UNIVERSITI PUTRA MALAYSIA

BEHAVIOUR OF SOLUTE TRANSPORT PHENOMENON FROM RAINFED SWEET CORN FIELD IN TROPICAL CLIMATE

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By

MAZHAR IQBAL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to;

My father and my mother for their endless love and wish for their son to achieve this higher dream. Especially, to my father (late) who encouraged me, rather insisted to pursue my study overseas when he was suffering from cancer. Being a well-wisher, his sacrifice is unmatched. My sisters, who have been supportive during my study. Finally, to my wife for her sacrifices and my son who needed me during the early days of his life.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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July 2020

Chairman : Md Rowshon Kamal, PhD
Faculty : Engineering

Solute transport from agricultural fields is the main cause of non-point contamination, resulting in degradation of surface and groundwater due to runoff and deep percolation. It varies significantly among agricultural fields of different climates. The amount and duration of rainfall occurrence in the tropical climate is of great importance in controlling solute movement from agricultural fields. The heavy rainfall in tropical climate results in the solute loss to increase manifold as compared to arid and semi-arid climate. Therefore, assessment of water and solute balance in rainfed conditions is essential for the efficient use of water and fertiliser in increasing productivity. The study intended to assess the water and solute dynamics from a sweet corn field under tropical rainfed conditions using the HYDRUS-1D numerical model. The intensive field investigations were carried out to explore the water and solute losses in a sweet corn field for two growing seasons (Feb.-May and Sep.-Nov. 2018) under the rainfed conditions at the Malaysian Agricultural Research and Development Institute (MARDI), Malaysia. The water and solute balance components were observed using modern devices integrated with data loggers in real field conditions and the empirical relationships between solute concentrations and EC were developed. Then HYDRUS-1D numerical analysis was performed to simulate soil water balance in the sweet corn field. The HYDRUS-1D numerical model was also used to simulate solute transport dynamics in the field. The observed soil water content and solute concentrations were used for calibration and validation of the model. Finally, the AquaCrop simulations of crop growth were performed to predict crop yield using the data obtained from the intensive field experiments.

The empirical relationships between the observed NPK concentrations and EC were developed during the first season using polynomial regression analysis. Based on the developed empirical equations, the NPK concentrations were determined and compared with observed concentrations during the second season. The average R^2

values for NPK were 0.91, 0.97, and 0.98 (first season) and 0.97, 0.95 and 0.98 (second season). The empirical relationship is an important and easier way to know the NPK status in the soil at any given time during the crop growing seasons and could be helpful in the efficient use of fertiliser. The total water inputs during the first and second seasons were 75.8 cm and 79.7 cm, respectively. HYDRUS-1D simulation results of evapotranspiration (ET) accounted for 40.7% and 33.1% of total water input during the first and second seasons, respectively. Surface runoff accounted for 41.0% (first season) and 28.6% (second season). Water leaching accounted for 10.6% and 26.8% of total water input during both seasons, respectively.

The total NPK input to sweet corn was 120:60:60 kg/ha for both seasons. The nitrogen (N) surface runoff loss accounted for 35.3% and 22.2% of total nitrogen input during the first and second seasons, respectively. The N leaching loss at 60 cm depth accounted for 4.0% (first season) and 18.5% (second season). The crop N uptake was 37.5% (first season) and 24.9% (second season). The phosphorus (TP) losses were negligible. The simulated amounts of K lost through runoff and leaching were 43.1% and 17.0% (first season), 34.1% and 38.6% (second season). The K uptake accounted for 32.1% and 21.4% of total K input during the first and second seasons, respectively. NPK losses through surface runoff and leaching were dominating pathways. Overall, the HYDRUS-1D simulation results of soil water fluxes and NPK concentrations were found in good agreement with observed data. The simulated total biomass of 11.2 ton/ha and 8.8 ton/ha were obtained using the AquaCrop model during the first and second seasons, respectively. The total yields were 5.4 ton/ha (first season) and 4.2 ton/ha (second season). The simulated results show higher water productivity (WP_{ET}) 1.69 kg/m^3 during the first season as compared to 1.58 kg/m^3 during the second season. The AquaCrrop simulation results matched the observed results well. The overall simulation results validate the HYDRUS-1D as an effective tool for improved water and fertiliser use and AquaCrop to simulate the crop growth in the tropical climate.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERILAKU FENOMENON PERGERAKAN LARUTAN DARI LADANG JAGUNG MANIS YANG BERGANTUNG KEPADA PENGAIRAN AIR HUJAN DI KAWASAN IKLIM TROPIKA

Oleh

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Kehilangan zat larutan dari ladang pertanian adalah punca utama pencemaran tidak-bertitik yang mengakibatkan kemerosotan sumber air tanah dan permukaan yang berlaku disebabkan oleh penyusupan dan larian masing-masing. Ianya sangat berbeza antara ladang-ladang pertanian dan iklim-iklim yang berbeza. Jumlah dan jangka masa berlakunya hujan sangat penting dalam mengawal pergerakan larutan dari ladang pertanian di iklim tropika. Hujan lebat di iklim tropika mengakibatkan kehilangan larutan meningkat berkali ganda berbanding dengan iklim gersang dan separa-gersang. Oleh itu, penilaian air dan keseimbangan larutan dalam keadaan hujan adalah penting dalam penggunaan air dan baja yang efektif bagi meningkatkan produktiviti. Kajian ini bertujuan untuk menilai air dan dinamik larutan dari ladang jagung manis di bawah keadaan hujan tropika dengan menggunakan model numerikal HYDRUS-1D. Kajian ladang intensif dijalankan untuk meneroka air dan kehilangan larutan dalam ladang jagung manis bagi dua musim (Feb.-Mei dan Sep.-Nov. 2018) di bawah keadaan hujan di Institut Penyelidikan dan Kemajuan Pertanian Malaysia (MARDI), Malaysia. Komponen-komponen air dan imbangan larutan diperhatikan dengan menggunakan alat moden yang disepadukan dengan logger data dalam keadaan ladang sebenar dan hubungan empirikal antara kepekatan larutan dan EC yang dihasilkan. Kemudian analisis numerikal HYDRUS-1D dilakukan untuk mensimulasikan keseimbangan air tanah di ladang jagung manis. Model numerikal HYDRUS-1D kemudian digunakan untuk mensimulasikan pergerakan dinamik larutan di ladang. Kemudian, kandungan air tanah dan kepekatan larutan diperhatikan untuk digunakan sebagai penentukuran dan pengesahan model. Akhirnya, simulasi AquaCrop bagi pertumbuhan tanaman dilaksanakan bertujuan meramalkan hasil tanaman menggunakan data yang diperolehi daripada eksperimen ladang intensif.

Hubungan empirikal antara kepekatan NPK yang diperhatikan dan EC dibangunkan semasa musim pertama menggunakan analisis regresi polinomial. Berdasarkan persamaan empirikal yang dibangunkan, kepekatan NPK ditentukan dan dibandingkan dengan kepekatan semasa musim kedua. Nilai purata R^2 untuk NPK adalah 0.91, 0.97, dan 0.98 (musim pertama) dan 0.97, 0.95 dan 0.98 (musim kedua). Hubungan empirikal adalah penting dan cara paling mudah untuk mengetahui status NPK di dalam tanah pada bila-bila masa semasa musim tanaman dan dapat membantu dalam penggunaan baja yang cekap. Jumlah input air pada musim pertama dan kedua adalah 75.8 cm dan 79.7 cm masing-masing. Hasil simulasi HYDRUS-1D menunjukkan evapotranspirasi (ET) menyumbang sebanyak 40.7% dan 33.1% daripada jumlah input air pada musim pertama dan kedua masing-masing. Larian permukaan menyumbang sebanyak 41.0% (musim pertama) dan 28.6% (musim kedua). Penyusupan air menyumbang sebanyak 10.6% dan 26.8% daripada jumlah input air pada kedua-dua musim masing-masing.

Jumlah input NPK untuk jagung manis adalah 120:60:60 kg/ha untuk kedua-dua musim. Nitrogen (N) larian permukaan menyumbang sebanyak 35.3% dan 22.2% daripada jumlah input nitrogen semasa musim pertama dan kedua masing-masing. Kehilangan penyusupan N pada kedalaman 60 cm menyumbang sebanyak 4.0% (musim pertama) dan 18.5% (musim kedua). Pengambilan tanaman N adalah 37.5% (musim pertama) dan 24.9% (musim kedua). Kehilangan fosforus (TP) diabaikan. Jumlah simulasi K yang hilang melalui larian dan penyusupan adalah 43.1% dan 17.0% (musim pertama), 34.1% dan 38.6% (musim kedua). Pengambilan K menyumbang sebanyak 32.1% dan 21.4% daripada jumlah input K pada musim pertama dan kedua masing-masing. Kehilangan NPK melalui larian permukaan dan penyusupan adalah laluan dominasi. Secara keseluruhan, keputusan simulasi HYDRUS-1D menunjukkan fluks air tanah dan kepekatan NPK sepadan dengan data yang diperhatikan. Jumlah simulasi biomass sebanyak 11.2 tan/ha dan 8.8 tan/ha diperolehi menggunakan model AquaCrop semasa musim pertama dan kedua masing-masing. Jumlah hasil tanaman adalah 5.4 tan/ha (musim pertama) dan 4.2 tan/ha (musim kedua). Hasil simulasi menunjukkan produktiviti air yang lebih tinggi (WPET) 1.69 kg/m^3 semasa musim pertama berbanding 1.58 kg/m^3 semasa musim kedua. Keputusan simulasi AquaCrop adalah sepadan dengan keputusan hasil pemerhatian. Hasil simulasi keseluruhan mengesahkan bahawa HYDRUS-1D adalah satu alat yang sangat efektif dalam menambahbaikan penggunaan air dan baja dan AquaCrop untuk mensimulasikan pertumbuhan tanaman di iklim tropika.

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Mazhar Iqbal

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

DOA	Department of Agriculture
MARDI	Malaysian Agricultural Research and Development Institute
FAO	Food and Agriculture Organisation
SIRIM	Standard and Industrial Research Institute of Malaysia
UPM	Universiti Putra Malaysia
CNS	Carbon Nitrogen Sulphur
EC	Electric Conductivity
RF	Rainfall
SWS	Soil Water Sampler
ET	Evapotranspiration
Kc	Crop Coefficient
RO	Runoff
mg/L	Milligram per Litre
WI	Water Input
CC	Canopy Cover
B	Biomass
Y	Yield
HI	Harvest Index
WP	Water Productivity
TDR	Time Domain Reflectometer
RMSE	Root Mean Square Error

CHAPTER 1

INTRODUCTION

1.1 Background of the study

According to DOA (2017), about 10477 ha of the cultivated area produced 72,560 tons of sweet corn in Malaysia. Sweet corn is used for both human and animal consumption, along with its use in industry as raw material (Saeed et al., 2001). The country is self-sufficient in sweet corn production (Wahab, 2018). In Malaysia, sweet corn grows on acidic, weathered soils with low pH and soil fertility, which results in low yield (Shamshuddin et al., 2010). Imbalance of fertiliser is also one of the reasons for low corn production in tropical regions (Oad et al., 2004).

Solute losses from agricultural fields cause the fertiliser imbalance, which affects the sweet corn production. The solutes are dynamic in nature, especially nitrogen. Nitrogen (N) pollution has become a global environmental problem with serious implications on surface and ground waters (Chandna et al., 2011). The groundwater contamination due to agricultural activity depends on the amount of N applied and its effective use by crops (Becker et al., 2007). As Nitrogen (N) highly affects the crop yield (Wienhold et al., 1995), the farmers apply N-fertiliser to high-yield crops in large quantity. Corn also demands a large amount of N to achieve optimal yield. Due to a lack of management guidelines, most farmers apply fertiliser based on their experience and do not consider their environmental consequences (Wei et al., 2009). N leaching out of the root zone due to excessive application of N-fertilisers is a potential cause of water resource pollution, which has been observed in many parts of the world (Karandish et al., 2017; Zhu et al., 2005). In soil, N is present in different forms such as organic N, ammonia (NH_4^+-N) and nitrate (NO_3^- -N). Due to its mobility, NO_3^- -N contributes to groundwater pollution more than other forms (Wang et al., 2010).

In addition, the low recovery of fertiliser by crop increases the leaching of residual N to groundwater during off-season rainfall in the humid regions (Tamini & Mermoud, 2002). Rainfall triggers flow processes such as surface runoff, preferential flow, and nitrate leaching (McGrath et al., 2010; Wang et al., 2010). Water percolation below the root zone is a major factor controlling the N leaching (Tamini & Mermoud, 2002). Thus, the optimum use of water along with fertiliser is also important. The change in water balance components such as evapotranspiration, runoff, leaching, and rainfall might also affect the fertiliser imbalance.

Therefore, the accurate estimation of water balance in agricultural fields is key to water resources management. Evapotranspiration and leaching are the leading sinks of water that affect soil water status in a soil-plant-atmosphere environment (Shelia et al., 2018). Furthermore, devising water management strategies depends on information relating to evapotranspiration. Measuring other water balance components such as runoff, and capillary movement in field conditions is also a big challenge (Igbadun, 2012). Whereas, rainfall is the most important component of water balance. The response of the water balance components varies with climate geographically. The significant differences between regions necessitate a need to evaluate the response of water balance components in various geo-climatic regions (Wang et al., 2011). Climate change also has a significant effect in altering rainfall patterns in Malaysia (NAHRIM, 2014). The change in rainfall patterns is more crucial than the change in temperature in Malaysia.

The simulation models have been very effective in describing the water and solute transport processes and the extent to which management practices affect crop yield and the environment. However, the validation of simulation models for local conditions is crucial (Watts & Martin, 1981). The significance of their use is multiplied when the prediction of distribution is done based on local soil and climate conditions (Santos et al., 1997). Among different available models, a software package HYDRUS-1D (Šimůnek et al., 2008) has been widely used for simulating water flow and solute transport in soils, to analyse flow and transport processes in agricultural fields. Several researchers have applied the HYDRUS-1D model to evaluate water and solute balance. As compared to other models, HYDRUS-1D has the flexibility of accommodating different boundary conditions. The model can take into account the root uptake of water and nutrients simultaneously. The model is capable of simulating soil water and solute dynamics under different management practices (Gabiri et al., 2018; He et al., 2017a; Hou et al., 2017; Karandish & Šimůnek, 2017; Li et al., 2014; Li et al., 2015; Martello et al., 2015; Negm et al., 2017; Ramos et al., 2011; Ramos et al., 2019; Ren et al., 2016; Ursulino et al., 2019). All these researchers validated HYDRUS-1D as a reliable tool for such investigations.

Many researchers in the past have studied the effect of lower fertiliser rates on crop productivity. The reduction in fertiliser use, however, can also reduce the yield. Therefore the farmers are not keen to adopt this technique. Reducing the application of water could be an option, particularly in tropical regions to reduce fertiliser leaching. Also, validation of the model in quantifying water losses through field experiments is worthwhile. This study, therefore, considered rainfed conditions to evaluate the rainfall effect on nutrients distribution in the tropical region, based on intensive fieldwork avoiding scheduled irrigation.

1.2 Problem statement

Solute losses from agricultural fields result in the degradation of ground and surface water resource due to deep percolation and runoff, respectively. The heavy rainfall results in the solute loss to increase manifold in the tropical region. Indeed, heavy rainfall in Malaysia can potentially meet crop water requirements. However, the fluctuation in rainfall duration and frequency can affect the water and nutrients balance. It reduces nutrients availability and limits crop growth. Quantifying the water and nutrients balance components under rainfed conditions can be useful to improve water management and to assess the scale of fertiliser loss for sweet corn production. Based on a literature review, no research has yet been reported to assess rainfall impact on nutrients dynamics in the region. Therefore, it is essential to evaluate the rainfall potential to meet the water requirement of sweet corn and its impact on nutrients dynamics in the tropics.

1.3 Objectives of the research

The study aims to simulate water and solute dynamics for improved fertiliser use that will be helpful in increasing the productivity of rainfed sweet corn production in the tropical climate through intensive field investigations. The specific objectives include:

1. To monitor water and nutrients (NPK) balance components from rainfed sweet corn and the development of empirical equations.
2. To evaluate the temporal soil water dynamics using the HYDRUS-1D simulation.
3. To evaluate the temporal nutrients (NPK) dynamics using the HYDRUS-1D simulation.
4. To assess the water productivity of rainfed sweet corn due to nutrients transport using the AquaCrop model.

1.4 Scope of the study

This study used the modelling approach for better fertiliser use in sweet corn production in the field located at the Malaysian Agricultural Research and Development Institute (MARDI), Serdang, Malaysia. The intensive field investigations were carried out to monitor the water and solute balance and their losses for two growing seasons (Feb.-May and Sep.-Nov. 2018). The HYDRUS-1D and AquaCrop models were validated for the local climatic conditions. Various empirical equations were developed using polynomial regression analyses for NPK estimates to predict NPK concentrations in the soil profile at any time during the crop growing seasons. The study outcomes could be helpful in optimising the water and fertiliser use to improve sweet corn productivity. Further, the reduction in fertilisers cost and contamination of the surface and groundwater are within the research scope.

1.5 Outlines of the thesis

The thesis introduces the research work and its objectives in chapter 1. In chapter 2, previous studies related to current research have been discussed while chapter 3 explains the materials and methods involved in this study. Chapter 4 of the thesis illustrates the results and discussion on those results. Finally, chapter 5 concludes the research work and gives recommendations for future study in this field. Further, chapter-wise outlines of the thesis are given below.

Chapter 1 refers to the basic information of sweet corn, its production, factors affecting production, management of resources, water and fertiliser use, modelling approach to improve fertiliser efficiency. At the end of the chapter, the problem statement, research objectives along with the scope of the study have been described.

Chapter 2 consists of the literature review. It summarises the earlier studies on solute transport mechanism and important parameters involved in the transport process. The chapter also describes the use of models under different irrigation and fertiliser management practices in various climate regions to predict N P K losses. In the last part, the crop growth model AquaCrop and summary of the literature review have been presented.

Chapter 3 describes the study design and its implementation. The chapter gives an introduction to the study area and discusses the installation of equipment and sensors including soil water samplers, rain gage, 5TE sensors, RBC flume, subsurface water collection system. The chapter describes the monitoring process and computations involved to determine different components of water and nutrients balance along with the development of empirical equations. Sampling and testing of soil, water and plant have also been discussed. In the last part, the use of HYDRUS-1D and AquaCrop simulation models have been described.

Chapter 4 presents the field observations and simulation results of the study. The first part includes the graphical presentation of observed water balance components and NPK concentrations and development of NPK empirical equations. Later, the HYDRUS-1D simulation results were presented and analysed. In the last part of the chapter, the AquaCrop simulation results of crop growth parameters were discussed.

Chapter 5 presents the general conclusion and gives recommendations for future research in this field.

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