CD-SI treatments in 2009, and only 5% higher in 2008. Water management did not have a significant effect ($p > 0.05$) on WUE_{ET} of above-ground biomass of corn in either year. This was likely due to the fact that the rainfall distribution was uniform for both years with interquartile ranges of 2.8 and 3.8 mm in 2008 and 2009, respectively.

There was a significant interaction ($p = 0.0267$) between water management and nitrogen treatments in 2009. Table 3.6 shows that the effects of the two water treatments on WUE_{ET} were different at different nitrogen levels. At low and high nitrogen levels (Table 3.6), the two water treatments had significant effects ($p < 0.05$) on WUE_{ET}. Average WUE_{ET} of FD plots was 21%, compared to CD-SI plots at low N level and 7% for high N plots. However, as seen for grain yields, WUE_{ET} did not respond to the two water treatments at the medium nitrogen level.

3.3.6 Subirrigation water use efficiency

Subirrigation water use efficiency ($SWUE_{SI}$) of corn was considerably higher than WUE_{ET} estimated using evapotranspiration, and varied from 6.00 to 7.33 kg m^{-3} (Table 3.8). This is because while WUE_{ET} is independent of water supplied either due to rain or irrigation, subirrigation water was supplied only when the water table depth was lower than 0.6 m below the soil surface. The $SWUE_{SI}$ values are higher than those reported for other types of irrigation such as drip irrigation, 0.83 to 1.72 kg m^{-3} (Pablo, 2007), 2.7 to 4.2 kg m^{-3} for using alternate furrow irrigation (Kang et al., 2000), 1.6 to 3.6 kg m^{-3} for using sprinkler irrigation (Larson et al., 2001) and 1.35 to 2.13 kg m^{-3} for a low energy precision application center – pivot system (Howell 2001). However, these are not necessarily fair comparisons as these efficiencies are for a range of different climatic regions and soil types, than those of this study. Our results are comparable with Stampfli and Madramootoo,(2006) who reported $SWUE_{SI}$ values of 5.1 to 7.1 kg m^{-3} at the same study site under reasonably similar conditions. Global climate change will make water scarcity more prominent in many parts of the world (Oliver et. al., 2009). In these scenarios, even in humid and subhumid environments, irrigation will be very effective in overcoming short duration droughts (Howell et al., 1998).

3.3.7 Crop nitrogen use efficiency

The crop nitrogen use efficiency (NUE) for grain corn varied from as low as 41 kg kg^{-1} for high N (~250 N kg ha^{-1}) application to as high as 99 kg kg^{-1} for low N (~130 N kg ha^{-1}). Mean nitrogen use efficiency of grain corn and biomass is shown in Table 3.9. NUE of biomass varied from 27 to 73 kg kg^{-1}. These results are comparable to Liang and MacKenzie (1994) under similar conditions but without conventional or controlled drainage. Grain NUE was higher than 110 and 60% for low N when compared to high N and medium N (~180 kg ha^{-1}), respectively. Comparison of NUE values for different N levels under different water management scenarios is shown in Table 3.10. NUE of grain corn was higher for biomass. The effect of nitrogen rates was significant ($p < 0.05$) on grain and biomass NUE at 95% confidence level (Table 3.11). NUE decreased with the increased rate of nitrogen application. The effect of water treatment was statistically significant on grain NUE but not on biomass NUE ($\alpha = 0.05$) as shown in Table 3.11. There was no interaction between water and nitrogen treatments except for grain yield in 2009. This may be due to good climatic conditions along with 131 kg ha^{-1} for low N. Perhaps, this low rate of N was sufficient for crop growth, therefore not causing any nitrogen deficiency stress. Favourable climatic conditions substantially increased crop yield (Liang and MacKenzie, 1994). At the same time, higher rate of nitrogen application led to lower NUE, causing nitrogen loss due to leaching (Wienhold et al., 2005, Mejia and Madramootoo, 1998), residual nitrogen in soil, and denitrification (Liang et al., 1991). Hence, crop management decision should be based on climatic conditions, environmental impacts and economic analysis of nitrogen and water management scenarios.

3.4 Conclusions

This study compared the water balance, crop yield, water use efficiency, and nitrogen use efficiency of FD and CD-SI plots at three nitrogen levels (low, medium and high). The seasonal water balance demonstrated surplus water conditions in CD-SI plots, while the FD plots had deficit conditions.. The FD plots demonstrated higher yields than CD-SI plots by 1.84 and 0.49 Mg ha^{-1} in low N and high N treatments respectively. The biomass yield in FD plots was higher than CD-SI plots by 7 and 9% in 2008 and 2009, respectively. The water use efficiency (WUE_{ET}) of grain corn ranged from 2.3 to 2.5 kg m^{-3}. Average WUE_{ET} of FD plots was found 17% higher than in CD-SI plots at low N level. Subirrigation water use efficiency ($SWUE_{SI}$) of corn varied from 6.00 to 7.33 kg m^{-3}, higher than other conventional methods of irrigation. NUE decreased with the increased rate of nitrogen application. Grain NUE was higher than 110% and 60% for low N when compared to high N and medium N (~180 kg ha^{-1}), respectively. With increased competition of water, WUE data provides a tool for selection of crops depending on climatic, economic and environmental requirements. It is advantageous to have CD-SI systems in dry years and FD systems in wet years for optimum crop yields.

Table 3.1
Water table depth (m) from ground surface of two water table management treatments.

Year	FD[a]	CD-SI[b]	FD	CD-SI
	Mean		SD[c]	
2008	1.04	0.60	0.28	0.27
2009	1.13	0.75	0.16	0.15

[a] FD = Free or conventional drainage plots.
[b] CD-SI = Controlled drainage plots with subirrigation.
[c] SD = Standard deviation.

Table 3.2
Yearly nitrogen application rates (kg ha^{-1}) applied to corn cultivar.

Year	Low N	Medium N	High N
2008	131	186	277
2009	112	179	246

Table 3.3
Total amount of drainage (mm) and subirrigation (mm) water measured during the growing season (May – September).

Year	Drainage		Subirrigation[a]	
	FD[b]	CD-SI[c]	FD	CD-SI
2008	120.3	256.5	0	164.3
2009	82.8	174.5	0	171.3

[a] No subirrigation was applied to FD plots.
[b] FD = Free or conventional drainage.
[c] CD-SI = Controlled drainage plots with subirrigation.

Table 3.4
Monthly precipitation (mm) and crop evapotranspiration (ET_c; mm) at the experimental site.

	2008		2009	
Month	Rain	ET_c	Rain	ET_c
May	89.4	103.4	77.2	91.9
June	66.6	112.5	66.0	107.3
July	107.1	143.7	157.8	128.0
Aug.	112.2	135.3	102.1	134.9
Sept.	56.6	49.5	58.6	49.5
Total	431.9	544.4	461.7	511.7

Table 3.5
Statistical analysis of dry grain yields (Mg ha^{-1}), above-ground dry biomass yields (Mg ha^{-1}) and water use efficiency (kg m^{-3}) determined using evapotranspiration (WUE_{ET}).

Effect	Yields				Water Use Efficiency			
	2008		2009		2008		2009	
	Grain	Bio[a]	Grain	Bio.	Grain	Bio.	Grain	Bio.
Mean FD[b]	12.54	8.42	11.34	7.41	2.49	1.67	2.46	1.61
Mean CD-SI[c]	12.26	7.88	10.44	6.78	2.43	1.56	2.26	1.47
Water trt[d]	NS[g]	NS	0.0366*	NS	NS	NS	0.0392*	NS
Block	NS	NS	NS	NS	NS	NS	NS	NS
Water * N trt[e]	NS	NS	0.0055*	NS	NS	NS	0.0049*	NS
Block* Water trt[f]	NS	NS	NS	NS	NS	NS	NS	NS

[a] Bio = Biomass.
[b] FD = Free or conventional drainage.
[c] CD-SI = Controlled drainage with subirrigation.
[d] Water trt = FD and CD-SI factors.
[e] Water* N trt = Interaction between water and nitrogen treatments.
[f] Block*Water trt = Interaction between the block and water treatment.
* Significant at $\alpha = 0.05$ level.
[g] NS = Non-significant at $\alpha = 0.05$ level.

Table 3.6
Statistical analyses of simple effects of treatments for mean dry grain yields (Mg ha^{-1}) and mean water use efficiency (kg m^{-3}) in 2009.

Nitrogen Levels	Yield		WUE_{ET}	
	FD[a]	CD-SI[b]	FD	CD-SI
Low N	10.75*	8.91*	2.33*	1.93*
Medium N	11.20	10.82	2.43	2.35
High N	12.07*	11.58*	2.62*	2.51*

[a] FD = Free or conventional drainage plots.
[b] CD-SI = Controlled drainage plots with subirrigation.
* Significant at α = 0.05 level.

Table 3.7
Comparisons of grain corn yields in FD and CD-SI scenarios.

Year	Ppt[a] (mm)	Yield-FD[b] ($Mg\ ha^{-1}$)	Yield-CD-SI[c] ($Mg\ ha^{-1}$)	Higher yield	Difference in yields (%)	References
1993	482.4	8.0	8.2	CD-SI	2.5	Zhou et al. (2000)
1994	443.9	8.9	9.4	CD-SI	5.6	
1995	479.3	11.1	11.4	CD-SI	2.8	Mejia et al. (2000)
1996	500.9	6.8	7.3	CD-SI	6.9	
1998	618.2	8.8	6.6	FD	25.0	Madramootoo et al. (2001)
1999	482.0	9.7	9.5	FD	1.7	
2001	365.4	6.9	9.4	CD-SI	36.2	Stampfli & Madramootoo (2006)
2002	476.2	7.6	10.1	CD-SI	32.9	
2008	431.9	12.5	12.3	FD	2.2	This study
2009	461.7	11.3	10.4	FD	8.0	

[a] Precipitation from May to September. 30 yr average precipitation of the growing season at the site was 474.4 mm.
[b] FD = Free or conventional drainage plots.
[c] CD-SI = Controlled drainage plots with subirrigation.

Table 3.8
Water use efficiency (kg m^{-3}) determined using volume of water supplied through subirrigation (WUE_{SI}).

Year	Mean		SD	
	Grain	Biomass	Grain	Biomass
2008	7.33	5.14	0.59	0.26
2009	6.00	4.20	0.81	0.66

Table 3.9
Mean nitrogen use efficiency (kg kg^{-1}) of grain and biomass yield at different nitrogen and water treatments in 2008 and 2009.

Level of Nitrogen	2008				2009				Average			
	Grain		Biomass		Grain		Biomass		Grain		Biomass	
	FD[a]	CD-SI[b]	FD	CD-SI	FD	CD-SI	FD	CD-SI	FD	CD-SI	FD	CD-SI
Low N	95 (5)	93 (3)	66 (7)	58 (4)	87 (1)	72 (4)	59 (2)	51 (1)	91 (5)	83 (12)	62 (6)	55 (5)
Medium N	68 (2)	66 (2)	45 (3)	44 (0)	58 (2)	54 (2)	42 (5)	40 (5)	63 (6)	60 (6)	44 (4)	42 (4)
High N	45 (2)	45 (4)	30 (2)	28 (1)	46 (0)	43 (0)	33 (2)	31 (4)	45 (1)	44 (2)	31 (3)	29 (3)

[a] FD = Free or conventional drainage plots.
[b] CD-SI = Controlled drainage plots with subirrigation.
Numbers in parentheses are standard deviation.

Table 3.10
Comparison of NUE (%) for different nitrogen levels under different water management scenarios.

Comparison of NUE	2008				2009			
	Grain		Biomass		Grain		Biomass	
	FD[a]	CD-SI[b]	FD	CD-SI	FD	CD-SI	FD	CD-SI
L[c] vs H[d]	109	109	118	105	91	68	78	67
L vs M[e]	60	62	68	50	65	42	50	37
M vs H	49	47	50	55	27	26	20	30

[a] FD = Free or conventional drainage plots.
[b] CD-SI = Controlled drainage plots with subirrigation.
[c] L = Low nitrogen level (112 – 131 kg ha^{-1}).
[d H = High nitrogen level (246 – 277 kg ha^{-1}).
[e M = Medium nitrogen level (179 – 186 kg ha^{-1}).

Table 3.11
Statistical significance of the effects of water and nitrogen (N) treatments (trt) on dry grain and biomass NUE in 2008 and 2009 (n = 18).

Effect	Nitrogen use efficiency			
	2008		2009	
	Grain	Biomass	Grain	Biomass
Water trt[b]	*	NS[a]	*	NS
N trt[c]	*	*	*	*
Water X N trt[d]	NS	NS	*	NS

[a] NS = Non-significant at α = 0.05 level.
[b] Water trt = FD and CD-SI factors.
[c] N trt = Nitrogen factors, low, medium and high N.
[d] Water* N trt = Interaction between water and nitrogen treatments.
* Significant at α = 0.05 level.

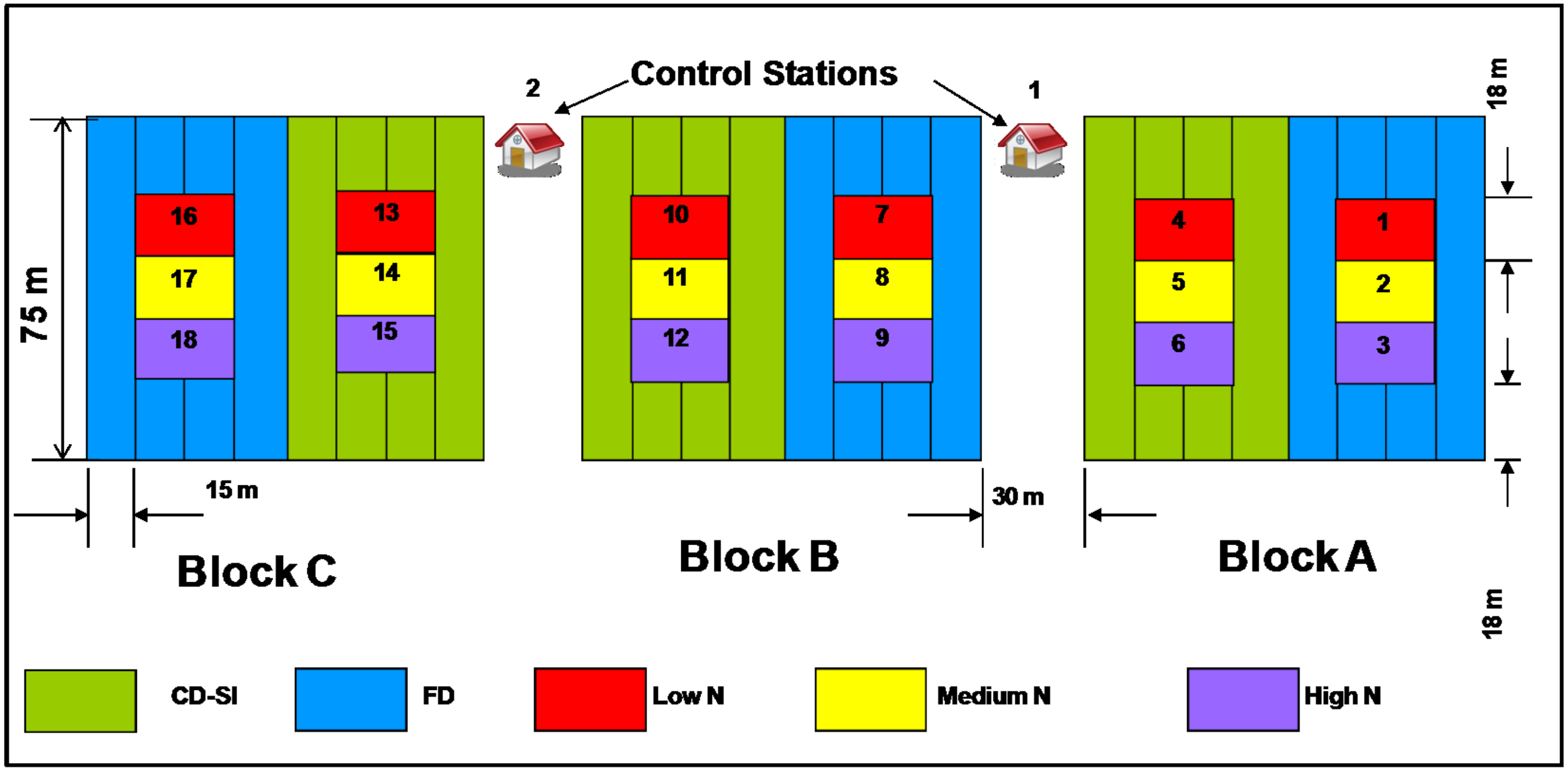


Fig. 3.1 Experimental layout. The numbers 1 - 18 denote plots.

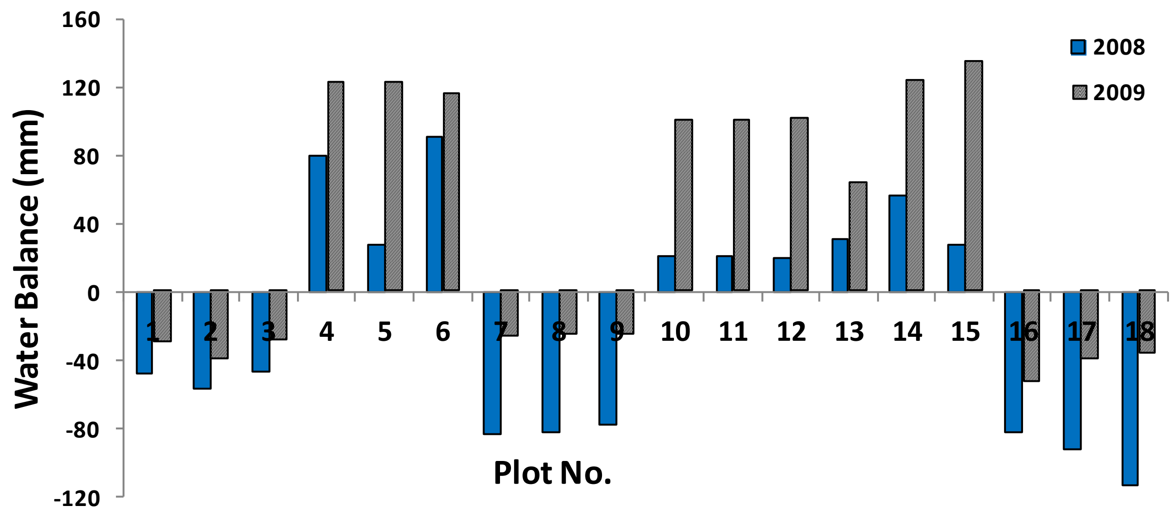


Fig. 3.2 Water balance for all plots for conventional drainage (FD) and water table managed plots (CD-SI) for the year 2008 and 2009. The numbers 1 - 18 denote plots. Plots 1, 2, 3, 7, 8, 9, 16, 17 and 18 were FD plots and 4, 5, 6, and 10 – 15 were CD-SI plots.

Connecting text to Chapter 4

This chapter addresses the second objective of the thesis, measuring daily water uptake of corn using heat balance sap flow method. The heat balance sap flow method and FAO-56 Penman-Monteith method (ET_c) are described. The sap flow method is evaluated against FAO-56 Penman-Monteith method (ET_c). Daily water uptake of corn is measured and compared to ET_c at various stages of corn growth. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Research paper based on the chapter:

Singh, A. K., Madramootoo, C.A. Smith, D.L., 2013. Determination of corn water uptake using sap flow method. Agricultural and Forest Meteorology (under review).

Chapter 4

Determination of corn water uptake using sap flow method

Ajay K. Singh, Chandra A. Madramootoo, Donald L. Smith

Abstract

Sap flow method has been used to measure the transpiration (T) in different plants and trees. It can also be used to determine water uptake by plants. The objectives of this study were to compare the transpiration rate with that of the Penman-Monteith evapotranspiration (ET_c) method, to evaluate the performance of sap flow method in humid conditions, and to quantify transpiration of corn (Zea mays L.) using the sap flow method under different water table management scenarios. Results were obtained from a field study conducted in 2008 and 2009 in Quebec, Canada. The transpiration rates measured by sap flow method were consistent with ET_c calculation for both years. The coefficient of determination (R^2) varied from 0.51 to 0.76. The residual analyses of ET_c and sap flow ranged from 0.51 to 1.01 mm. The daily sap flow errors were in the range of 12 to 24% of the mean ET_c. The maximum amount of water uptake occurred at the milk stage (45.63 to 59.80 mm, 12 days); transpiration during this stage constituted 10-12% of the total water requirement of the corn for the season. The silking to full dent stage (45 days) accounted for approximately 40% of the total water requirement of the crop.

Keywords: Sap flow; heat balance method; evapotranspiration; drainage; subirrigation; corn.

4.1 Introduction

The rate of water uptake by a plant can be measured using direct and indirect methods. Direct methods include sap flow methods, plant growth chambers, porometers, deuterium tracing (Baker and van Bavel, 1987; Green et al., 2003; Smith and Allen, 1996; Goulden and Field, 1994; Ansley et al., 1994; Calder et al., 1992). Indirect methods include Bowen ratio, eddy covariance, crop evapotranspiration, lysimeter, and water balance methods (Bethenod et al., 2000; Wang et al., 2012; Allen et al., 1998, 2011; Lopez-Urrea et al., 2012). For computation of water need by crops in indirect methods, many variables are required and several of them are assumed. Consequently, both measurement and assumption errors demonstrate bias in the reported data, caused by flaws in experimental design, measurement equipment, model parameterization, and interpretation of results (Allen et al., 2011). In addition, these calculations are for specific regions and need to be adapted for a given location. Therefore, direct methods offer a viable solution to reduce errors and improve accuracy.

The sap flow method is a direct, accurate, non-invasive and continuous measurement of sap flow on a plant stem (Baker and van Bavel, 1987). Sap flow methods are also referred to as heat balance methods, heat pulse methods and thermal dissipation techniques (Smith and Allen, 1996). Heat balance method involves the determination of water uptake by conducting a heat balance on sap movement from the roots to other parts of the plant. Sap flow gages based on thermal heat balance were used in this study. Stem gages used in this study were considered non-invasive because, unlike heat pulse method they don't penetrate into the plant stem. They wrap around the corn stem. Sap flow gages can be easily automated so that continuous data with high time resolution can be obtained (Smith and Allen, 1996) and calibration is not required (Baker and van Bavel, 1987).

Sap flow methods are useful for various purposes such as determination of crop coefficients, evapotranspiration components, sprinkler irrigation application efficiency, and to study the effect of environmental controls on transpiration as wells as drought avoidance mechanisms (Assouline et al., 2002; Tognetti et al., 2004; Bovard et al., 2005; Chirino et al., 2011; Zhang et al., 2011; Martinez-Cob et al., 2008). Sap flow methods are becoming increasingly popular for determining the water requirements of many crops such as sugarcane, apples, soybean, corn, potato, cotton, and grapes (Chabot et al., 2005; Gong et al., 2006; Johnson et al., 2004; Martinez-cob et al., 2008; Gordon et al., 1997; Zhang et al., 2011).

Previous studies have reported daily sap flow rates of corn plants that were within ±10% of ET_c determined by the Bowen ratio method with an 80% statistical confidence level (Jara et al., 1998). With reference to a gravimetric weight loss method, sap flow method had 4% error over a 24 h measurement interval and 15% error over a period of 15 min (Weibel and Boersma, 1995). Bethenod et al. (2000) compared sap flow transpiration to ET_c measured by

Bowen ratio. They found sap flow transpiration to be 88 to 90% of ET_c and inferred that the gap of 10 to 12% was related to soil water evaporation. The slope ranged between 0.8 and 0.9, and intercept was close to zero. Aiken and Klocke (2012) found that the coefficient of determination varied from 0.79 to 0.85 and standard errors of 45.1 to 74.6 between ET_c and sap flow.

There are no reported studies on the use of sap flow technique on corn in a humid climate for an extensive period. There are three reported field studies of the use of sap flow technique for about 40 days in arid or semi-arid conditions (Jara et al., 1998; Bethenod et al., 2000; Martinez-Cob et al., 2008). In this context, the first objective of this study was therefore to evaluate the performance of the sap flow heat balance method under two water management scenarios for a five week period in two years in the humid climate of Quebec. The second objective was to determine water uptake by corn at various stages of growth under these two water management scenarios. This study is novel because it is the first to quantify transpiration for corn using the sap flow technique under conventional drainage, and controlled drainage along with subirrigation.

4.2 Materials and methods

4.2.1 Experimental site

The experimental site of 4.2 ha in area was located at Coteau-du-Lac, approximately 60 km west of Montréal, Canada. The soil textures of the top 100 cm of soil were sandy loam, sandy clay loam and clay at depths of 0-25, 25-50 and 50-100 cm, respectively. The surface topography was flat, with an average slope of less than 0.5% (Kaluli, 1999).

The experiment was carried out in the years 2008 and 2009. Grain corn (Mycogen 2R426) was sown on 4 May 2008 and another variety of corn (Pioneer 38N8T) on 7 May 2009. The plant densities were determined 89000 and 85000 plants ha^{-1} in 2008 and 2009, respectively. The crop was harvested on 15 and 20 October in 2008 and 2009, respectively.

A randomized complete block design was set up to study the transpiration rates and water uptake of corn in two different water management scenarios. The two water management scenarios were i) Conventional drainage or Free drainage (FD) and ii) Controlled drainage with subirrigation (CD-SI). The two water table treatments were randomly allocated to each block. Stem gages were installed into subplots of 18 by 30 m, treated with nitrogen, at a rate of ~180 kg ha^{-1}. There were three blocks separated from each other by 30 m wide strips of undrained land.

The water table throughout the growing season was near the drain depth of one meter or below the ground surface in the FD plots. In CD-SI plots, the water table was maintained at 60 cm below the ground surface due to subirrigation. Once the producer had completed all the agronomic practices, drainage valves were closed and the irrigation pump was activated. Subirrigation was started on 25 and 23 June in 2008 and 2009, respectively. A groundwater well located at the north-east corner of the field supplied water for subirrigation. At the end of the 2008 season, the subirrigation was stopped on 9 September and the drainage pipes were opened on 15 September. In 2009, the irrigation pump was turned off and drainage pipes were opened on 20 September. This was done to enable grain corn harvesting.

4.2.2 Sap flow measurement

The sap flow method as described by Baker and van Bavel, (1987), Dynagage Flow32-1K system (Dynamax, Houston, Texas, USA) was used to measure the sap flow of corn. Three plants were selected in each plot for installing the stem gages, avoiding areas near the edges. A total of 18 gages were installed each year (3 gages per treatment *2 treatments * 3 blocks). The mean diameter of the plants was 22 and 23 mm in 2008 and 2009, respectively. Gages of models SGB19 and SGB25, were used to measure the sap flow. They were installed on 22 July in 2008 (79 days after planting, DAP) and on 30 July in 2009 (84 DAP). Leaf sheaths where the gages were installed were removed. Gages were checked every 7 to 10 days for maintenance. The corn stems were checked for damage due to constant heating or any condensation. Stem gages were either transferred to another plant to prevent damage to stems or replaced with dry gages if they were wet after rain. All the steps of gage installation were repeated. Stem gages installed on the stem were connected to data logger with 20 to 24 gage cables. Due to instrument failure, data from only two blocks were available in 2008.

Sap flow readings were made every 60 s and averaged over 30 min intervals. Data were processed in MS-Excel 2007 (Microsoft, Redmond, Wash.) to produce daily sap flow rates (g d^{-1}). Martinez-Cob et al. (2008) measured transpiration rates for corn during the night. They found it almost negligible (0.04 – 0.15 mm), hence night-time transpiration was assumed to be negligible in this study. Therefore, power to the stem gages was turned off at 9 pm and turned on again the following day at 5 am. This saved power and avoided damage to the plant stems. Gages were taken off on 8 September in both 2008 and 2009. Sap flow data were available from 80 to 126 DAP in 2008, and 85 to 119 DAP in 2009. To compare the sap flow of 2008 and 2009, the data for 35 days from 85-119 DAP was considered for both years. Canopy transpiration was calculated from the sap flow per plant and plant density data (Cohen and Li, 1996). Water uptake by corn plants at various stages of growth was obtained by integrating the daily sap flow measurements for that stage of growth, and then compared with corresponding ET_c values.

4.2.3 Evapotranspiration

Reference evapotranspiration (ET_r) was calculated using the FAO Penman-Monteith method (Allen et al., 1998) as presented in Eq. (4.1). Information required for ET_r was collected from a weather station installed on the north-east corner of the site. $ET_{r,}$ calculated from measured microclimatic data over a well watered corn field, can be used as a substitute for the data measured above a reference surface (Irmak and Odhiambo, 2009).

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4.1)$$

where ET_r is reference evapotranspiration (mm d^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), (e_s-e_a) is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa °C^{-1}), and γ is psychrometric constant (kPa °C^{-1}). Eq. 4.1 is derived from the original Penman-Monteith equation, and equations for aerodynamic and surface resistance (s m^{-1}) (Allen et al., 1998). Surface resistance or its inverse, stomatal conductance (m s^{-1}) is a boundary condition included in Eq. 4.1 (Aiken and Kloche, 2012). Net radiation (R_n) was estimated by the difference between net short wave and net long wave radiation measured at the site using a net radiometer (Kipp & Zonen, Model: CR1, Delft, The Netherlands). Albedo was taken into account by the net radiometer, as the difference between the incoming global solar radiation and the solar radiation reflected from the surface below. ET_c calculations were made under neutral stability conditions i.e. where temperature, atmospheric pressure, and wind velocity distributions follow nearly adiabatic conditions (Allen et al., 1998). Saturation vapour pressure (e_s) was computed as the mean between the saturation vapour pressure at the mean daily maximum and minimum air temperatures for the day. Actual vapour pressure (e_a) was derived from relative humidity data (Allen et al., 1998).

Dual crop coefficient – basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_c) was used to find the crop transpiration and soil evaporation components of total evapotranspiration (ET_r), respectively (Allen et al., 1998). Crop transpiration component of ET_r, denoted as ET_c is shown in Eq. 4.2, was used to evaluate sap flow system performance. Value of K_{cb} was adjusted for local climatic conditions as shown in Eq. 4.3 (Allen et al., 1998). Various corn growth stages were identified according to the literature (OMAFRA, 2009; Ritchie et al., 1993).

$$ET_c = K_{cb} * ET_r \tag{4.2}$$

$$K_{cb} = K_{cb\,(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](\tfrac{h}{3})^{0.3} \tag{4.3}$$

where $K_{cb\,(Tab)}$ is 1.15 for mid-stage and 0.5 for end stage of corn, u_2 is mean value of wind speed at 2 m height over grass during the mid or late season growth stage (m s^{-1}) for 1 m s^{-1} ≤ u2 ≤ 6 m s^{-1}, RH_{min} is the mean value of daily minimum relative humidity during the mid or late season growth stage (%) for 20% < RH_{min} < 80% and h is the mean plant height during the mid-season stage (m) for 0.1 m < h < 10 m. The wind speed was measured at 5 m height because of the height of the corn, and was calibrated to 2 m height as shown in Eq. 4.4 (Allen et al., 1998). Mean value of daily minimum relative humidity (RH_{min}) and wind speed (u_2) are listed in Table 4.1. The adjusted K_{cb} values for mid-season (81 to 121 DAP) are shown in Fig. 4.1.

$$u_2 = u_z \frac{4.87}{\ln(67.8\, z - 5.42)} \quad (4.4)$$

4.2.4 Statistical Analysis

Both qualitative and quantitative methods were utilized to compare the sap flow method performance to ET_c. These methods included graphical inspection, scatter diagram, coefficient of determination, regression, root mean square (RMSE), and index of agreement (d). RMSE and d were defined as follow:

$$\mathrm{RMSE} = \sqrt{n^{-1} \sum_{i=1}^{n} (P_i - O_i)^2} \quad (4.5)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P'_i| + |O'_i|)^2}\right], \quad 0 \le d \le 1 \quad (4.6)$$

where n is the number of observations, i denotes the i th observation, P is the sap flow value, O is the ET_c value, P_{avg} is the average sap flow values, $P' = P_i - P_{avg}$ and $O' = O_i - O_{avg}$. O_{avg} is the mean of the ET_c values. The coefficient of determination (R^2) indicates reliability and strength of the linear model. Although the magnitudes of R^2 are not consistently related to the accuracy of prediction because it is more sensitive to outliers than to observations near the means (Legates and McCabe Jr, 1999) and insensitive to additive and proportional differences between the model predictions and observations (Willmott, 1984), nevertheless it is shown in order to compare the performance of the sap flow method with other studies. Intercept and slope pair indicates whether or not there is a bias. A value of one for slope and zero for intercept denotes perfect prediction of transpiration compared to ET_c. The value of RMSE can vary from 0 to infinity however; lower numerical values of RMSE indicate a better performance of the model. Index of agreement is the ratio of mean square error and the potential error(Willmott, 1984, Legates and McCabe, 1999). Index of agreement varies between 1.0 and 0.0 where higher value means better agreement between observed values and predicted values, whereas 0.0 describes complete disagreement (Willmott, 1984). Index of agreement represented an improvement over R^2 but also is sensitive to extreme values, owing to squared differences (Legates and McCabe, 1999).

4.3 Results and discussion

4.3.1 Climatic conditions

The daily climatic conditions at the site are presented in Fig. 4.2. Precipitation patterns were similar in both years. The total seasonal rainfall (May to September) was 432 mm in 2008 and 462 mm in 2009. The maximum daily precipitation of 35.3 mm occurred on 22 July in 2008 and 49 mm on 11 July 2009. The average precipitation for August was 112.2 and 102.1 mm in 2008 and 2009, respectively. The 30 yr average normal precipitation for August (1980-2009) was 95.4 ± 32.4 mm. The mean temperatures during the growing season were 17.2 ± 4.6^{o}C in 2008, and 16.7 ± 4.2^{o}C in 2009 compared to the 30 yr average temperature of 17.0 ± 3.1^{o}C during the same period. The hottest day in 2008 was 30.4^{o}C on 10 June while the hottest day was 31.7^{o}C in 2009 on 25 June. The soil temperature does not change at 1 and 15 cm depth during the growing season. The mean soil temperature was 17.1 ± 3.6 and 16.9 ± 3.5^{o}C in 2008 at 1 and 15 cm depth, respectively. In 2009, the mean soil temperature was 17.2 ± 3.6 and 17.0 ± 3.4^{o}C at 1 and 15 cm depth, respectively. The mean solar radiation received during this period was 15.8 MJ m^{-2} d^{-1} in 2008 and 15.3 MJ m^{-2} d^{-1} in 2009. The growing season mean vapor pressure deficit was 0.8 and 0.7 kPa in 2008 and 2009. The mean water table depth during the growing season in the FD plots was 1.04 ± 0.28 and 1.13 ± 0.16 m in 2008 and 2009, respectively. In CD-SI plots, the mean water table depths were 0.60 ± 0.27 and 0.75 ± 0.15 m in 2008 and 2009, respectively.

4.3.2 Sap flow and evapotranspiration

Sap flow dynamics for the period of study (85-119 DAP) are shown in Fig. 4.3 and 4.4. The mean sap flow varied from 3.80 to 4.23 mm. Table 4.2 shows the quantitative assessment of the sap flow measurements compared to ET_c calculated from Eq. 4.1. The residual analyses (RMSE) of ET_c and daily sap flow varied from 0.51 to 1.01 mm. The errors were in the range of 12 to 24% of the mean ET_c. Other researchers have reported similar range of errors. Zeggaf et al. (2008) reported sap flow relative errors of 19 to 24%, compared to the lysimeter method. Cohen et al. (1993) reported overestimation of sap flow by 25% using the heat pulse technique. The coefficient of determination (R^2) ranged from 0.51 to 0.76 (Table 4.2) indicating moderate to fair prediction. Similar R^2 values, from 0.68 to 0.97, were also reported by other investigators (Gong et al., 2006; Cohen et al., 1993). Examination of intercept and slope that varied from 0.85 to 2.08 and 0.40 to 0.76, respectively, indicated a positive bias in sap flow prediction of transpiration. The index of agreement ranged from 0.74 to 0.90 indicating moderate to good prediction of transpiration by the sap flow method.

Sap flow variation with ET_c was consistent during the period of study (85-119 DAP) in both years (Fig. 4.3). The mean ET_c for the period of study was 4.29 ± 0.84 mm and 4.28 ± 1.29 mm for 2008 and 2009, respectively. However, during the study period (35 days), large variation in ET_c was observed in 2009 with a range of 5.11 mm (1.21 – 6.32), twice as much as in 2008. The range of ET_c was only 2.93 mm (2.59 – 5.52) during the same period in 2008 (Table 4.3). However, such fluctuations of sap flow in the FD and CD-SI plots in 2009 were not observed. In 2009, sap flow ranged 2.70 (2.22 – 4.92) and 3.97 mm (1.61 – 5.58) for FD and CD-SI conditions, respectively. While observing extreme values of sap flow and ET_c, corresponding solar radiation (R_s) and vapour pressured deficit (VPD) values were also examined and shown in Table 4.3. High and low values of both sap flow and ET_c correspond to high and low values of R_s and VPD on given days, indicating proper functioning of the sap flow system.

The cumulative sap flow measurement for 35 days for the FD treatment was 142.19 and 133.14 mm in 2008 and 2009, respectively (Fig. 4.5). The cumulative sap flow for CD-SI treatment was 148.16 and 139.91 mm in 2008 and 2009, respectively. The cumulative ET_c during this period was 150.31 and 149.77 mm in 2008 and 2009, respectively. The seasonal error in sap flow measurement varies from 1% for CD-SI plots in 2008 to 11% for FD plots in 2009. The high error in sap flow measurements in 2009 may be due to the sap flow gage not being sufficiently sensitive enough to respond quickly to sap flow fluctuations (ET_c range of 5.11 mm) during the study period.

The main difficulty that we experienced with the sap flow system on a corn plant was moisture penetration after rain. To avoid this problem, leaves at the nodes where the stem gages were installed, were removed. This might alter the micro-environment of the plant. Despite our best efforts, the insulation got wet after prolonged rainfall, although the gage itself remained dry. Hence, besides regular maintenance of gages every 10 to 14 days, gages should also be checked after a rainfall event. Sap flow system software filtered any low flow rate when the sensor signals were either below the minimum threshold or above the flow capacity of the senor. Erroneous data were removed by checking the computed values against the other corresponding gage values, and by cross validating with the solar radiation, vapor pressure deficit and ET_c values. Another limitation of sap flow method was that it was highly sensitive to gage constant (K_{sh}). It could not be assigned perfectly (Dynamax, 2005) because it had to be calculated when the sap flow is zero. The K_{sh} values are estimated at all times except when sap flow value is zero, which happens only when air humidity has reached 100% and the plant is fully saturated with water (Liu and Schweighoefer, 2012). All guidelines of the manufacturer (Dynamax Inc.) were followed during calibration of the K_{sh}. Also, sap flow method is not suitable for corn stem diameter less than 15 mm. The minimum input voltage of 3.5 V recommended for optimal gage performance would damage the plant stem. Under these limitations, the sap flow method can be used to determine water requirement of corn under humid conditions.

4.3.3 Water uptake

The total water uptake for the season from sowing to maturity of corn (146 days) was 497.28 and 448.72 mm using the Penman-Monteith FAO-56 for 2008 and 2009 respectively. The total water uptakes during the study period and the rates of water uptake at different growth stages are given in Table 4.4. Complete data for only three stages were available in 2009. Maximum water uptake was seen at milk stage (~60 mm) when 12% of the total water demand took place with 9, 6 and 8% water uptake at the silk, blister and early dent stages, respectively in 2008. The silking to full dent stage growth phase (45 days) accounted for 39% of the total water requirement of the crop.

Rate of water uptake varied from 3.55 to 5.93 mm d^{-1} for various stages of corn growth (Table 4.5). Although, silking is reported as the most critical stage for maximum yield (Kranz et al., 2008), maximum rate of water uptake occurred at the milk stage for both FD (4.98 mm d^{-1}) and CD-SI (4.76 mm d^{-1}) treatments in 2008. This is consistent with the ET demand (4.50 mm) of the crop during this stage (Table 4.5). A high rate of water uptake was also observed at the early dent stage. Thus, it is important to maintain adequate water supply to meet the corn water requirement till late stages of crop growth stage for optimum yield.

4.4 Conclusions

Sap flow was measured under field conditions for FD and CD-SI treatments and compared to ET_c determined by FAO Penman-Monteith method. Sap flow fluctuations were consistent with ET_c both diurnally and seasonally. The index of agreement ranged from 0.74 to 0.90. The sap flow method can be used on corn plants with stem diameters 15 mm and above. The water demand was maximum at the milk stage (~60 mm) when 12% of the total water demand took place. The daily water uptake of corn varied from 3.55 to 5.93 mm d^{-1} from silking to full dent stage (87 to 126 DAP). Adequate water supply strategy has to be developed to meet the water demand (~40%) of corn from silking to full dent stage. The results indicate the applicability of sap flow in humid conditions. Water can be saved by matching the water supply to water requirement of crop determined using sap flow method.

Table 4.1
Mean value of daily minimum relative humidity (RH_{min}) and wind speed (u_2) at 2 m height from ground surface at mid and late season growth of corn.

Year	RH_{min} (%)		u_2 (m s^{-1})	
	mid	late	mid	late
2008	55.08	52.55	1.63	1.65
2009	52.36	53.12	1.25	1.29

Table 4.2
Statistical comparison of sap flow values with crop evapotranspiration values where FD: free drainage; CD-SI: controlled drainage with subirrigation.

Statistic	2008			2009		
	ET_c	FD	CD-SI	ET_c	FD	CD-SI
Mean (mm)	4.29	4.06	4.23	4.28	3.80	4.00
Standard deviation (mm)	0.84	0.88	0.82	1.29	0.70	0.98
Coefficient of Determination, R^2		0.51	0.54		0.55	0.76
Linear regression, intercept		0.85	1.10		2.08	1.33
Linear regression, slope		0.75	0.73		0.40	0.76
Root mean square error, RMSE (mm)		0.51	0.60		1.01	0.70
Index of agreement, d		0.82	0.85		0.74	0.90

Table 4.3
Effect of solar radiation (R_s) and vapour pressure deficit (VPD) on sap flow and ET_c.

Treatment	2008				2009			
	Value[a]	R_s	VPD	DAP[b]	Value	R_s	VPD	DAP
	mm	MJ m^{-2} d^{-1}	kPa		mm	MJ m^{-2} d^{-1}	kPa	
ET_c	5.52	14.67	0.83	102	6.32	16.21	0.99	86
	2.59	6.44	0.57	92	1.21	3.55	0.26	87
FD	5.96	14.67	0.83	102	4.92	15.41	0.96	98
	2.11	7.88	0.55	89	2.22	7.98	0.49	115
CD-SI	5.26	13.45	0.82	105	5.58	15.29	1.05	99
	1.48	7.88	0.55	89	1.61	1.59	0.44	114

[a] Maximum and minimum value during the period of study (85-119 DAP)
[b] Days after planting
ET_c Crop evapotranspiration determined using Penman-Monteith method
T_{FD} Transpiration for the Free Drainage treatment
T_{CD-SI} Transpiration for the Controlled drainage with subirrigation treatment

Table 4.4
Total water uptake (mm) at different reproductive stages of corn growth.

Corn growth stages	Days[a]	Water uptake for each stage					
		2008			2009		
		ET_c	T_{FD}	T_{CD-SI}	ET_c	T_{FD}	T_{CD-SI}
Silking	10	42.28	39.16	42.21	-	-	-
Blister	8	29.59	29.62	28.36	37.21	35.95	34.85
Milk	12	53.98	59.80	57.09	52.15	46.98	45.63
Early dent	9	41.05	37.95	35.31	53.40	44.80	46.00
Full dent	6	27.02	22.88	23.00	-	-	-
Sum[b]	45	193.92	189.41	185.98	142.77	127.74	126.48

[a] Number of days to reach this stage from previous stage
[b] Sum of only 29 days in 2009
ET_c Crop evapotranspiration determined using Penman-Monteith method
T_{FD} Transpiration for the Free Drainage treatment
T_{CD-SI} Transpiration for the Controlled drainage with subirrigation treatment

Table 4.5
Average rate of water uptake (mm d^{-1}) at different reproductive stages of corn growth.

Corn growth stages	Days[a]	Average water use rate for each stage					
		2008			2009		
		ET_c	T_{FD}	$T_{CD\text{-}SI}$	ET_c	T_{FD}	$T_{CD\text{-}SI}$
Silking	10	4.23	3.92	4.22	-	-	-
Blister	8	3.70	3.70	3.55	4.65	4.36	4.66
Milk	12	4.50	4.98	4.76	4.35	3.80	4.04
Early dent	9	4.56	4.22	3.92	5.93	5.11	4.86
Full dent	6	4.50	3.81	3.83	-	-	-

[a] Number of days to reach this stage from previous stage
ET_c Crop evapotranspiration determined using Penman-Monteith method
T_{FD} Transpiration for the Free Drainage treatment
$T_{CD\text{-}SI}$ Transpiration for the Controlled drainage with subirrigation treatment

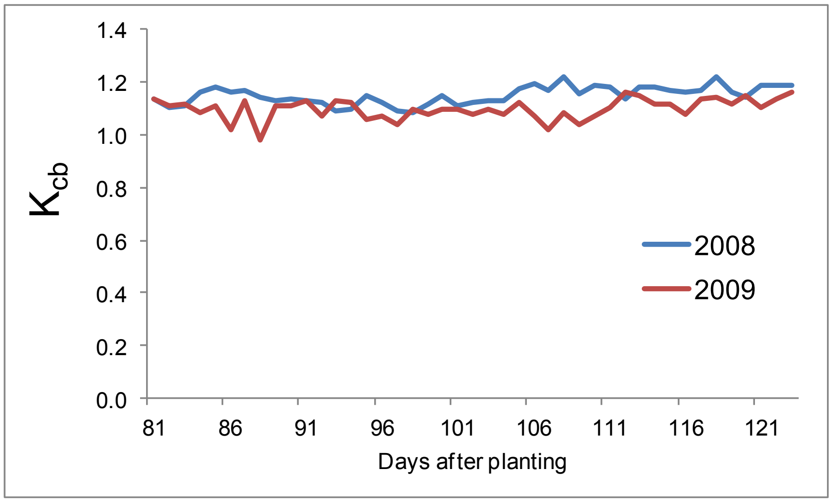
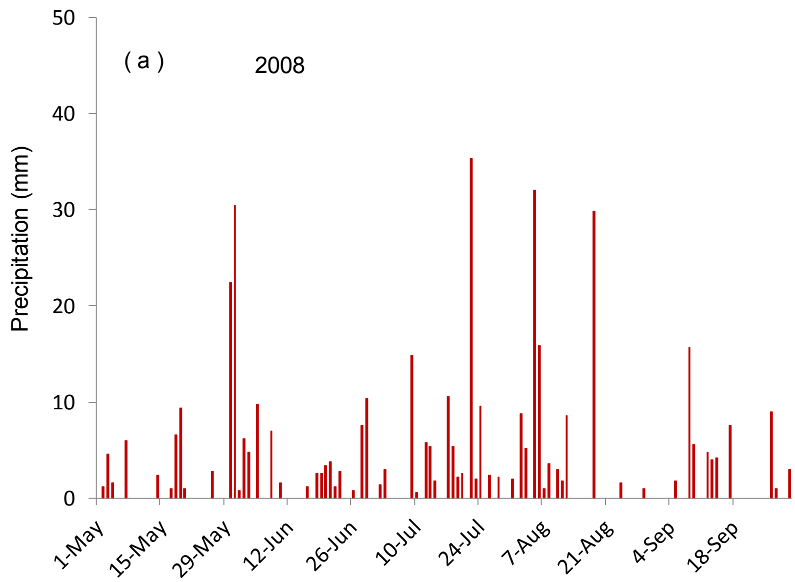
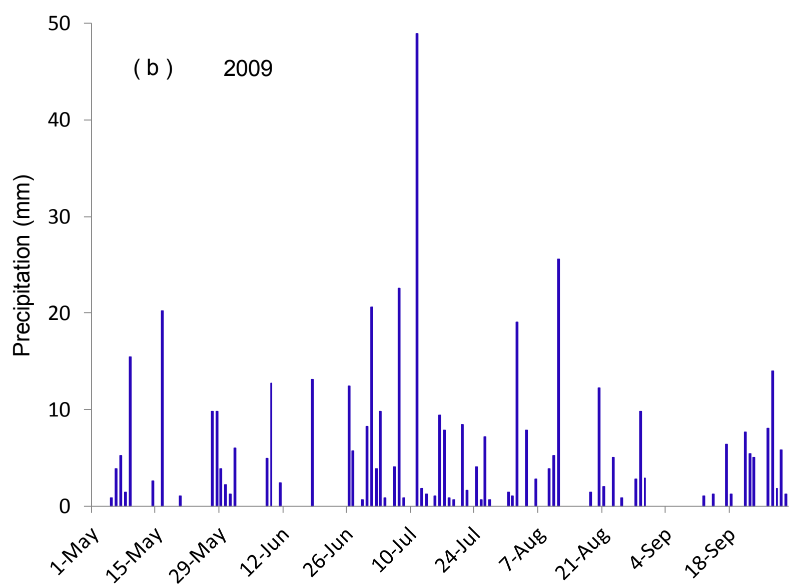


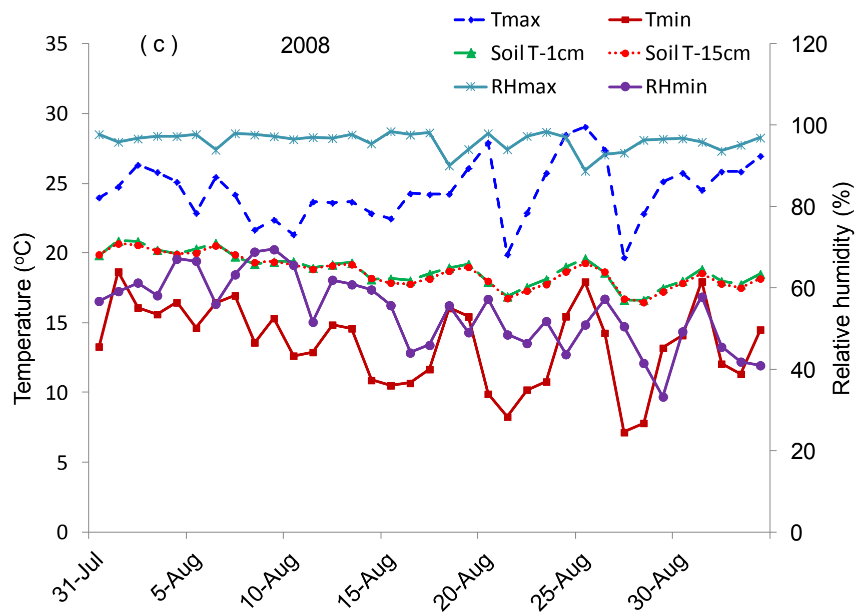
Fig. 4.1 Adjusted basal crop coefficient (K_{cb}) values for the mid stage of corn growth calculated from Eq. (4.3) for the period of study. $K_{c\ mid\ (Tab)}$ = 1.15



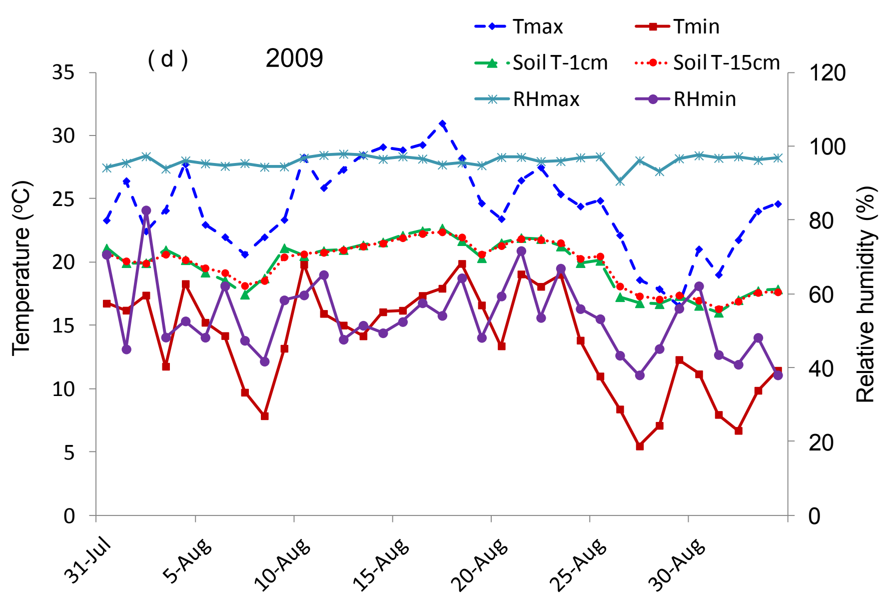
(a)
2008
Precipitation (mm)
50
40
30
20
10
0
1-May
15-May
29-May
12-Jun
26-Jun
10-Jul
24-Jul
7-Aug
21-Aug
4-Sep
18-Sep



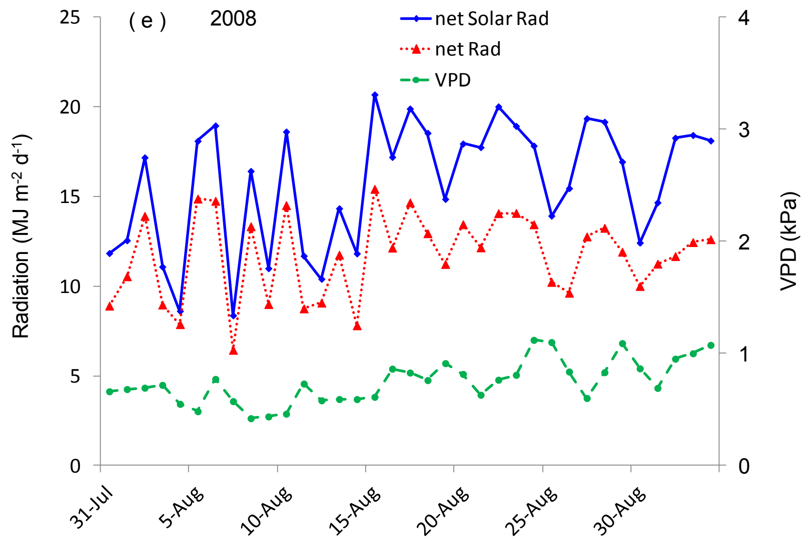
(b)
2009
Precipitation (mm)
50
40
30
20
10
0
1-May
15-May
29-May
12-Jun
26-Jun
10-Jul
24-Jul
7-Aug
21-Aug
4-Sep
18-Sep



(c)
2008
Tmax
Tmin
Soil T-1cm
Soil T-15cm
RHmax
RHmin
Temperature (ºC)
Relative humidity (%)
31-Jul
5-Aug
10-Aug
15-Aug
20-Aug
25-Aug
30-Aug



(d)
2009
Tmax
Tmin
Soil T-1cm
Soil T-15cm
RHmax
RHmin
Temperature (ºC)
Relative humidity (%)
31-Jul
5-Aug
10-Aug
15-Aug
20-Aug
25-Aug
30-Aug



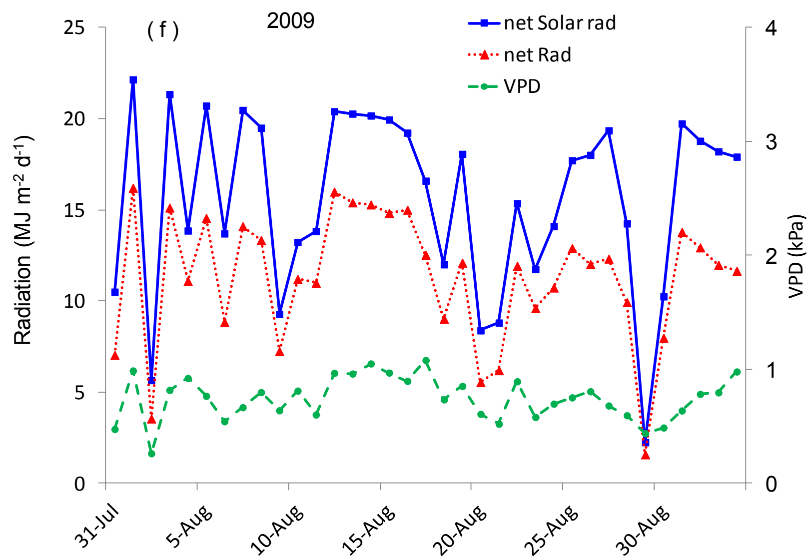


Fig. 4.2 Daily meteorological conditions measured for the two experimental periods in 2008 (**a, c, e**) and 2009 (**b, d, e**): **a, b** rain (mm); **c, d** maximum and minimum air temperatures and mean soil temperature of soil at 1 and 15 cm depth (^{o}C); **e, f** vapour pressure deficit (kPa), net solar radiation and net radiation (MJ m^{-2} d^{-1})

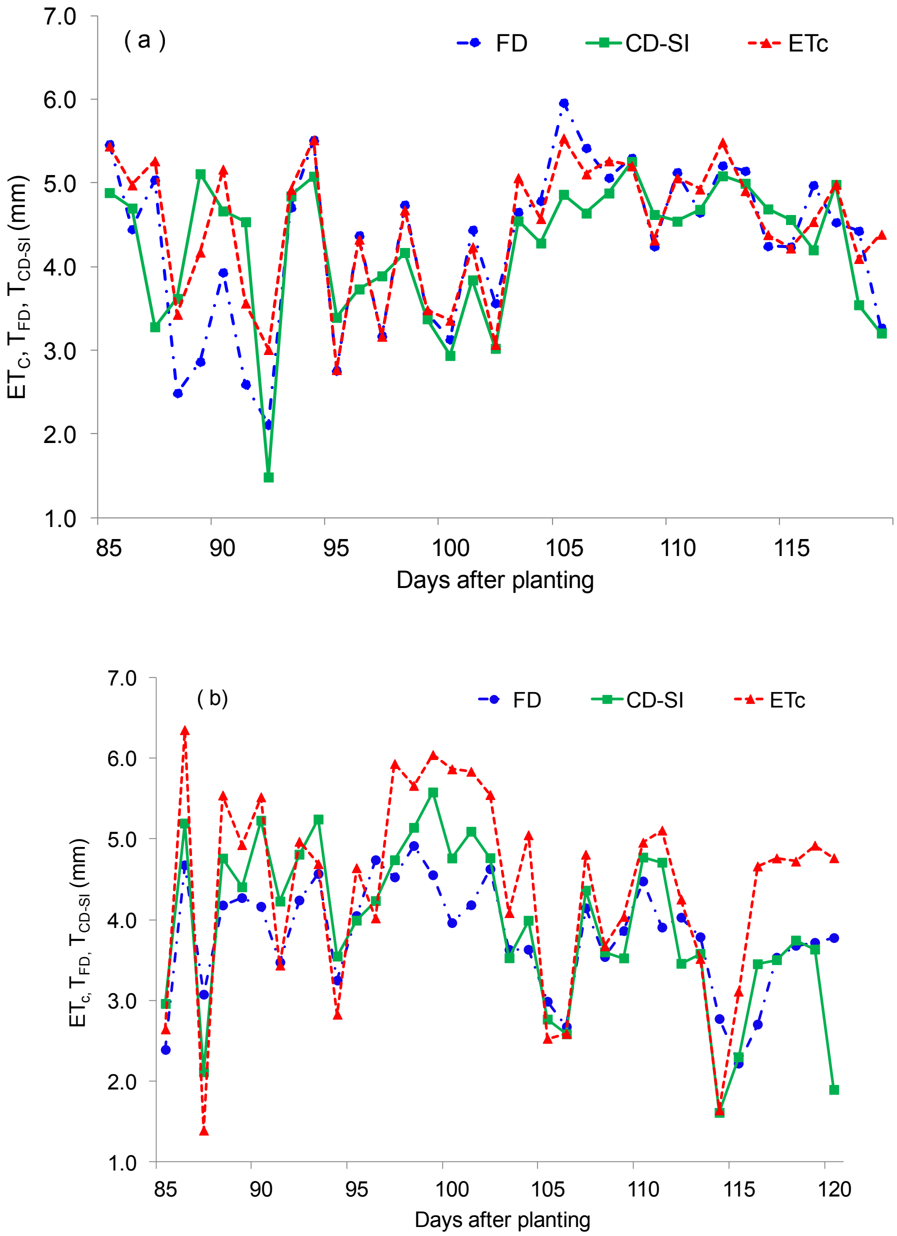


Fig. 4.3 Daily sap flow (T) fluctuation of corn plants with respect to crop evapotranspiration, ET_c (a) 2008 and (b) 2009. FD: Free drainage; CD-SI: controlled drainage with subirrigation.

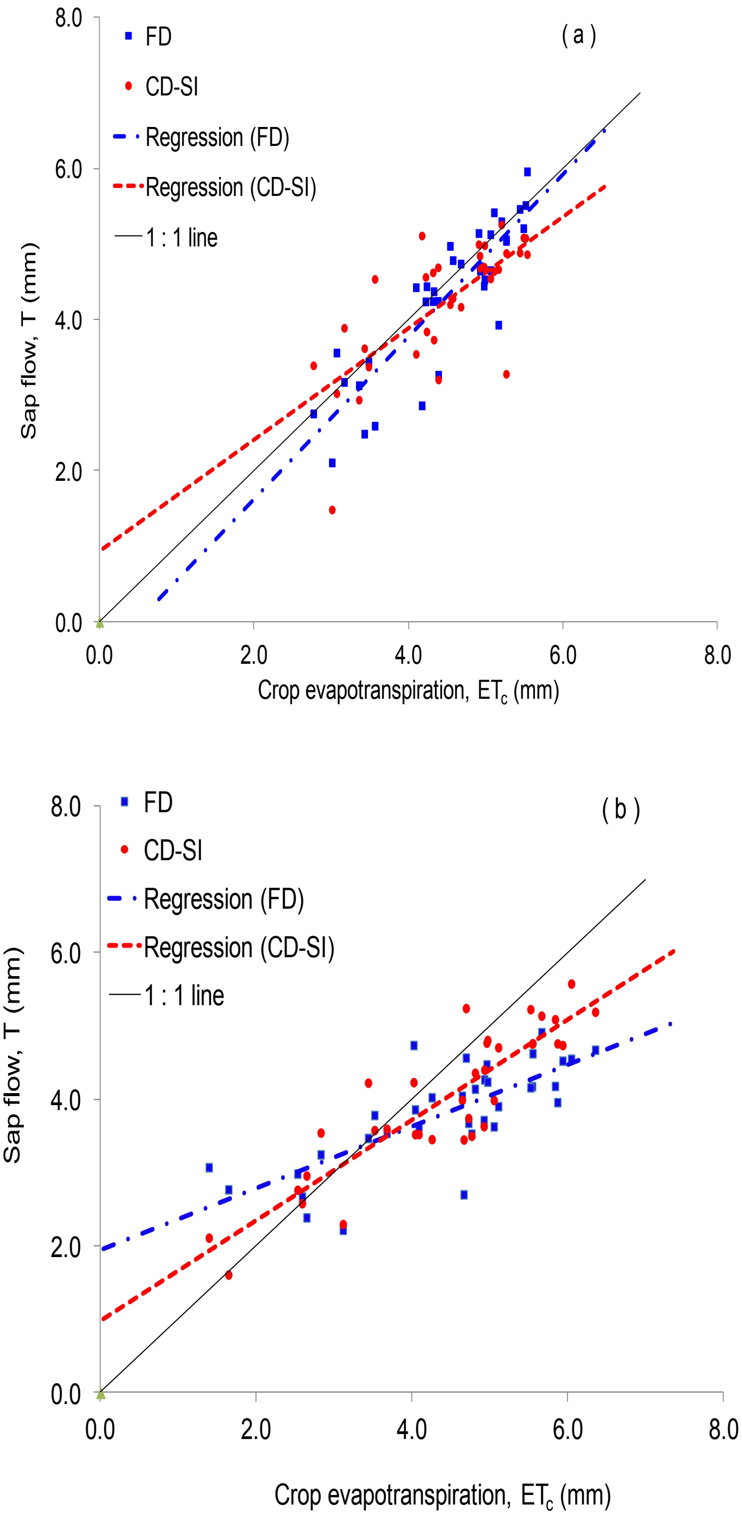


Fig. 4.4 Correlation between daily sap flow (mm) and daily crop evapotranspiration (mm) along with regression lines (a) 2008 and (b) 2009. FD: Free drainage; CD-SI: controlled drainage with subirrigation. n = 35.

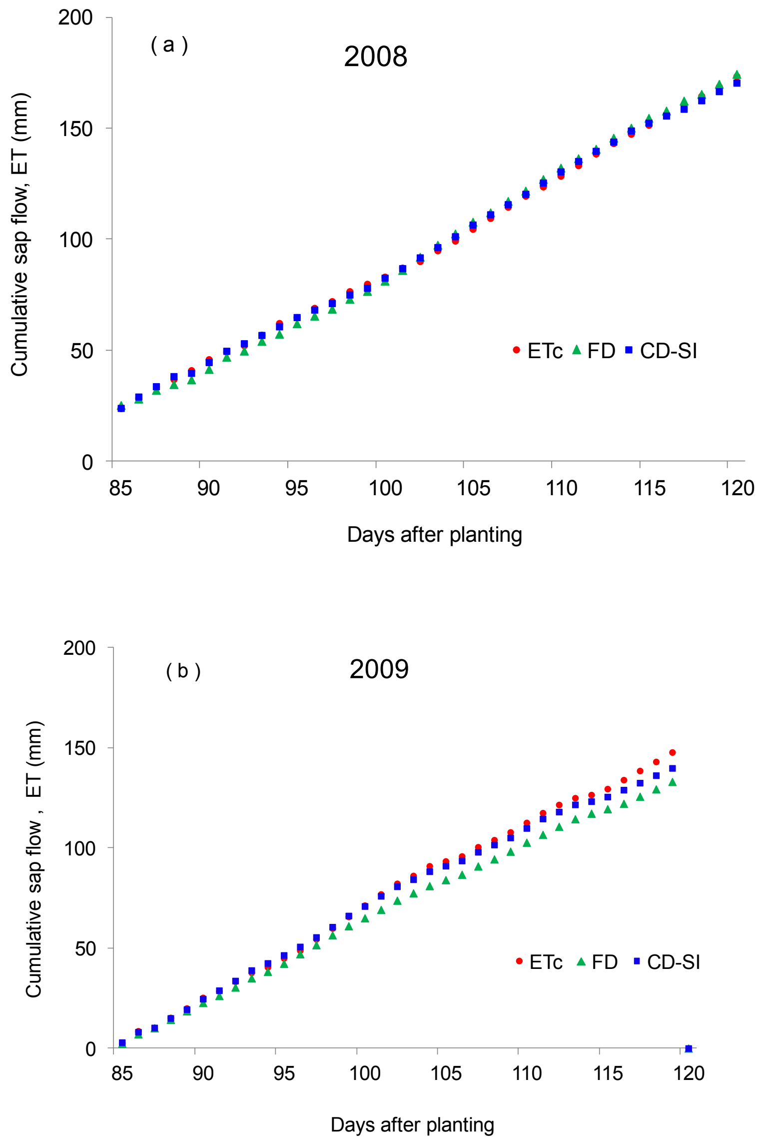


Fig. 4.5 Cumulative daily water uptake (sap flow) by corn in (a) 2008 and (b) 2009. FD: Free drainage, CD-SI: controlled drainage with subirrigation, ET_c : crop evapotranspiration.

Connecting text to Chapter 5

The two previous chapters measured the yield and daily water uptake of corn under subsurface drainage conditions. This chapter evaluates the potential effects of climate change on corn yield using synthetic weather from 2040 to 2069 under B1 emissions scenario using STICS crop model. The STICS crop model was evaluated using experimental results presented in Chapter 3. A description of the model is provided along with calibration and validation procedures and statistical analyses. Simulations results of corn grain and biomass yield under these conditions and trend analysis are presented. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Research paper based on the chapter:

Singh, A. K., Madramootoo, C.A. Smith, D.L., 2013. Corn yield simulation using the STICS model under varying nitrogen management and climate change scenarios. (under review).

Chapter 5

Corn yield simulation using the STICS model under varying nitrogen management and climate change scenarios

Ajay K. Singh, Chandra A. Madramootoo, Manish K. Goyal, and Donald L. Smith

Abstract

This study evaluated the performance of the STICS crop model (JavaStics v1.0) for predicting grain yield and dry biomass of corn under three nitrogen (N) treatments – low, medium, and high N levels applied on a conventional drainage field in eastern Canada over a two year period. The impacts of climate change on simulated grain corn and biomass yield in eastern Canada under tile drained conditions was also evaluated over a 30 year future period (2040-69). The 2008 dataset was selected for calibration while 2009 dataset was used for validation of the model. Corn grain yield was underestimated by 1.5 to 2.6 Mg ha^{-1} for the two years of measurement. Total dry biomass was also underestimated by 0.9 to 2.6 Mg ha^{-1}. Tukey's studentized range (HSD) test of corn grain yield indicated that yields at high and low N, and high and medium N were different at the 95% confidence level. Grain and biomass production from 2040-2069 under B1 emission scenarios responded differently ($p < 0.05$) for the three N treatments. A Mann–Kendall, non-parametric test performed on simulated corn grain and biomass yields due to climate change under B1 emission

scenarios showed neither increasing nor decreasing trend with MK-stat > -1.96 at a 95% confidence level.

Keywords: Crop model; STICS; conventional drainage; nitrogen management; corn (Zea mays L)

5.1 Introduction

Global food security is now a key issue due to increasing population and limited land and water resources. World population will grow by three billion by 2050 (USCB, 2007), resulting in increased demands for food and water in upcoming decades. Therefore, forecasting of crop yields can be considered as a tool for future planning to assure global food security.

It is widely recognized that crop production is highly dependent upon weather. Due to climate change, some researchers have projected increases in corn yield where crop heat units are currently below optimum (Bootsma et al., 2004, El Maayar et al., 1997; Singh et al., 1998), while others have predicted decreases due to increase in temperature (De Jong et al., 2001, Lobell and Asner, 2003). Climatic factors such as July temperature and May precipitation caused more than half of corn yield variability in south-western Quebec (Almaraz et al., 2008). They reported lower yields when May precipitation was above normal (30 yr average) and July temperature was below normal.

State-of-the-art general circulation models (GCMs) are the most advanced tools to assess climate change impacts on the global environment and climate system (Goyal et al., 2012). These numerically coupled models simulate time series of climate variables, accounting for the effects of the concentration of greenhouse gases in the atmosphere (Prudhomme *et al*., 2003). Greenhouse gas emission scenarios such as A1, A2, B1, and B2, include various driving forces of climate change, such as demographic change, technological change, and socio-economic development (IPCC, 2000), and are summarized in Table 5.1. These four scenarios are called ‘families’, and within each scenario family, two main types of scenarios were developed; those with harmonized assumptions about global population, economic growth, and final energy use; and those with alternative quantification of the storyline (IPCC, 2000). Altogether, 40 different scenarios have been developed, and all are equally valid with no assigned probabilities of occurrences (IPCC, 2000).

The B1 storyline and scenario family was selected as it represents a world more integrated, and more ecologically friendly. It describes: (1) a convergent world with rising global population that peaks in mid-century and declines thereafter; (2) rapid economic growth but with rapid change in economic structures towards a service and information economy; (3) reductions in material intensity and the introduction of clean and resource-efficient technologies, and (4) an emphasis on global solutions to economic, social and environmental stability (IPCC, 2000). Prediction of future climate scenarios has some degree of uncertainty and consequently crop yield predictions have inherent uncertainty (Changnon and Hollinger, 2003).

Crop growth models such as STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard), DSSAT (Decision Support System for Agrotechnology Transfer), and RZWQM (Root Zone Water Quality Model) are used to simulate plant growth and yield. Crop growth models have the potential to generate forecasts of regional yields in advance of harvest or maturity, as well as the time of harvest under varying climatic conditions (Hodges et al., 1987). The model facilitates detail and systemic analyses by providing rapid and detailed estimations of crop growth and yield (Liu et al., 2011). Qian et al. (2011) observed that the standard deviations of crop yield and biomass simulations with synthetic weather data was less than the observed weather data with DSSAT crop model.

The STICS model was selected for this study because of its open architecture where parameters can be easily adjusted for the local cultivars. Moreover, it had been tested on over 30 crops in different climatic zones indicating its robustness. It has been used under semi-arid conditions (Hadria et al., 2007), tropical climate (Sierra et al., 2003), for study of climate change impacts (Ma et al., 2012), environmental impacts due to nitrate leaching (Jégo et al., 2008), and crop management practices (Debaeke, 2004). STICS is the most generic model dealing with cereal crops, legumes, cash crops, grasslands, catch crops and intercrops

(Brisson et al., 2006). STICS can predict nitrogen uptake, soil water status, and nitrate leaching with efficiencies of 0.5, 0.9, and 0.4, respectively, where 1.0 is the highest efficiency (Beaudoin et al., 2008). STICS was modified by Tournebize et al. (2004) to take account of subsurface drainage conditions by adapting the SIDRA (Simulation du Drainage).

Although STICS version 6.9 has been calibrated for corn in eastern Canada (Jégo et al., 2011), no study has been conducted to evaluate the STICS model on a conventional or free drainage system (FD). This has motivated the present study, in which the new Java based JavaSTICS version 1.0 (INRA, 2013) of the STICS model was evaluated for a set of nitrogen application levels on a free drainage system in eastern Canada under predicted climate change conditions. Subsurface drainage has been implemented on over 12.4 million ha in Midwest U.S., and over 2.5 million ha of agricultural land in the provinces of Ontario and Quebec, Canada (Sugg, 2007; ICID, 2011). Drained lands are reported to be among the most productive in the world (Wright and Sands, 2001). Hence, the objectives of this study were to (1) evaluate the new Java based JavaSTICS version 1.0 for eastern Canada, (2) evaluate the STICS model for different nitrogen application levels on a conventional drainage system, and (3) evaluate the impacts of climate change on corn grain and biomass yield in eastern Canada under tile drained conditions and B1 emission scenarios.

5.2 Materials and methods

5.2.1 The study area

The STICS model was evaluated over a two year period for grain corn yield, biomass, and leaf area index (LAI) at an experimental field in Coteau-du-Lac, southern Quebec. This site is approximately 60 km west of Montréal, in Soulanges County. The soil is classified as a Soulanges very fine sandy loam (Lajoie and Stobbes, 1951). It has a mean depth of 50-90 cm and overlies clay deposits from the Champlain Sea. The field has a flat topography, with an average slope of less than 0.5% (Kaluli, 1999).

5.2.2 Field layout and agronomic practices

A strip-plot design was set up to study the effects of nitrogen treatments on corn produced on a conventional drainage system (FD). The site had provision for controlled drainage with subirrigation. However, the data from the FD system were only considered as the STICS model did not have provision for subirrigation. The study field consisted of 4.2 ha of land separated into three blocks. The three nitrogen treatments (Table 5.2) were applied orthogonally along the direction of ploughing across each block in a 18 m wide strip (Fig. 3.1).Thus, each block was comprised of 6 plots of 18 by 30 m. Data from plots 1, 2, 3, 7, 8, 9, 16, 17, and 18 were used for this study. In these plots, the mean water table depth (May – September) from the ground surface was 1.04 ± 0.28 m, and 1.13 ± 0.16 m in 2008 and 2009, respectively. Grain and biomass yield sampling is explained in section 3.3.4.

In 2008, corn cultivar ‘Mycogen-2R426’ was planted on 4 May 2008 with seeding rate of 89000 plants ha^{-1}. The date of emergence was 15 May 2008. In 2009, corn variety ‘Pioneer 38N88’ was planted with seeding rate of 85000 plants ha^{-1} with an emergence date of 19 May.

5.2.3 Climatic conditions

Precipitation patterns were similar for both years at the site. The total seasonal rainfall (May to October) was 541.6 and 579.1 mm in 2008 and 2009, respectively (Table 5.3). The mean solar radiation from May to September was 11.4 MJ m^{-2} d^{-1} in 2008. The mean solar radiation during the same period was 10.6 MJ m^{-2} in 2009. The growing degree days (GDD) based on 8 ^{o}C was 1485 and 1357 ^{o}C days in 2008 and 2009, respectively. The crop heat unit (CHU) value was calculated as:

$$Daily\ CHU = (Y_{max} + Y_{min}) \div 2 \tag{5.1}$$

where

$$Y_{max} = (3.33 \times (T_{max}-10)) - (0.084 \times (T_{max}-10.0)^2) \tag{5.2}$$

$$Y_{min} = (1.8 \times (T_{min} - 4.4)) \tag{5.3}$$

where T_{max} is daily maximum air temperature (°C), and T_{min} is daily minimum temperature (°C). If values of Y_{max} and Y_{min} were negative, they were set to 0. The night time base temperature for CHU was assumed to be 4.4 ^{o}C, while the maximum or daytime relationship uses 10°C as the base temperature and 30°C as the ceiling (OMAFRA, 2009).

5.2.4 STICS

STICS is a generic crop model with a daily time-step, which was developed in 1996 at INRA (Brisson et al., 2002). Its main aim is to simulate the effects of the physical medium and crop management schedule variations on crop production and environment at the field scale. The upper boundary of the model is the atmosphere characterized by standard climatic variables and the lower boundary corresponds to the soil/subsoil interface (Brisson et al., 2003). The latest version of STICS known as JavaStics v1.0 released in October 2012 was used in this study.

5.2.4.1 Model input parameters

The required input parameters for the JavaStics v1.0 model are classified as global and local parameters. Global parameters are related to plant and genotype parameters, and general parameters. Plant and genotype variables are the physiological and genetic properties related to plant growth such as cultivar parameters, shoot biomass growth, roots, water, nitrogen, frost, and yield information. General parameters relate to simulation options such as water and nitrogen stress activation, soil carbon and nitrogen process, and soil hydrology and compaction. The model comes with standard input values with an option for the user to modify default parameters. However, there is a range limit within which the user can change input values.

Local parameters are soil, crop management, climate, and initialization parameters where the user can input the site specific values. Soil parameters, crop management practices, and climate parameters were measured at the site. The minimum climatic parameters required for the model are rain, maximum and minimum temperature, solar radiation, wind speed, and vapor pressure deficit. The 30 yr future daily climate data (2040-2069) under B1 emissions scenarios were made available by Eastern Cereal and Oilseed Research Centre (ECORC), Agriculture and Agri-Food Canada, Ottawa, Ontario. The initialization parameters are the initial conditions of the plant and the soil at the start of the simulation. The simulations were run from 22 April to 30 November for 2008 and 2009.

5.2.4.2 Calibration and validation of the STICS crop model

Calibration and validation procedures were followed as described by Brisson et al. (2002), Flénet et al. (2004), and Jégo et al. (2011). The model was calibrated for leaf area index, grain yield, and biomass, in that order. In this article, biomass refers to the aerial biomass less grain yield. After analysis of the default values of the variables in the model, the climatic variables, soil parameters and crop management practices values were replaced with the site specific inputs. The STICS model comes with inbuilt European cultivar data. The first step was therefore to identify the cultivar which best matched with the local Pioneer 38N88 and Mycogen 2R426 cultivar. Based on Jégo et al. (2011), cultivar DK250 and Pactol were evaluated. Cultivar parameters such as the duration of the vegetative (*stlevdrp, stamflax, durvieF*), and reproductive (*stdrpmat*) stages, and the yield parameters (*pgrainmax* and *nbgrmax*), were adjusted until the lowest root mean square error (RMSE) of grain and biomass yield was achieved. Once STICS was calibrated and validated, the simulations were run with synthetic weather data (2040-2069) for the B1 emission scenario simulated by the CGCM3 without changing any model input parameters.

5.2.4.3 Model evaluation

The model was evaluated qualitatively with visual inspection of the graph, and quantitatively using descriptive statistics, mean, standard deviation, and root mean square (RMSE) and mean bias error (MBE). RMSE and MBE are defined as follows:

$$RMSE = \sqrt{n^{-1} \sum_{i=1}^{n} (P_i - O_i})^2 \quad (5.4)$$

$$RMSE\% = (RMSE / O_{avg}) \times 100\% \quad (5.5)$$

$$MBE = n^{-1} \sum_{i=1}^{n} (P_i - O_i) \quad (5.6)$$

where n is the number of observations, i denotes the i th observation, P is the predicted value, and O is the observed value. The value of RMSE can vary from 0 to infinity however; lower numerical values of RMSE indicate a better performance of the model. Jamieson et al. (1991) had rated an RMSE < 10% to be excellent, 10% < RMSE < 20% to be good, 20% < RMSE < 30% to be fair, and RMSE > 30% indicated poor results. The MBE gives the estimate of the bias of the model. A negative MBE value indicates that the model is underestimating while a positive MBE value indicates that the model is overestimating the observed value. A low value of MBE, closer to zero, indicates that there is little bias. Analyses of variance (PROC GLM) were performed with the Statistical Analysis System (SAS, 2010) using a 95% confidence level. Further, a Tukey's studentized range (HSD) test was run to compare the means of grain and biomass yield in different nitrogen management scenarios using a 95% confidence level under the B1 emission scenario.

The Mann–Kendall - test, widely used to test randomness against trend, that is to determine whether the probability distribution of the selected variable (yield) has changed over time (2040-2069), was first proposed by Mann (1945) and then Kendall (1975). It is robust to the influence of extreme values and performs well with skewed variables due to its rank-based procedure (Arora et al., 2005), and has the ability to cope with missing values (Goyal et al., 2012). The test statistic that has a zero mean and a finite variance is calculated as (Burn and Elnur, 2002):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(X_j - X_k) \tag{5.7}$$

$$sgn(x) = \begin{cases} 1 & if\ x > 0 \\ 0 & if\ x = 0 \\ -1 & if\ x < 0 \end{cases} \tag{5.8}$$

$$Var(S) = [n(n-1)(2n+5) - \sum t\,(t-1)(2t+5)/18] \tag{5.9}$$

where S is the Kendall score, X_j, X_k are the sequential data values, *n* is the length of the data, and *t* is the extent of any given tie. The standard normal variate *z* is computed as (Douglas et al., 2000):

$$z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S-1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \tag{5.10}$$

The null hypothesis H_0 should be accepted if $|z| \leq \alpha/2$ at the α level of significance in a two sided test for trend. A positive value of *S* indicates an upward trend, and a negative value indicates a downward trend.

5.3 Results and discussion

5.3.1 Calibration and validation of the model

As a first step, the LAI was calibrated. The sowing date, emergence date, amounts of nitrogen, and other crop managements practices were inputs to the model. The STICS has a separate subroutine that calibrates

LAI automatically against measured LAI data and uses it for crop growth simulation. The LAI calibration is shown in Fig. 5.1. The RMSE was 0.6 and 0.3 in 2008 and 2009, respectively.

After LAI calibration, the model was calibrated for grain yield and dry biomass production. The cultivar growth parameters *stlevdrp* (degree days between emergence and the beginning of grain filing), *stlevamf* (degree days between emergence and the maximum leaf growth rate), *stamflax* (degree days between the maximum leaf growth rate and the maximum leaf area index), *durvieF* (maximum lifespan of an adult leaf), were changed in accordance with the default values for DK250 cultivar (Table 5.4). The predicted and observed physiological maturity date were also compared. The optimum temperature for the calibration process was considered a 22 ^{o}C (Karimi-Zindashty, 2005). It is recognized that the optimum temperature for corn varies over the growing season and between daytime and nighttime (Wiatrak, 2012). The predicted emergence date was 16 May which is 3 days earlier than that observed. The *sensrec* parameter (sensitivity of roots to soil dryness; 1 = insensitive) was changed from 0.0 to 0.5 as reported by Jégo et al., (2011), but it did not improve the emergence date. However the physiological maturity date was improved from 8 September to 15 September, closer to the estimated maturity date of 24 September. Both the grain and biomass yield were underestimated. Jégo et al. (2011) and Liu et al. (2011) noted that STICS has default radiation use efficiencies (RUE) of 1.9, 3.8 and 3.8 g MJ^{-1} for the juvenile phase (*efcroijuv*), vegetative phase (*efcroiveg*), and grain filling stage (*efcroirepro*), respectively, of shoot biomass growth. However the RUE can be as high as 4.9 g MJ^{-1} (Loomis and Amthor, 1999). Hence, RUE for *efcroirepro* was increased to 4.6, and RMSE improved to 13.9%. For the validation process, cultivar parameter was changed for the new cultivar Mycogen 2R426 in 2006. LAI was again calibrated for this cultivar. The soil properties, sowing date, emergence date, and nitrogen application were adjusted accordingly. The final parameters are listed in Table 5.4.

Both the corn grain and dry biomass yield were underestimated by 0.9 Mg ha^{-1} for the grain, and 2.6 Mg ha^{-1} for biomass (Table 5.5). RMSE varied from 11 to 28% for the calibrated year 2008. RMSE varied from 14 to 32% for 2009. In general, grain yield was better predicted than biomass yield in both years. The least bias in grain yield was 0.9 Mg ha^{-1} for the low N, while the largest bias, of 2.6 Mg ha^{-1}, was observed for the grain and biomass yield under high N in 2009. These differences in grain yield may be due to higher than average measured yield (12.5 and 11.3 Mg ha^{-1} in 2008 and 2009, respectively) observed at the experimental site, compared to approximately 8.1 Mg ha^{-1} (Karimi-Zindashty, 2005), and 10.5 Mg ha^{-1} or less reported at St Jean (Jégo et al., 2011), within 100 km of the field experiment. These results are comparable to other reported studies indicating RMSE of 20%, 25 – 35% and 13 – 28% for linseed, barley, and corn respectively (Jégo et al., 2011; Corre-Hellou et al., 2009; Flénet et al., 2004).

5.3.2. Simulated corn yields for B1 emissions scenario

The trend analysis (Mann-Kendall test) of synthetic weather data (2040 -2069) was compared with the historical weather data (1961-1990). No trend for any of the weather parameters, rainfall, maximum and minimum temperature, and solar radiation, was observed (Table 5.6). Simulations for the B1 emission scenario using synthetic weather data was run under the same conditions as in 2008. The effect of B1 emission scenarios on grain yield and biomass production under the three N scenarios is shown in Fig. 5.2a and 5.2b, respectively. The grain yield had a range of 8.9 – 11.8, 9.4 – 12.5, and 9.8 – 12.6 Mg ha^{-1} for N levels of low, medium and high, respectively, from 2040-2069. During the same period, the biomass production varied from 4.8 – 6.4, 5.1 – 6.8, and 5.3 – 6.8 Mg ha^{-1} for low, medium, and high N levels, respectively. Under these conditions, analysis of variances of the corn grain and biomass yields showed that the yields responded differently to the three nitrogen management scenarios ($p < 0.05$). Tukey's studentized range (HSD) test of grain yield indicated that yields at high and low N, and high and medium N were significant at a 95% confidence level (Table 5.7). Yields at low and high N, and low and medium N were significant for biomass yield. While higher nitrogen applications do give higher yields, one should take into account the environmental consequences due to nitrogen and nitrous oxide (N_2O) emissions, and nitrate (NO_3-N) leaching. These predicted losses simulated by the model varied from 19 to 42 kg N ha^{-1} for low and high N applications, respectively.

The mean simulated grain and biomass yields of 2040-2069 were similar to the mean observed yields in 2008 and 2009 (Table 5.8). Low standard deviation values indicated consistency in model prediction. The lowest and the highest crop yields were predicted for the years 2055 and 2067, respectively for all the nitrogen treatments. Examining the simulated weather data for these years, seasonal rainfall was 456.6 and 497.7 mm in 2055 and 2067, respectively; less than the present 30 yr average of 563.5 mm. Year 2055 was also particularly hot with 26 d (May – September), when temperatures were greater than 30 ^{o}C (optimum temperature for corn growth range from 20 – 23 ^{o}C) compared to 17 d in 2067, and only 3 d in 2008 and 2009 growing seasons.

For trend analysis, the Mann–Kendall (MK) non-parametric test was performed for the B1 scenario based on yield and biomass data. The alpha value of 0.05 was chosen as the local significance level for a two-sided test. Based on this significance level, values larger than 1.96 or lower than 1.96, respectively, indicate a significantly ($p<0.05$) positive or negative trend. The Mann–Kendall test was carried out for the time period, 2040–2069, and the results are shown in Table 5.9. Although it was observed that both the grain and biomass yield are decreasing, there is no statistically detectable trend (MK-stat > - 1.96).

5.4 Conclusions

Crop models are used to predict the crop growth and yield under various climatic conditions. The latest version of the STICS model, JavaStics v1.0 was calibrated and validated for corn on conventional drainage systems under different nitrogen management scenarios in eastern Canada. The RMSE varied from 14 – 21% for grain yield, and 11 – 32% for biomass indicating good to fair performance of the model for the simulated conditions. However, both grain and biomass yield predictions were consistently underestimated.

The impact of climate change on corn grain and biomass yield under the B1 emission scenario was also studied using 30 yr synthetic weather data (2040 – 2069). Variances across years in grain and biomass yield were found to be smaller with the synthetic weather data. The Mann–Kendall non-parametric test demonstrated no statistical trend, with 95% confidence level, from 2040-2069 based on the B1 emissions scenario. No statistically significant increase or decreases in grain and biomass yields are projected by the model. Analysis of variances of the corn grain and biomass yields showed that the yields responded significantly ($p < 0.05$) to three nitrogen levels. This study adds to the knowledge of crop growth model performance in several nitrogen management and climate change scenarios for corn production with subsurface tile drainage systems. Although there might be a change in agricultural management scenarios through adaptation to climate change, change in soil properties and genetic improvement over time, nevertheless these simulations provides a tool to policy makers to assess the economic and environmental impacts associated with corn production.

Table 5.1
The main characteristics of the four SRES[a] storylines scenario families
IPCC, 2000).

	More economic focus	More environmental focus
Globalization	**A1** • Rapid economic growth • Global population that peaks in mid-century and declines thereafter • Rapid introduction of new and more efficient technologies • Substantial reduction in regional differences in per capita income	**B1** • Convergent world • Global population that peaks in mid-century and declines thereafter • Economic development shifts towards service and information economy • Introduction of clean and more efficient technologies
Regionalization	**A2** • Heterogeneous world and self reliance • Continuously increasing population • Economic development is primarily regionally oriented • Economic development and technological change is slower than other storylines	**B2** • Emphasis on local solutions to social, economic, and environmental sustainability • Continuously increasing population at a lower rate than A2 • Intermediate levels of economic development • Less rapid and more diverse technological change than in B1 and A2 storylines

[a] SRES - Special Report on Emissions Scenarios

Table 5.2
Yearly nitrogen application rates (kg ha^{-1}) applied to corn cultivar.

Year	Low N	Medium N	High N
2008	131	186	277
2009	112	179	246

Table 5.3
Climatic data recorded at the site from May to October.

Year	Rain mm	Radiation[a] MJ m^{-2}	GDD 8 ^oC base ^oC days	CHU index[b]
2008	541.6	1851.0	1485.1	3198.0
2009	579.1	1597.3	1357.0	2978.8
30 yr average[c]	563.5	NA	1428.8	3026.4

[a] In 2009, from May to September only.
[b] CHU = Crop heat units. Till first -3 ^oC is observed.
[c] 30 yr average from 1980-2009.

Table 5.4
Calibration parameters of corn cultivar.

Cultivars	stlevamf[a]	stamflax[b]	stlevedrp[c]	stdrpmat[d]	durvieF[e]	pgrainmax[f]	nbgrmax[g]
DK250[h]	225	450	995	640	153	0.313	4500
Mycogen 2R426	253	550	1030	500	200	0.33	4200
Pioneer 38N88	253	500	990	450	200	0.33	4200

[a] stlevamf = degree days between emergence and the maximum leaf growth rate.
[b] stamflax = degree days between the maximum leaf growth rate and the maximum leaf area index.
[c] stlevdrp = degree days between emergence and the beginning of grain filing.
[d] stdrpmat = degree days between the beginning of grain filling and maturity.
[e] durvieF = maximum lifespan of an adult leaf, degree days.
[f] pgrainmax = maximum weight of one grain, g.
[g] nbgrmax = maximum number of grains.
[h] cultivar already defined in the STICS model.

Table 5.5
Statistical evaluation of STICS model for annual corn grain and dry biomass yield predictions.

Treatment		2008			2009		
		RMSE[a]	RMSE%	MBE[b]	RMSE	RMSE%	MBE
Low N	Grain	2.0	16.0	-1.9	1.5	13.9	-1.5
	Biomass	1.0	11.1	-0.9	1.4	21.7	-1.4
Normal N	Grain	1.9	15.1	-1.9	1.8	16.2	-1.8
	Biomass	1.9	23.0	-1.8	2.2	29.4	-2.1
High N	Grain	1.7	13.9	-1.7	2.6	21.3	-2.6
	Biomass	2.3	27.9	-2.3	2.6	32.2	-2.6

[a] RMSE = Root Mean Square Error (Mg ha^{-1}).
[b] MBE = Mean Bias Error (Mg ha^{-1}).

Table 5.6
Mann-Kendall (MK) test for synthetic weather data from 2040-2069 under B1 emission scenarios compared to historical weather data (1961-1990).

	2040-69			
	Rain mm	Tmax ^oC	Tmin ^oC	Rad kJ d^{-1}
S[a]	7161520	-2502948	-891360	-12225583
MK-Stat	0.55	0.84	0.94	0.31
p_value	0.59	-0.21	-0.07	-1.01
Trend	No trend	No trend	No trend	No trend

[a] S is the Kendall score, defined in Eq. 5.7 – 5.10..

Table 5.7
Tukey's studentized range (HSD) test for corn yield (Mg ha^{-1}). Comparisons significant at the alpha 0.05 are indicated by *.

Yield	Nitrogen comparison	Difference between means	Simultaneous 95% confidence limits		
Grain	H – M[a]	7.66	7.11	8.21	*
	H - L	8.18	7.63	8.73	*
	M - L	0.52	-0.03	1.07	
Biomass	H – M	0.09	-0.12	0.30	
	H – L	0.39	0.18	0.61	*
	M - L	0.30	0.09	0.52	*

[a] H, M, and L denote high, medium and low N level of nitrogen

Table 5.8
Comparison of observed and simulated corn grain and biomass yield (Mg ha^{-1}).

Treatment	Yield	Mean Yield	
		2008-2009	2040-2069
Low N	Grain	11.1 ± 0.3	10.5 ± 0.6
	Biomass	7.6 ± 0.5	5.8 ± 0.3
Normal N	Grain	11.5 ± 0.1	11.0 ± 0.7
	Biomass	8.0 ± 0.7	6.1 ± 0.4
High N	Grain	11.9 ± 0.2	11.2 ± 0.7
	Biomass	8.2 ± 0.4	6.2 ± 0.3

Table 5.9
Mann-Kendall (MK) test for corn grain and biomass yield from 2040-2069 under B1 emission scenarios.

	Low N		Medium N		High N	
	Grain	Biomass	Grain	Biomass	Grain	Biomass
S[a]	-27	-35	-26	-27	-28	-44
MK-Stat	-0.46	-0.61	-0.45	-0.46	-0.48	-0.77
p-value	0.64	0.54	0.66	0.64	0.63	0.44
Trend	No trend	No trend	No trend	No trend	No trend	No trend

[a] S is the Kendall score, defined in Eq. 5.7 – 5.10.

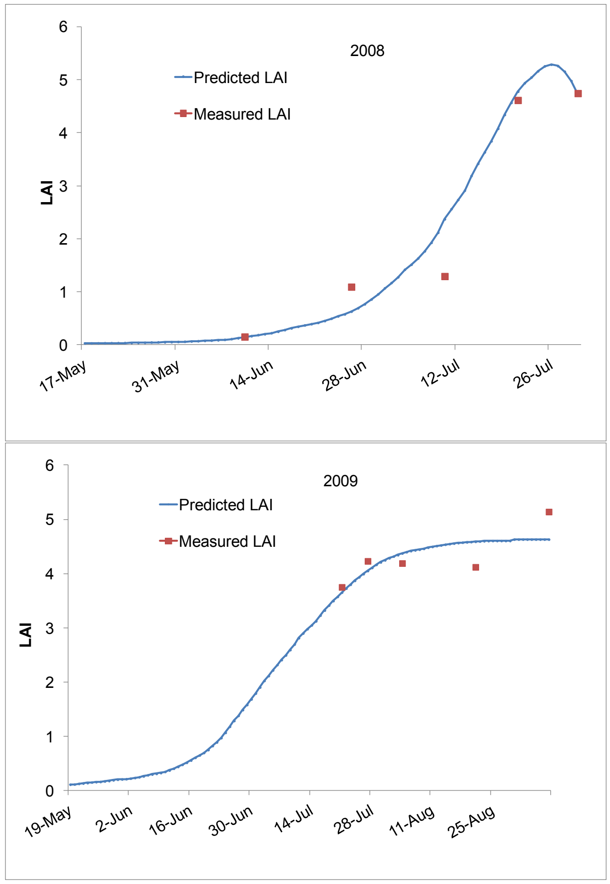
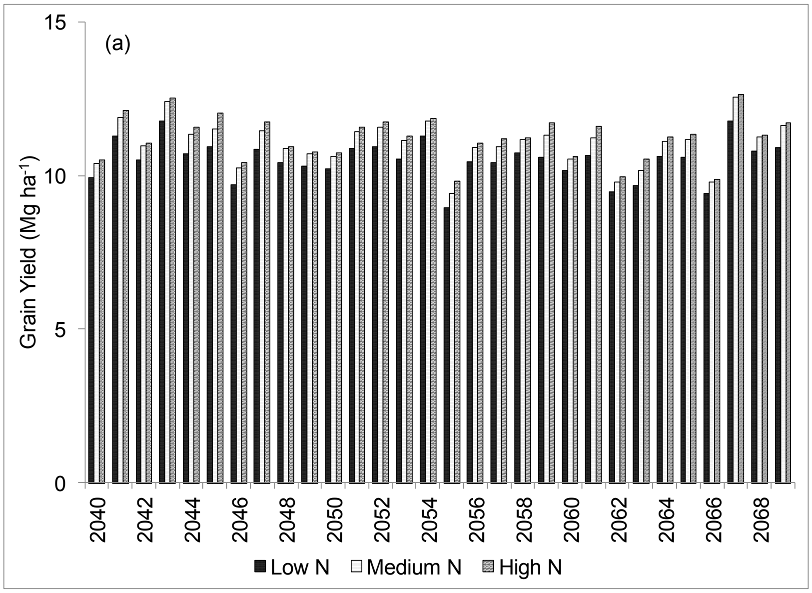


Fig. 5.1 Leaf area index for the year 2008 and 2009.



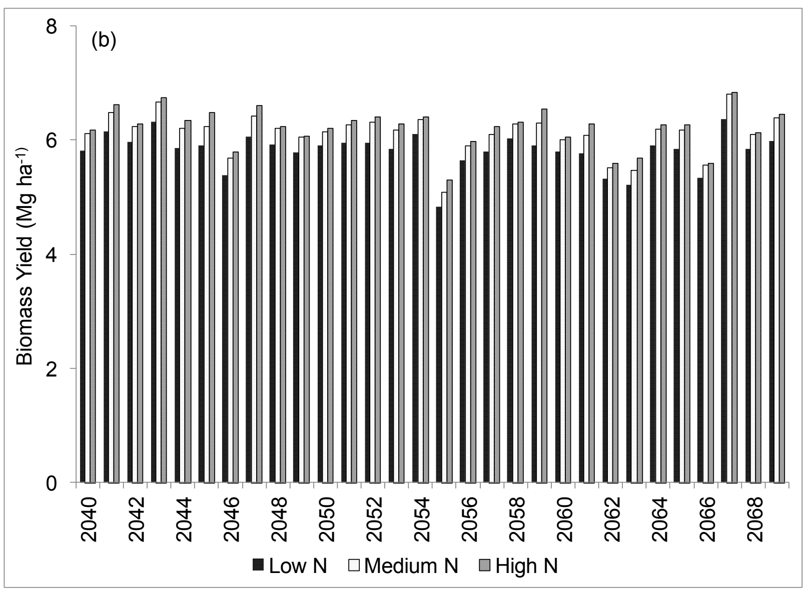


Fig. 5.2 Comparison of (a) corn grain and (b) biomass yield for different nitrogen treatments on a conventional drainage system using synthetic weather data from 2040-2069 under B1 emission scenarios.

Chapter 6

General summary and conclusions

6.1 General summary and conclusions

The goal of this study was to investigate the effects of different water table management scenarios, under varying nitrogen levels, on corn water uptake, and water and nitrogen use efficiency of corn. Based on two years of field investigations, a seasonal water balance showed that the CD-SI plots experienced surplus water conditions; while the FD plots showed deficit conditions (crop water demand exceeded the precipitation). The surplus water conditions in CD-SI plots were due to extra volumes of water supplied by subirrigation, despite the fact that system was automated. Results from the study showed that approximately 20 to154 mm of water can be saved by better managing the subirrigation system, under the rainfall conditions experienced in 2008 and 2009 at the study site.

Corn grain yields ranged from 10.44 Mg ha^{-1} in 2009 to 12.54 Mg ha^{-1} in 2008. Yields in the FD plots were higher than in CD-SI plots by 0.49 to 1.84 Mg ha^{-1}. Grain yields responded differently to the two water treatments at different nitrogen levels in 2009. However, there was no significant response in 2008. A possible explanation for this lack of response in 2008 was due to high residual soil nitrogen levels (43 kg N ha^{-1}) the year before, since the field was cropped to peas in 2007.

In 2009, the two water treatments (FD and CD-SI) showed significant effects ($p < 0.05$) on grain yields at low and high nitrogen levels. However, at the medium nitrogen level, grain yields were not significantly different for the two water management treatments ($p = 0.32$). This might be due to sufficient nitrogen and moisture conditions that have negated the effect of two water treatments. It rained every other day during the growing season. The crop water use efficiency (WUE_{ET}) of grain corn in FD plots was found to be 21% higher than in CD-SI plots at the low N level. The two water management treatments did not have a significant effect ($p > 0.05$) on WUE_{ET} of above-ground biomass in either year. The crop nitrogen use efficiency (NUE) for grain ranged from 41 to 99 kg kg^{-1}. Under low N (~120 kg ha^{-1}), grain NUE was higher by 110% and 60%, when compared to high N (~250 kg ha^{-1}) and medium N (~180 kg ha^{-1}), respectively. High N application did not contribute to higher NUE because excess N was lost due to leaching, residual N in soil or denitrification. The subirrigation WUE ($SWUE_{SI}$) values varied from 6.00 to 7.33 kg m^{-3} and are higher than those reported for other types of irrigation such as drip, alternate furrow, sprinkler, and low energy precision application center – pivot system.

Heat balance stem gages were used to measure the transpiration rate of corn under FD and CD-SI at the medium N level. This study was the first to quantify transpiration for corn using the sap flow technique under these two water management conditions. The sap flow transpiration data was compared to FAO-56 Penman-Monteith evapotranspiration (ET_c). Sap flow was measured from 58 to 119 days after planting. The mean sap flow varied from 3.80 to 4.23 mm, and standard deviation ranged from 0.70 to

0.98 mm. The mean ET_c for the equivalent number of days was 4.29 ± 0.84 mm, and 4.28 ± 1.29 mm for 2008 and 2009, respectively. A graphical representation of the sap flow data versus the FAO-56 Penman-Monteith ET_c (two water table treatments in two years) indicated an intercept varying from 0.85 to 2.08, and a line slope varying from 0.40 to 0.76 indicating a positive bias in sap flow prediction of transpiration. The coefficient of determination (R^2) ranged from 0.51 to 0.76, indicating moderate to fair prediction.

The total sap flow for the period of measurement varied from 133.14 to 148.16 mm in 2008 and 2009, respectively, for the two water treatments. The cumulative ET_c for the corresponding period of measurement was 150.31 and 149.77 mm in 2008 and 2009, respectively. The error in sap flow measurement compared to ET_c ranged from 1 to 11% for FD and CD-SI plots. Rate of water uptake of corn varied from 3.55 to 5.93 mm d^{-1} from silking to full dent stage. The maximum rate of water uptake occurred at the milk stage; 4.98 for the FD treatment and 4.76 mm d^{-1} for the CD-SI treatment. Hence, the maximum amount of water uptake occurred at the milk stage (45.63 to 59.80 mm). During milk stage, transpiration constituted 10 -12% of the total water requirement of the corn crop. The silking to full dent stage accounted for approximately 40% of the total water requirement of the crop.

With concerns about crop productivity under a future climate, the impact of climate change, under the B1 emissions scenario, on corn biomass and yield prediction for 2040-2069 was simulated using the STICS crop model. The model was evaluated for predicting corn grain and biomass yield for three nitrogen levels on a conventional drainage system. This was the first evaluation of the STICS (JavaStics v1.0) model on a conventional drainage system. The model was calibrated using 2008 data, and 2009 data was used for validation. RMSE varied from 11 to 32%. These results are comparable to other reported studies indicating an RMSE of 13 to 25% for the STICS model. Model performance was therefore considered fair. The model underestimated the grain and biomass yield for all N levels. The least MBE was 0.9 Mg ha^{-1} for the low N, while the largest MBE of 2.6 Mg ha^{-1} was observed for the high N. The grain and biomass yield ranged from 8.9 to 12.6, and 4.8 to 68 Mg ha^{-1}, respectively, for three N levels over two years. The mean simulated grain and biomass yields for 2040-2069 were found to be similar to the observed yields in 2008 and 2009. Differences in grain yields at high and low N, and high and medium N were significant at a 95% confidence level. This might be due to interaction effect between the water treatment and nitrogen levels (Table 2.5) which requires further investigation. Biomass yields at low and high N, and low and medium N were significantly different (α = 0.05). Mann-Kendall test showed no statistically detectable trend (MK-stat > - 1.96) for both the grain and biomass yield from 2040-2069.

6.2 Contributions to knowledge

Based on the objectives of this research, this thesis provides following contributions to knowledge:

- **Grain corn nitrogen use efficiency under low N (~120 kg ha^{-1}) was higher by 110% and 60% when compared to high N (~260 kg ha^{-1}) and medium N (~180 kg ha^{-1}) under subsurface drainage conditions.**

- **This was the first study to use heat balance sap flow technique to measure transpiration rate for corn on FD and CD-SI in humid conditions.** The transpiration rate of corn was measured for 35 days (85 - 119 DAP) and validated with FAO-56 Penman-Monteith evapotranspiration method. The accuracy of daily sap flow measurement compared to ET_c ranged from 89 to 99% for FD and CD-SI plots.

- **Corn water uptake rate was maximum at the milk stage for both conventional drainage (4.98 mm d^{-1}) and controlled drainage with subirrigation (4.76 mm d^{-1}) treatments.** Although, silking is considered to be the critical stage for maximum yield of corn, adequate supply of water needs to be maintained at the milk stage. Water demand at milk stage was ~60 mm, which was equivalent to

12% of total water requirement of corn. Silking to full dent stage of corn requires ~40% of total water demand.

- **No statistically significant increase or decreases in grain and biomass yields are projected by the STICS model from 2040-2069 under B1 emissions scenario**.

6.3 Recommendations for future research

This study investigated the effect of two water table management scenarios over a range of nitrogen levels on water and nitrogen use efficiency, corn daily water uptake using heat balance sap flow method, and effect of climate change on corn yield using the STICS crop model. There are several areas where further research is needed:

1. To study the cost-benefit analysis of corn yield at different nitrogen levels and different water table management scenarios. Low N has given better WUE and NUE. However, higher yields are reported for high N applications. An interactive web tool can help corn producers to compare the maximum yield to N application versus the most profitable N rate based on corn and N fertilizer prices.
2. The study has shown over-irrigation under CD-SI system in both years. The subirrigation water supply was based on water table depth. Further research is recommended to better regulate the inflows to the subirrigation system.

3. To validate the crop coefficient of corn in humid conditions for eastern Canada using stem gages. There are different methods to calculate reference evapotranspiration. Researchers use the crop coefficient to calculate the actual evapotranspiration for a given area. Crop coefficients for different crops at different growth stages for different locations can be calculated using the sap flow method.
4. Corn water uptake was studied for reproductive stages from silking stage to full dent stage using heat balance sap flow method (35 days). Further investigation is required to measure water uptake rate of corn from vegetative stage to full maturity at several nitrogen levels.
5. To study the impact of climate change under A1, A2, A1B and other likely greenhouse gas emissions scenarios using the STICS crop model.
6. To compare the performance of Decision Support System for Agrotechnology Transfer (DSSAT) crop model with STICS crop model in simulating nitrogen and water balance at a field scale.

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