UNIVERSITI PUTRA MALAYSIA

NUTRIENT LOSS IN RUNOFF AND GROWTH RESPONSE OF IMMATURE OIL PALM FOLLOWING APPLICATION OF CONTROLLED-RELEASE FERTILIZERS

ALAGIE BAH

FP 2015 60

NUTRIENT LOSS IN RUNOFF AND GROWTH RESPONSE OF IMMATURE OIL PALM FOLLOWING APPLICATION OF CONTROLLED-RELEASE FERTILIZERS

By

ALAGIE BAH

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

January 2015

DEDICATION

Dedicated to

Mbondi Bah (Late dad)

Juma Sowe (Mum)

Binta Bah (Wife)

Buba Sowe (Uncle)

Dr. Syed Omar Syed Rastan (Mentor)

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

NUTRIENT LOSS IN RUNOFF AND GROWTH RESPONSE OF IMMATURE OIL PALM FOLLOWING APPLICATION OF CONTROLLED-RELEASE FERTILIZERS

By

ALAGIE BAH

January 2015

Chairman: Ahmad Husni Mohd Hanif, PhD

Faculty: Agriculture

Implementation of sound fertilizer management program in the tropics is essential in optimizing production and economic returns. Controlled-release fertilizers (CRFs) are intended to supply plant nutrients in synchrony with crop demand, which should ultimately minimize nutrient loss from crop fields. Studies on the fate and plant response of CRFs in tropical oil palm agro-ecological fields are still lacking. In this study, a one-year field trial was established to investigate whether application of CRFs rather than conventional water-soluble mixture fertilizer can reduce nutrient loss and enhance growth of oil palm at the immature stage. Soil and nutrient loss were monitored in 2012/2013 under erosion plots of 16 m^2 each planted with immature old oil palm tree on a 10% slope gradient. Fertilizer treatments applied included granular and briquette forms of CRFs (AJIB® CRF) in 100% and 60% dosages, a conventional mixture fertilizer in 100% dosage and an unfertilized control. Water Erosion Prediction Project (WEPP) model was also used to predict runoff and soil erosion from the study field. On an annual basis, mean sediments concentration in runoff amounted to about 6.41 t ha^{-1}. On average, total captured runoff as percentage of annual rainfall amounted to 14 %, with yearly total rainfall events of 219 days. Nutrient loss was higher from mixture fertilizer treatments than those treated with CRF. Runoff loss of N was greater ($p=\leq 0.001$) in plots that received conventional mixture fertilizer, amounting to 7% of ammonium sulfate-N applied, and that with CRF application accounted for between 1-2% N loss. Runoff P losses were usually lower for all fertilized treatments than unfertilized control. Large runoff losses of K (13%) and Mg (15%) were observed in plots that received mixture fertilizer. However, runoff losses of K and Mg from applied CRFs were in the range of 4-7%. Meanwhile, runoff process exported less sediment-associated nutrients, ranging from 0.39-0.93 kg N, 0.15-0.31 kg P, 1.03-2.14 kg K and 0.17-0.29 kg Mg ha^{-1} yr^{-1} in fertilized plots. Total yearly precipitation, number of rainfall events and soil loss were predicted fairly well by the WEPP model with a mean difference of 2% and 4% and 15%, respectively. However, the actual and simulated yearly runoff volume differed by 36%. Also, the WEPP model showed good tendency to predict monthly precipitation ($r^2 = 0.57$), rainfall days ($r^2 = 0.79$) and soil erosion ($r^2 = 0.62$). Prediction of monthly runoff was less accurate ($r^2 = 0.32$). Plant growth parameters such as frond number and bole diameter were significantly greater with granular CRF (100%) than the control and mixture treatments. In conclusion, CRFs proved effective in maintaining robust oil palm growth and in reducing runoff-

associated nutrient loss compared to mixture fertilizer. This could be attributed to the fact that nutrient elements in CRFs are readily and slowly available for plant uptake over a given period.

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

KEHILANGAN NUTRIEN MELALUI AIR LARIAN DAN RESPON TUMBESARAN KELAPA SAWIT BELUM MATANG TERHADAP APPLIKASI BAJA LEPAS TERKAWAL

Oleh

ALAGIE BAH

Januari 2015

Pengerusi: Ahmad Husni Mohd Hanif, PhD

Fakulti: Pertanian

Pelaksanaan program pengurusan baja yang baik di kawasan tropika adalah penting bagi memastikan pengeluaran dan pulangan ekonomi yang optimum. Baja lepas terkawal (CRFs) adalah bertujuan untuk membekalkan nutrien tumbuhan sesuai dengan keperluan tanaman, di samping meminimumkan kehilangan nutrien di kawasan ladang. Kajian ke atas keadaan dan respon tanaman terhadap CRF dalam bidang agro-ekologi kelapa sawit tropika masih belum mencukupi. Dalam kajian ini, ujian lapangan selama setahun telah diwujudkan untuk mengkaji sama ada penggunaan CRFs dan bukannya baja campuran larut air konvensional boleh mengurangkan kehilangan nutrien dan meningkatkan pertumbuhan kelapa sawit muda. Kehilangan tanah dan nutrien dipantau dalam tahun 2012/2013 pada plot hakisan 16 m^2 di mana setiap plot ditanam dengan pokok muda pada kecerunan 10%. Rawatan baja yang digunakan termasuk bentuk butiran dan briket CRFs (AJIB® CRF) pada 100% dan 60% dos, baja campuran konvensional pada dos 100% dan kawalan yang tidak dibaja. Model Projek Ramalan Hakisan Air (WEPP) juga digunakan untuk meramalkan aliran dan hakisan tanah dari plot kajian. Min kepekatan sedimen dalam air larian secara tahunan berjumlah kira-kira 6.41 t ha-1. Secara purata, jumlah air larian yang dikumpul sebagai peratus hujan tahunan adalah sebanyak 14% setiap tahun dengan jumlah peristiwa hujan sebanyak 219 hari. Kehilangan nutrien adalah lebih tinggi pada rawatan baja campuran jika dibandingkan denagan mereka yang dirawat dengan CRF. Kehilangan N melalui air larian adalah lebih besar ($p = \leq 0.001$) pada plot yang menerima baja campuran konvensional, sebanyak 7% dalam bentuk ammonium sulfat-N yang ditabur, dan daripada CRF kehilangan N sebanyak 1-2%. Kehilangan P melalui air larian biasanya lebih rendah untuk semua rawatan yang diberi baja berbanding kawalan yang tidak dibaja. Kehilangan K (13%) dan Mg (15%) yang tinggi telah diperhatikan pada plot yang menerima baja campuran melalui air larian. Walau bagaimanapun, kehilangan air larian yang mengandungi K dan Mg dari CRFs yang digunakan adalah dalam lingkungan 4-7%. Sementara itu, air larian yang dieksport mengandungi mendakan-nutrien yang kurang, antara 0.39-0.93 kg N, P 0.15-0.31 kg, 1.03-2.14 kg K dan Mg 0.17-0.29 kg ha^{-1} $tahun^{-1}$ pada plot yang dibaja. Jumlah hujan tahunan, beberapa peristiwa hujan dan hakisan tanah telah diramalkan dengan baik menggunakan model WEPP dengan perbezaan min sebanyak 2%, 4% dan 15% masing-masing. Walau bagaimanapun, jumlah air larian tahunan sebenar dan simulasi berbeza sebanyak 36%. Selain itu, model WEPP juga menunjukkan kecenderungan yang baik untuk meramal

hujan bulanan (r2 = 0.57), bilangan hari hujan (r2 = 0.79) dan hakisan tanah (r2 = 0.62). Ramalan air larian bulanan adalah kurang tepat (r2 = 0.32). Parameter pertumbuhan tanaman seperti bilangan pelepah dan diameter pangkal batang nyata lebih besar dengan butiran CRF (100%) berbanding kawalan dan campuran rawatan. Kesimpulannya, CRFs terbukti berkesan dalam mengekalkan pertumbuhan kelapa sawit yang mantap dan mengurangkan kehilangan nutrien daripada air larian berbanding baja campuran. Perkara ini disebabkan oleh unsur-unsur nutrien dalam CRFs adalah tersedia dan secara perlahan boleh didapati untuk pengambilan tumbuhan dalam suatu jangka masa tertentu.

ACKNOWLEDGEMENTS

In the name of ALLAH, the Most Beneficent and the Most Merciful

I thank Almighty ALLAH (SWT) for granting me the wisdom, health and strength to undertake this research task

May Peace and Blessings be upon our Prophet Muhammad (SAW)

I would like to gratefully express my appreciation to Commonwealth Scholarship and Fellowship Plan (CSFP) through the Ministry of Education, Malaysia for the scholarship provided to pursue my PhD program. My deepest and sincere gratitude to Diversatech (M) Fertilizer Sdn. Bhd. for the sponsorship and logistical support provided throughout my PhD journey.

I would like to express my deepest and sincere gratitude to my committee chairman, Associate Professor Dr. Ahmad Husni Mohd Hanif for his outstanding intellectual expertise, guidance and support. His perpetual energy, wide knowledge and enthusiasm in research had greatly motivated me.

I am immensely grateful to Dr. Syed Omar Syed Rastan, my external committee member and Honorary President of Diversatech (M) Fertilizer Sdn. Bhd for providing me with the much needed financial assistance and for his unwavering intellectual support. Dr. Syed Omar's inspiring guidance and tremendous mentorship has made my work a thoughtful and rewarding journey.

I am deeply grateful to Dr. Christopher Teh Boon Sung, my internal committee member for his scholarly and constructive contribution, especially on the soil physics aspect of this work. My warm thanks are also due to Professor Dr. Mohd Rafii Yusop, internal committee member his intellectual support and guidance.

I extend my appreciation to Haji Syed Osman Syed Rastan (President), Syed Muhamad Amir Syed Omar (Executive Director), Haji Muhammad Fairus Bin Hussain (General Manager), Dr. Muhammad Imran Khan (Technical Manager), Mr. Najmi Yani Bin Ahmad (Financial Executive), Haji Faisal, Farhan, Khusairi, Firdaus, Fakhruddin and Fiqree of Diversatech (M) Fertilizer Sdn. Bhd for their support and the co-operation rendered during the tenure of my work.

During this work I have collaborated with many colleagues and academicians for whom I have great regard. I am extremely thankful to the Faculty of Agriculture, Universiti Putra Malaysia, especially the academic and technical staff at the Department of Land Management for providing me with the necessary facilities for the research. In particular, I wish to express special thanks to the late Junaidi Jaafar (May Allah grant him a place in Jannah), Mr Rosli, Madam Nor Asma, Norfarhana binti Abdul Khalil, Puan Sarimah Bt Hashim, Jamil Bin Omar, Mohd Fuzi Bin Mohd Sharif and Noorashikin Salha Bt Zamzuri for their assistance in my research. I wish to sincerely thank all those who assisted me directly or indirectly in the research work.

I would like to thank my fellow postgraduate students and friends for their comradeship and encouragement. I would especially like to thank Dr. Qurban Ali Panhwar, Yussof Salam Mohamed, Ahmed Muhammed Aida, Dawda Badgie, Dr. Babucarr Njie, Lamin Sanyang, Omar Sowe, Lamin Drammeh, Aunty Haddy Jallow, Sister Binta Bah, Samba Bah, Rehema M Said, Bangally Kanuteh, Dr. Ali Reza Bahraminejad, Assan Sowe, Pa Samba Sowe, Momodou Jallow, Paul L Mendy, Peter L Mendy, Paul Fanu Mendy, Dr. Demba B Jallow, Carlos Gomez, Matthew Mendy and many others for their constant support and wholehearted solidarity.

Special appreciation is also expressed to my wife, Binta Bah for her care, support, patience and love. My deepest gratitude goes to my family for their unflagging love and support throughout my life. I offer my profound gratitude to Uncle Buba Sowe for the inspiration and exemplary guidance in my life. I am also grateful to my siblings and relatives who have always encouraged me during this time. Last, but certainly not the least, I am forever indebted to my late father (Mbondi Bah) and mum (Juma Sowe) for their enduring love, support and prayers.

I certify that a Thesis Examination Committee has met on 12 January 2015 to conduct the final examination of Alagie Bah on his thesis entitled "Nutrient Loss in Runoff and Growth Response of Immature Oil Palm Following Application of Controlled-Release Fertilizers" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohamed Hanafi bin Musa, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Aminuddin bin Hussin, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Internal Examiner)

Siva Kumar Balasundram, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Internal Examiner)

Joann K Whalen, PhD
Associate Professor
Mcgill University
Canada
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 15 April 2015

This thesis was submitted to the Senate of 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:

Ahmad Husni Mohd Hanif, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Mohd Rafii Yusop, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Christopher Teh Boon Sung, PhD
Senior Lecturer
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Syed Omar Syed Rastan, PhD
Associate Professor
Honorary President
Diversatech Fertilizer (M) Sdn. Bhd.
(External Member)

BUJANG KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: _____ Date: _____

Name and Matric No.: Alagie Bah (GS26489)

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) are adhered to.

Signature: _____
Name of Chairman of Supervisory Committee: Ahmad Husni Mohd Hanif

Signature: _____
Name of Member of Supervisory Committee: Mohd Rafii Yusop

Signature: _____
Name of Member of Supervisory Committee: Christopher Teh Boon Sung

Signature: _____
Name of Member of Supervisory Committee: Syed Omar Syed Rastan

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AnnAGNPS	Annualized Agricultural Non-Point Source Pollutant Loading model
ANSWERS	Areal Non-Point Source Watershed Environment Response Simulation
CCF	Common Compound Fertilizer
CREAMS	Chemicals Runoff and Erosion from Agricultural Management Systems
CRFs	Controlled-release Fertilizers
EPIC	Environmental Policy Integrated Climate
FAO	Food and Agriculture Organization
FBMPs	Fertilizer Best Management Practices
FFB	Fresh Fruit Bunch
FRE	Fertilizer Recovery Efficiency
FUE	Fertilizer-use efficiency
KINEROS	Kinematic Runoff and Erosion Model
LCP	Legume Cover Plants
MPOB	Malaysia Oil Palm Board
NUE	Nutrient Use Efficiency
POME	Palm Oil Mill Effluent
RUSLE	Revised Universal Soil Loss Equation
SRFs	Slow-release Fertilizers
SWAT	Soil and Water Assessment Tool
USDA	United States Department of Agriculture
WEPP	Water Erosion Prediction Project

CHAPTER 1

INTRODUCTION

1.1 Background

The world's population is projected to reach around 8 billion by 2030, which will disproportionally require an equivalence of 60% increase in global food production through intensive agricultural practices (Fresco, 2003). Globally, the world's oilseed market is characterized by rising demand for consumption of vegetable oils (Oil World, 2008). Owing to its capability of producing five to seven times more oil per hectare than all other oil crops, the planting of oil palm (*Elaeis guineensis* Jacq.) is currently a lucrative business in some countries in the humid tropics (Sheil *et al.*, 2009). The crop has emerged as the most important source of vegetable oil due to its very high productivity, versatility and profitability compared with other oil seeds such as soya bean, rapeseed, sunflower and peanut.

Oil palm cultivation is one of the most rapidly expanding agricultural ventures in the tropics (Comte *et al.*, 2012), attaining nearly 15 million hectares in 2009 and accounting for 10% of the world's permanent crop land (FAOSTATS, 2011; Sheil *et al.*, 2009). According to estimates by Corley (2009) in 2050, the demand for vegetable oil will reach between 201 and 340 Mt and that of palm oil alone is expected to be in the range of 93 and 190 million Mt. In 2012 alone, the estimated global production of total palm oil was about 65 million Mt (USDA, 2012). Oil palm accounts for nearly 30% of the world's vegetable oil, of which Malaysia and Indonesia are the world's largest producers of palm oil, commanding nearly 85% of the total global annual production of 46.5 million Mt of crude oil palm (Oil World, 2013). In Malaysia, oil palm production increased from 1.5 million hectares in 1985 to over 5 million hectares as of 2012, with an estimated total export value of over $20 billion in 2013 (MPOB, 2014). Oil palm is unique in the sense that with good agronomic management under optimum agro-ecological conditions, it can potentially yield over 10 Mt of oil per hectare. However, according to recent observation, current yields are below this figure and typically about 4-6 t ha^{-1} for the best commercial plantations and between 3-4 t ha^{-1} for the small holders (Murphy, 2014). This yield disparity can be partly due to low efficiency of conventional fertilizers used in most oil palm plantations. On average, the current fresh fruit bunch (FFB) yield in Malaysia is about 19 t ha^{-1} (MPOB, 2014).

1.2 Importance of fertilizers in oil palm

Fertilizer input is a key determinant in our quest to augment food production and plays a vital role in our pursuit to attain global food security (Yan *et al.*, 2008). It has been noted that our efforts to cater for the world's increasing food demands may not be achieved in the absence of fertilizers, and commercial fertilizers alone account for 40-60% of global food production (Stewart and Roberts, 2012; Roberts, 2009). Oil palm is predominantly cultivated on highly weathered soils such as Ultisols and Oxisols. These soils are chemically acidic and low in fertility (Shamshuddin and Anda, 2012). Fertilizers are therefore crucial in oil palm production, accounting for 50-70% of field operational costs and about 25% of the total cost of production (Caliman *et al.*, 2007;

Goh and Härdter, 2003). In general, the oil palm requires quite large quantities of fertilizers to achieve good yields (Comte *et al.,* 2012). In Malaysia, mineral fertilizers account for more than 90% of the fertilizers used by all the farming systems (FAO, 2004) and the main types are conventional water-soluble forms.

The main goal of fertilizers is to increase or sustain optimal crop yield (Chien *et al.*, 2009). Therefore, improving fertilizer use efficiency is pertinent to both fertilizer manufacturers and users. Accelerated use of chemical fertilizers in the tropics during the past few decades raises major environmental and economic concerns regarding sustainability. In the tropics, the high level of precipitation on deeply weathered tropical soils, often results in rapid depletion of nutrients, eventually leaving such soils incapable of sustaining crop production. Frequent application of large amounts of conventional water-soluble fertilizers in crop fields under high rainfall conditions may lead to substantial loss of nutrients through various pathways such as surface runoff, soil erosion, leaching and volatilization, consequently causing environmental contamination and financial loss. Excess application of conventional compound fertilizer can potentially cause huge loss of nutrients to the surface or sub-surface soil environment, subsequently affecting water quality, human health and biodiversity (Goulding *et al.,* 2008). The amount of nutrient runoff from crop fields in the tropics can be substantial and is mainly influenced by weather, rainfall intensity, soil and aquifer characteristics, land management practices, fertilizer management and the chemical properties of the nutrient compounds used (American Farm trust, 2013). It is believed that even when such fertilizers are applied at the recommended agronomic rates, only 30-50 % of the added nutrient (nitrogen) to the soil is utilized by the plant (McAllister *et al.,* 2012). Previous study on corn-based cropping systems reported that most of the systems had nitrogen recovery efficiency below 50% (Cassman *et al.,* 2002). For example, urea application is associated with low crop utilization efficiency, causing environmental contamination (Rahman *et al.,* 2009). In oil palm ecosystems, the recovery of applied fertilizers is inherently low, due to susceptibility of the fertilizers to surface runoff and leaching losses (Gerendas *et al.,* 2013).

Our goal of achieving long-standing agricultural sustainability in the tropics necessitates judicious soil management during field production (Prochnow, 2008). Improving efficient crop productivity can be attained by adopting the concept of 4R nutrient stewardship - right source, right rate, right time and right place (Roberts, 2010). Proper implementation of improved fertilizer-use efficiency (FUE) is associated with the benefits of boosting crop production, augmenting farm profitability and minimizing environmental contamination emanating from nutrient loss (Chien *et al.,* 2009). In the humid tropics, considering the fact that oil palm is mostly grown on highly weathered soils, coupled with problems of low fertilizer efficiency, there is need to develop improved fertilizer management programs that are economically viable and ecologically compatible. It is strongly believed that boosting crop yields and closing the gap between actual and attainable yield can be accomplished by the implementation and advancement of fertilizer management approaches and technologies (Stewart and Roberts, 2012).

Among several crop management practices geared towards improving crop nutrient use efficiency (Aziz and El-Asry, 2009; Prasad, 2009), the use of controlled- (CRFs) and slow-release (SRFs) fertilizers appear promising for widespread use in agriculture (Jarosiewicz and Tomaszewska, 2003; Blaylock *et al.,* 2005; Motavalli *et al.,* 2008; Nelson *et al.,* 2008). In comparison with the use of conventional water-soluble

fertilizers, the gradual release of nutrients from CRFs can match better with plant demand at the different growth stages. According to Isherwood (2000) of the International Fertilizer Industry Association, the use of controlled release fertilizers in tropical agro-eological regions where rainfall is high can be agronomically advantageous. Research efforts on the potential efficiency of CRFs under tropical environmental and agronomic cropping systems are not extensively explored.

Oil palm is a heavy nutrient feeder, and requires proper agronomic management to obtain robust growth and high yields. Efficient fertilization is pertinent for oil palm growers due its cultivation in highly weathered soils under high precipitation agro-ecological conditions. In Malaysia, most of the large scale oil palm plantations have their own tailored fertilization programs. The fact that most oil palm agronomists recommend fertilizers in the form of singly applied straight fertilizers or in the form of dry blends, poses a colossal challenge to oil palm growers. Presently, one of the major challenges of the oil palm industry is the shortage of labor to carry out large scale fertilization in several splits. There is a need for research efforts to review the impacts of current fertilizer management practices in oil palm fields, with the aim of providing vital information in planning and implementing management interventions that can improve yields and farm profitability.

To date, there have been limited reports regarding the performance of CRFs in oil palm production. This research was undertaken to determine both surface runoff loss and plant response to application of briquette and granular controlled-release (AJIB® CRF) and conventional mixture fertilizers under immature oil palm cropping.

1.3 Justification of the study

Despite their crucial roles in improving crop productivity and profitability, the nutrient use efficiency (NUE) of most fertilizers remained significantly low in the tropics. This raises serious economic and environmental concerns, especially in the light of much greater chemical fertilizer use in oil palm fields in the tropics. In most oil palm fields, nutrients are prone to runoff and leaching loss, which ultimately result in poor crop performance, and increased risk of environmental contamination. Therefore, proper adoption of best fertilizer management strategies in cropping systems is fundamental in attaining optimum crop production potential, input efficiency and minimal environmental contamination. The quest to boost global food production requires efficient management of chemical fertilizers in the soil-plant environment. Improvement of fertilizer efficiency is vital to reduce excess nutrients entering the environment and to increase economic returns.

Malaysia's oil palm plantations predominantly rely on the application of chemical fertilizers, accounting for over 50% of the field operational costs. Due to periodic events of high rainfall intensity (> 60mm/hr), there is high risk of occurrence of surface runoff. As a result of this, coupled with problems of inherent low soil fertility, oil palm productivity is affected. Another major challenge to the oil palm industry in Malaysia is the shortage of labor. Presently, the standard fertilizer practices involve the application of straight or water-soluble fertilizers in 4-6 splits per annum, which is both costly and labor intensive. In order to curb the growing challenge of labor shortage with over 5.2 million hectares of oil palm cultivation in Malaysia, there is need to adopt improved fertilizer use stewardship for efficient nutrient utilization by the crop.

The use of CRFs can reduce fertilizer application to 2 splits per annum; however there are limited reports about their performance on tropical crops such as oil palm, especially at the immature growth stage. So far, studies on the extent of nutrient efficiency and loss through runoff in the Malaysia's oil palm plantations have only been limited to straight fertilizers (Kee and Chew, 1996). Against this backdrop, field studies need to be conducted to address this knowledge gap in an effort to provide improved and efficient fertilizer recommendation program for sustainable oil palm production.

1.4 Research objectives

This study was primarily aimed at investigating the effect of application of controlled-release (AJIB® CRF) and conventional water-soluble fertilizers (mixture of straight fertilizers) on runoff loss of nutrients and growth of oil palm at the immature stage.

Specifically, the study was conducted to investigate the following objectives:

1. To quantify and compare surface runoff loss of nutrients among conventional water-soluble and controlled-release fertilizers (briquette and granular) under immature oil palm cropping.

2. To evaluate nutrient release patterns of conventional water-soluble and controlled-release fertilizers.

3. To predict runoff and soil erosion from oil palm crop field using Water Erosion Prediction Project (WEPP) model.

4. To evaluate the effects of controlled-release and water-soluble fertilizers on growth and mineral nutrition of oil palm during immature stage.

5. To quantify the economic value of fertilizer loss resulting from application of controlled-release and water-soluble fertilizers.

1.5 Significance of the study

Efficient fertilizer management is essential in in improving crop growth and yields. This requires adopting new fertilizer management practices and technologies in our agronomic practices. The advancement of new fertilizer technologies, coupled with innovative management approaches from research and development can increase crop yield significantly without compromising quality of the environment. In consideration of the long term economic implications and environmental factors associated with fertilizer use in oil palm plantations, there is a need to evaluate the fate of added fertilizers in oil palm fields. The findings from this study provide useful information concerning crop use and surface runoff loss of nutrients from the addition of fertilizers in oil palm fields. Furthermore, the prospects of using CRFs in oil palm plantations under tropical agro-ecological conditions are explored. The study also investigates the economic significance of fertilizer loss aimed at improving fertilizer management in oil palm fields. The findings of this study provide important information to agronomists, field managers, environmentalists and policy makers to make informed decisions. In

this experiment, considering climatic, slope and soil conditions, runoff and soil erosion predictions can emploed using process-based models such as WEPP. Since runoff plays a major role in nutrient and sediment transport, implementation of WEPP model in oil palm cropping fields may help in agronomic management practices.

1.6 Scope and limitations of the study

This study primarily focused on plant response and surface runoff loss of added fertilizers from immature oil palm. The investigation was concentrated on runoff loss of nutrients due to the fact that runoff and topsoil erosion are considered to be usually greater than loss associated with leaching. Due to time and logistical constraints, the investigation could not be conducted on mature oil palm fields. The nutrient loss investigation was only limited to surface runoff and erosion pathways. Other pathways of nutrient loss such as leaching and volatilization were not explored in this study. Results from nutrient loss study should be exercised with caution especially in extrapolating the data for use in other field conditions due to huge field variability that may relate to palm age, weather, soil properties, land gradient and contrasting agronomic conditions. This study also applied field scale erosion with emphasis on surface runoff that contributes to soil loss. Processes related to nutrient loss, subsurface flow and seep were not considered in this model. Nevertheless, given the in-depth descriptions of the cases treated in this study, it is hoped that many of the results obtained here will resonate in similar contexts within Malaysia.

1.7 Organization of the thesis

The thesis is organized into four chapters. Chapter one pinpoints background, justification, research objectives, significance, scope and limitations of the study. Chapter two presents review of relevant literature. Chapter three provides comprehensive study on runoff loss of nutrients; nutrients release patterns, runoff and soil loss prediction using WEPP model, growth and mineral nutrition of oil palm and economic value of nutrient loss from application of fertilizers. Chapter four provides a summary of major findings of the study. It further articulates recommendations and possible future directions and perspectives of the research.

REFERENCES

Aglukon. 1993. *Nutralene, Nitroform, AZOLON– Biologically Controlled Nitrogen Release*. Publisher: Aglukon Spezialdünger GmbH, Düsseldorf, Germany.

Ahmed, S.I., Rudra, R.P., Gharabaghi, B., Mackenzie, K. and Dickinson W.T. 2012. Within-storm rainfall distribution effect on soil erosion rate. *ISRN Soil Science* 2012, Article ID 310927.

Alexandratos, N. and Bruinsma, J. 2012. *World agriculture towards 2030/2050: the 2012 revision.* ESA Working paper No. 12-03. Rome, FAO.

Alkabbashi, A.N., Alam, M.Z., Mirghani, M.E.S. and Al-Fusaiel, A.M.A. 2009. Biodiesel production from crude palm oil by transesterification process. *Journal of Applied Sciences* 9: 3166-3170.

Alva, A.A. 1992. Differential leaching of nutrients from soluble vs. controlled-release fertilizers. *Environmental Management* 16(6): 769-776.

American Farm Trust. 2013. Controlling Nutrient Runoff on Farms: Center for Agriculture in the Environment DeKalb, Illinois.

Amkha, S., Inubushi, K. and Takagaki, M. 2007. Effects of Controlled-release nitrogen fertilizer application on nitrogen uptake by a leafy vegetable (Brassica campestris), Nitrate Leaching and N2O Emission. Japanese Journal of Tropical Agriculture 51(4): 152-159.

Azeem, B., KuShaari, K., Man, Z.B. Basit, A. and Thanh, T.H. 2014. Review on materials & methods to produce controlled-release coated urea fertilizer. *Journal of Controlled Release* 181: 11-21.

Aziz, E. E. and El-Asry, S. M. 2009. Efficiency of Slow Release Urea Fertilizer on Herb Yield and Essential Oil Production of Lemon Balm (*Melissa officinalis* L.) Plant. *American-Eurasian Journal of Agricultural and Environmental Sciences* 5(2): 141-147.

Baigorria, G.A. and Romero, C.C. 2007. Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes. *Environmental Modelling and Software* 22(8): 1175–1183.

Banabas, M.A., Scotter, D.R. and Nelson, P.R. 2008. Losses of nitrogen fertilizer under oil palm in Papua New Guinea: water balance, and nitrogen in soil solution and runoff. *Australian Journal of Soil Research* 46: 332-339.

Beasley, D.B., Huggins, L.F. and Monke. E.J. 1980. ANSWERS: A model for watershed planning. *Transactions of the ASAE* 23(4): 938-944.

Besford, R. and Maw, G.1975. Effect of potassium nutrition on tomato plant growth and fruit development. *Plant Soil* 42: 395-412.

Bhuyan, S.J., Kalita, P.K., Janssen, K.A. and Barnes, P.L. 2002. Soil loss predictions with three erosion simulation models. *Environmental Modelling and Software* 17(2): 137-146.

Bingner, R.L., Theurer, F.D. and Yuan, Y. AnnAGNPS Technical Processes. 2003. http://www.ars.usda.gov/Research/docs.htm?docid=5199. Retrieved 10 March 2010.

Blaylock, A.D., Kaufmann, J. and Dowbenko, R.D. 2005. *Nitrogen Fertilizer Technologies*. Western Nutrient Management Conference. Salt Lake City, UT. Vol. 6, pp. 8-13.

Bonilla, C.A., Reyes, J.L. and Magri, A. 2010.Water erosion prediction using the revised universal soil loss equation (RUSLE) in a GIS Framework, Central Chile. *Chilean Journal of Agricultural Research* 70 (1): 159-169.

Borah, D.K. and Bera, M. 2003. Watershed-scale hydrologic and nonpoint-source pollution models: review of mathematical bases. *American Society of Agricultural Engineers* 46(6): 1553-1566.

Bouraoui, F. and Dillaha, T.A. 1996. Answers-2000: Runoff and sediment transport model. *Journal of Environmental Engineering* 122(6): 493-502.

Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil Science* 59: 39-45.

Bricker, S., Longstaff, B.W., Dennison, A., Jones, K., Boicourt, C. and Woerner, J. 2007. *Effects of nutrient enrichment in the nation's estuaries: a decade of change*. NOAA coastal ocean program decision analysis series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD.

Brito, G.G., Sofiatti, V., Brandão, Z.N., Silva, V.B., Silva, F.M. and Silva, D.A. 2011. Non-destructive analysis of photosynthetic pigments in cotton plants. *Acta Scientiarum. Agronomy* 33(4): 671-678.

Broschat, T.K. 2008. Release Rates of Soluble and Controlled-release Boron Fertilizers. *HortTechnology* 18(3): 471-474.

Cabrera, R.I. 1997. Comparative evaluation of nitrogen release patterns from controlled release fertilizers by nitrogen leaching analysis. *HortScience* 32: 669-673.

Cai, G.X., Chen, D.L., Ding, H., Pacholski, A., Fan, X.H. and Zhu, Z.L. 2002. Nitrogen losses from fertilizers applied to maize, wheat and rice in the North China Plan. *Nutrient Cycling in Agroecosystems* 63: 187-195.

Cakmak, I. and Yazici, A.M. 2010. Magnesium: a forgotten element in crop production. *Better Crops* 94(2): 23-25.

Caliman, J.P., Carcasses, R., Perel, N., Wohlfahrt, J., Girardin, P., Wahyu, A., Pujianto., Dubos, B. and Verwilghen, A. 2007. Agri-environmental indicators for sustainable palm oil production. *Palmas* 28: 434-445.

Caliman, J.P., Dubos, B., Tailliez, B., Robin, P., Bonneau, X. and De Barros I. 2003. Oil palm mineral nutrition management: current situation and prospects. In *XIV International Oil Palm Conference*, 23-26 September 2003, Cartagena de Indias, Columbia, pp. 33.

Campbell, C.R. and Plank. C.O. 1998. Preparation of plant tissue for laboratory analysis. pp. 37-49. In *Handbook of Reference Methods for Plant Analysis* (Y.P. Kalra, Ed.) CRC Press, Boca Raton, FL, pp. 37-49.

Carson, L.C. and Ozores-Hampton, M. 2013. Factors affecting nutrient availability, placement, rate, and application timing of controlled-release fertilizers for Florida vegetable production using seepage irrigation. *HortTechnology* 23: 553-562.

Carson, L.C., Ozores-Hampton, M. and Morgan, K.T. 2013. Nitrogen release from controlled-release fertilizers in seepage-irrigated tomato production in SouthFlorida. *Proceedings of the Florida State Horticultural Society* 126: 131-135.

Cassman, K.G., Dobermann, A. and Waters, D.T. 2002. Agroecosystems, nitrogen-use efficiency and nitrogen management. *Ambio* 31: 132-140.

Chen, J.Y. and Adams, B.J. 2006. Integration of artificial neural networks with conceptual models in rainfall-runoff modeling. *Journal of Hydrology* 318: 232-249.

Chen, X., Jiang, S.Q., Zhang, K.Z., Bian, Z.P. 1999. Law of phosphorus loss and its affecting factors in red soil slope land. *Journal of Soil and Water Conservation* 5(3): 38-41.

Chien, S.H., Prochnow, L.I., and Cantarella, H. 2009. Chapter 8: Recent developments of fertilizer production and use to improve nutrient efficiency and minimize environmental impacts. *Advances in Agronomy* 102: 267-322.

Chew, P.S and Pushparajah, E. 1995. Nitrogen management and fertilization of tropical plantation tree crops. In *Nitrogen Fertilization in the Environment* (P. E. Bacon, Ed.), pp. 225–293. Marcel Drekker Inc., New York.

Comte, I., Colin, F., Whalen, J.K., Grünberger, O. and Caliman, J.-P. 2012. Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: A Review. *Advances in Agronomy Volume* 116: 71-124.

Cottenie, A. 1980. *Soil and plant testing as a basis of fertilizer recommendations*, FAO. Soil Bulletin 38/2. FAO, Rome.

Corley, R.H.V. 2009. How much palm oil do we need? *Environmental Science and Policy* 12(2): 134-139.

Corley, R.H.V. and Tinker, P.B. 2003. *The Oil Palm* (4th ed.). John Wiley and Sons, Hoboken, NJ. pp. 380-381. CRC Press.

Csizinszky, A.A. 1994. Yield response of bell pepper and tomato to controlled release fertilizer on sand. *Journal of Plant Nutrition* 9: 1535-1549.

Diversatech Fertilizer. AJIB Controlled Release Fertilizer. http://www.diversatechfertilizer.com/kamila-crf/. Retrieved 20 August 2014.

Donough, C.R., Oberthür, T., Cock, J., Rahmadsyah., Abdurrohim, G., Indrasuara, K., Lubis, A., Dolong, T., Witt, C. and Fairhurst, T. 2011. Successful yield intensification with best management practices (BMP) for oil palm at six plantation locations representing major growing environments of Southeast Asia. In P*roc. PIPOC 2011 Int. Palm Oil Cong, – Agric, Biotech & Sustainability Conf.*, Malaysian Palm Oil Board, Kuala Lumpur, pp. 464-469.

Driessche, R.V.D. 1974. Prediction of Mineral Nutrient Status of Trees by Foliar Analysis. *The Botanical Review* 40(4): 347-394.

Drost, D., Koenig, R., Tindall, T. 2002. Nitrogen use efficiency and onion yield increased with polymer-coated nitrogen source. *HortScience* 37: 338-342.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T. and Mearns, L.O. 2000. Climate extremes: observations, modelling, and impacts. Science 289: 2068-2074.

Ebrahimpour, E., Balasundram, S.K. Talib, J., Anuar, A.R. and Memarian, H. 2011. Accuracy of GeoWEPP in estimating sediment load and runoff from a tropical watershed. *Malaysian Journal of Soil Science* 15: 25-33.

Elliot, W.J., Luce, C.H. and Robichaud, P.R. 1996. Predicting sedimentation from timber harvest areas with the WEPP model. In *Proc. Sixth Federal Interagency Sedimentation Conf.*, Las Vegas, March 10-14, IX:46-53.

Elliot, W.J., Elliot, A.V., Qiong, W. and Laflen, J.M. 1991. *Validation of the WEPP model with rill erosion plot data*. ASAE Paper No. 91-2557. St. Joseph, MI: American Society of Agricultural Engineers. pp.11.

Epstein, E and Bloom, A.J. 2005. *Mineral nutrition of plants: principles and perspectives* (2nd ed.). Sunderland, MA, USA: Sinauer.

Fairhurst, T.H. and Mutert, M. 1999. Interpretation and management of oil palm leaf analysis data. *Better Crops International* 13(1): 3-6.

Fan, X.H. and Li, Y.C. 2010. Nitrogen release from slow-release fertilizers as affected by soil type and temperature. *Soil Science Society of America Journal* 74: 1082-1089.

Fan, M.X. and Mackenzie, A.F. 1993. Urea and phosphate interactions in fertilizer microsites: ammonia volatilization and pH changes. *Soil Science Society of America Journal* 57: 839-845.

Fan, Z., Moore, J.A. and Wenny, D.L. 2004. Growth and nutrition of container- grown ponderosa pine seedlings with controlled-release fertilizer incorporated in the root plug. *Annals of Forest Science* 61: 117-124.

FAO. 2015. *World Fertilizer Trends and Outlook to 2018*. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2012. *Current World Fertilizer Trends and Outlook to 2016.* Food and Agriculture Organization of the United Nations, Rome.

FAO. 2010. *Global Forest Resources Assessment 2010*. Food and Agriculture Organization of the United Nations. Rome.

FAOSTATS. 2011. http://faostats.fao.org. Retrieved 20 February 2014.

FAO. 2009. FAOSTAT online statistical service. Food and Agriculture Organization of the United Nations, Rome. http://faostat.fao.org. Retrieved 20 August 2011.

FAO. 2006. *Fertilizer Use by Crop*. Fertilizer and Plant Nutrition Bulletin no. 17. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2004. *Fertilizer use by crop in Malaysia*. Food and Agriculture Organization of the United Nations, Rome.

FAO). 2004. *The use of Phosphate Rock for Sustainable Agriculture*. Fertilizer and Plant Nutrition Bulletin 13, Food and Agriculture Organization of the United Nations, Rome.

Felda Agricultural Services Sdn. Bhd. 2012. Oil Palm Seedlings Fertility Color Chart.

Flanagan, D.C., Frankenberger, J.R. and Ascough, J.C. 2012. WEPP: Model use, calibration, and validation. *American Society of Agricultural and Biological Engineers* 55(4): 1463-1477.

Flanagan, D.C. and Frankenberger, J.R. 2002. *Water Erosion Prediction Project (WEPP) Windows Interface Tutorial USDA-Agricultural Research Service & Purdue University National Soil Erosion Research Laboratory*, West Lafayette, Indiana, USA.

Flanagan, D.C., Nicks, A.D., Nearing, M.A. and Laflen, J.M. 1995. Chapter 1: Overview of the WEPP Erosion Prediction Model. In *USDA- Water Erosion Prediction Project : Hillslope Profile and Watershed Model Documentation* (D.C. Flanagan and M.A. Nearing, Eds.). Vol. NSERL Report No.10.USDA-ARS national Soil Erosion Research Laboratory.

Flanagan, D.C., and Livingston S.J. (eds.). 1995. "*WEPP user summary: USDA- Water Erosion Prediction Project (WEPP)",* USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN, USA, NSERL Report No. 11.

Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielson, F., Brühl, C.A., Donald, P.F.and Phalan, B. 2008. How will oil palm expansion affect biodiversity? *Trends in Ecology and Evolution* 23: 538- 545.

Foster, G.R. 2005. RUSLE 2.0 science documentation (draft). Washington, D.C.: USDA Agricultural Research Service.

Foster, H. 2003. Assessment of oil palm fertilizer requirements. In *Oil Palm: Management for Large and Sustainable Yields* (T. Fairhurst and R. Härdter, Eds.), pp. 231-254. PPI/PPIC and IPI, Singapore.

Foster, G.R., Lane, L.J., Nowlin, J.D., Laflen, J.M. and Young, R.A. 1980. A model to estimate sediment yield from field-sized areas: Development of model. In *CREAMS: A field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems* (W.G. Knisel, Ed.), U. S. Dept. of Agric., Sci. and Educ. Admin., Conser. Rep. No. 26. pp. 36-64.

Foster, H.L. and Goh, H.S. 1997. Fertilizer Requirement of Oil Palm in West Malaysia. In *International Development in Oil Palm* (W. Newall, Ed.). Incorporated Society of Planters, Kuala Lumpur, Malaysia.

Foster, H.L., Prabowo N.E. 2002. Overcoming the limitations of foliar diagnosis in oil palm. In *International Oil Palm Conference*, July 8–12, 2002, Nusa Dua, Bali, IOPRI, Medan, Indonesia, pp. 269–281.

Freeman, A.M., Lamon III, E.C., Stow, C.A. 2009. Nutrient criteria for lakes, ponds, and reservoirs: A Bayesian TREED model approach. *Ecological Modelling* 220(5): 630-639.

Fresco, L.O. 2003. *Fertilizer and the future*. IFA/FAO Agriculture Conference on "Global Food Security and the Role of Sustainability Fertilization". Rome, Italy, 26-28 March 2003.

Fu, T., Ni, J.P., Wei, C.F. and Xie, D.T. 2002. Research on nutrient loss from terra gialla soil in three Gorges Region under different rainfall intensity. J*ournal of Soil and Water Conservation* 16(2): 33-35.

Fujinuma, R., Balster, N.J. and Lee, H. 2011. *Reduced rates of controlled-release fertilizer lower potential nitrogen leaching from a Wisconsin bare-root tree nursery*. Proceedings of the 17th Central Hardwood Forest Conference GTR-NRS-P-78.

Gee, G.W. and Bauder, J.W.1986. Particle size analysis. In *Methods of soil analysis. Part 1. Physical and mineralogical methods* (A. Klute, Ed.), 2nd. Ed. ASA-SSSA, Wisconsin, pp.383-411.

Gandeza, A.T., Shoji, S. and Yamada, L. 1991. Simulation of crop response to polyolefin-coated urea: I. Field dissolution. *Soil Science Society of American Journal* 55: 1462-1467.

Gelencsér, G., Centeri, C., Jakab, G. and Vona, M. 2009. *Comparison of the results of modeling soil loss with WEPP and USLE in the Koppány Valley*. Hungary. 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia. Published on DVD.

Gerendas, J., Utomo, B., Martoyo, K., Donough, C.R and Oberthür, T. 2013. *Effect of nutrient application Frequency on nutrient uptake in oil palm production on sandy soils*. Paper presented at PIPOC, Kuala Lumpur, Malaysia. 19-21 November 2013.

Gerendas, J. and Heng, A. 2010. *Oil palm fertilization – sharing some perspectives*. Paper presented at the ISP Selangor Seminar (8-Jun, 2010) *"Plantation Industry: Competitive Strategies In Achieving A Sustainable Future"*.

Glauser, J., Janshekar, H. and Funada, C. 2013. *Controlled- and slow-release fertilizers. Chemical Economics Handbook* (CEH). United States.

Goh, K.J. and Hardter, R. 2003. General Oil Palm Nutrition. In *Oil Palm: Management for Large and Sustainable Yields* (T.H. Fairhurst and R. Hardter, Eds.), (pp. 191-230). PPI/PPIC and IPI, Singapore.

Goh, K.J., Chew, P.S. and Kee, K.K. 1994. *K nutrition for mature oil palm in Malaysia*. Applied Agricultural Research, Locked Bag 212. Paper presented at the "Workshop on K nutrition for oil palm in Indonesia", 4th October, 1993 at Medan, Indonesia. IPI Research Topics No. 17.

Goh, K.J., Härdter, R. and Fairhurst, T. 2003. Fertilizing for maximum return. In *Oil palm: management for large and sustainable yields* (T. Fairhurst and R. Härdter, Eds.), pp. 279-306. PPI/PPIC and IPI, Singapore.

Goh, K.J., Ng, P.H.C. and Lee, C.T. 2009. Fertilizer management and productivity of oil palm in Malaysia. Advanced Agroecological Research (AAR). http://www.aarsb.com.my/AgroMgmt/OilPalm/FertMgmt/Research/ FertMgmt&Product.pdf. Retrieved 20 May 2014.

Goulding, K., Jarvis, S. and Whitmore, A. 2008. Optimizing nutrient management for farm systems. Philosophical Transactions of the Royal Society B: *Biological Sciences*, 363: 667-680.

Gruhn, P., F. Goletti, and Yudelman, M. 2000. *Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges*. Food, agriculture, and the environment discussion paper 32. International food policy research institute, Washington, D. C. USA.

Hanson, E.J. and Retamales, J.B. 1992. Effect of nitrogen source and timing on high bush blueberry performance. *HortScience* 27: 1265-1267.

Hardy, K. and Guarnieri, F. 2011. Modeling and hazard analysis for contaminated sediments using Stamp Model. *Chemical Engineering Transactions* 25: 737-742.

Hartemink, A.E. 2006. *Soil erosion: perennial crop plantations*. Encyclopedia of Soil Science (R. LAL Ed.). *Dekker*, pp. 1613-1617.

Hauck, R. D. 1972. Synthesis slow-release fertilizers and fertilizer amendments. In *Proc. Organic Chemicals in the Soil Environment*, New York, 1972, pp. 633-690.

Hauck, R.D. 1993. *Controlled Availability Fertilizers: Technical vs Public Perspectives*. Proceedings: Dahlia Greidinger Memorial International Workshop on Controlled/Slow Release Fertilizers, Technion–Israel Institute of Technology, Haifa, Israel.

He, X., Li, Z., Hao, M., Tang, K. and Zheng, F. 2003. Down-scale analysis for water scarcity in response to soil-water conservation on Loess Plateau of China. *Agriculture*, Ecosystems *and Environment* 94(3): 355-361.

Hua, L., He, X., Yuan, Y. and Nan, H. 2012. Assessment of runoff and sediment yields using the AnnAGNPS Model in a three-Gorge watershed of China. *International Journal of Environmental Research and Public Health* 9: 1887-1907.

Hutchinson, C., Simonne, E., Solano, P., Meldrum, J.,Livingston-Way, P.2002. Testing of controlled release fertilizers programs for seep irrigated Irish potato production. *Journal of Plant Nutrition 2*6(9): 1709-1723.

Huth, N.I., Banabas, M., Nelson, P.N. and Webb, M. 2014. Development of an oil palm cropping systems model: Lessons learned and future directions. *Environmental Modelling & Software* 62: 411-419.

Hyatt, C.R., Venterea, R.T., Rosen, C.J., McNearney, M., Wilson, M.L. and Dolanc, M.S. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. *Soil Science Society of American Journal* 74: 419-428.

Ibitoye, A.A. 2006. *Laboratory Manual on Basic Soil analysis* (2nd ed.). Foladave Nig. Ltd. pp. 32-36.

Isherwood, K.F. 2000. Mineral fertilizer use and the environment. International Fertilizer Industry Association (IFA), Paris. ISBN: 2-9506299-3-8.

Irvem, A., Topaloglu, F. and Uygur, V. 2007. Estimating spatial distribution of soil loss over Seyhan River Basin in Turkey. *Journal of Hydrology* 336: 30-37.

Jarosiewicz, A. and Tomaszewska, M. 2003. Controlled-release NPK fertilizer encapsulated by polymeric membranes. *Journal of Agricultural and Food Chemistry* 51: 413-417.

Jin, S.H., Huang, J.Q., Li, X.Q., Zheng, B.S., Wu, J.S., Wang, Z.J., Liu, G.H. and Chen, M. 2011. Effects of potassium supply on limitations of photosynthesis by mesophyll diffusion conductance in *Carya cathayensis* Tree. *The Journal of Physiology* 31(10): 1142-1151.

Jin, K., Cornelis, W.M., Gabriels, D., Baert, M., Wu, H.J., Schiettecatte, W., Cai, D.X., Neve, S. de., Jin, J.Y., Hartmann, R. and Hofman, G. 2009. Residue cover and rainfall intensity effects on runoff soil organic carbon losses. *Catena* 78(1): 81-86.

Jones, J.B., Jr. 2001. *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. CRC, Press, Boca Ranton, F.L. pp. 81-82.

Junakova, N. and Balintova, M. 2012. Predicting nutrient loads in chosen catchment. *Chemical Engineering Transactions* 26: 591-596.

Kang, B.K. and Han, S.H. 2005. Production of seed potato (*Solanum tuberosum* L.) under the recycling capillary culture system using controlled-release fertilizers. *Journal of the Japanese Society for Horticultural Science* 74:295-299.

Kariya, K., Matsuzaki, A. and Machida, H. 1982. Distribution of chlorophyll content in leaf blade of rice plant. *Japanese Journal of Crop Science* 51(1): 134- 135.

Kee, K.K. and Chew, P.S. 1996. *A13: Nutrient losses through surface runoff and erosion- Implications for improved fertilizer efficiency in mature oil palm*. Applied Agricultural Research Sdn. Bhd, Locked Bag No. 212.

Kenzo, T., Roneda, R., Matsumoto, Y., Azani, M.A. and Majid, N.M. 2008. Leaf photosynthetic and growth responses on four tropical tree species to different light conditions in degraded tropical secondary forest, Peninsular Malaysia. *Japan Agricultural Research Quarterly* 42 (4): 299-306.

Khakbazan, M., Grant, C.A. Finlay, G., Wu, R., Malhi, S.S., Selles, F., Clayton, G.W., Lupwayi, N.Z., Soon, Y.K. and Harker, K.N. 2013. An economic study of controlled release urea and split applications of nitrogen as compared with non-coated urea under conventional and reduced tillage management. *Canadian Journal of Plant Science* 93: 523-534.

Kim, J.S., Seung, Y.O. and Kwang, Y.O. 2006. Nutrient runoff from a Korean rice paddy watershed during multiple storm events in the growing season. *Journal of Hydrology* 327(1–2): 128-139.

Kleinman, P.J., Srinivasan, M.S., Dell, C.J., Schmidt, J.P., Sharpley, A.N and Bryant, R.B. 2006. Role of rainfall intensity and hydrology in nutrient transport via surface runoff. *Journal of Environmental Quality* 35(4): 1248-59.

Klik, Andreas. 2000. Soil erosion on agricultural land. In *Ecosystem service and sustainable watershed management in North China* (B. Stoecker, Ed.). International conference, Beijing, P. R. China, August 23-25.

Kamphorst, A. 1987. A small rainfall simulator for the determination of soil erodibility. Netherlands. *The Journal of Agricultural Science* 35: 407-415.

Kouli, M., Soupios, P. and Vallianatos, F. 2009. Soil erosion prediction using the Revised Universal Soil Loss Equation (RUSLE) in a GIS framework, Chania, Northwestern Crete, Greece. *Environmental Geology* 57(3): 483-497.

Kramer, L.A. and Alberts, E.E. 1995. *Validation of WEPP 95.1 daily erosion simulation*. ASAE Paper No. 95-2385. St. Joseph, Mich.: ASAE.

Lammel, J. 2005. *Cost of the different options available to the farmers: Current situation and prospects*. IFA International Workshop on Enhanced-Efficiency Fertilizers, Frankfurt. International Fertilizer Industry Association, Paris, France.

Laflen, J.M., Flanagan, D.C. and Engel, B.A. 2004. Soil erosion and sediment yield prediction accuracy using WEPP. *Journal of the American Water Resources Association* 40: 289-297.

Laflen, J.M., Elliot, W.J., Flanagan, D.C., Meyer, C.R. and Nearing, M.A.. 1997. WEPP predicting water erosion using a process-based model. *Journal of Soil and Water Conservation* 52: 96-103.

Lamont, G.P., Worrall, R.J. and O'Connell, M.A. 1987. The effects of temperature and time on the solubility of resin-coated controlled-release fertilizers under laboratory and field conditions. *Scientia Horticulturae* 32: 265-273.

Law, C.C., Zaharah, A.R., Husni, M.H.A. and Siti Nor Akmar, A. 2014. Leaf nitrogen content in oil palm seedlings and their relationship to SPAD chlorophyll meter readings. *Journal of Oil Palm, Environment & Health* 5:8-17.

LECO Corporation. 2003. *Total/organic carbon and nitrogen in soils*. LECO Corporation, St. Joseph, MO, Organic Application Note 203-821-165.

Liu, G., Zotarelli, L., Li, Y., Dinkins, D., Wang, Q. and Ozores-Hampton, M. 2014. *Controlled-release and slow-release fertilizers as nutrient management tools*. Horticultural Sciences Department, University of Florida/IFAS Extension.

Liu, Z.A., Yang, J.P. and Yang, Z.C. 2012. Using a chlorophyll meter to estimate tea leaf chlorophyll and nitrogen contents. *Journal of Soil Science and Plant Nutrition* 12(2): 339-348.

Liu, G., Simonne, E. H., Li, Y., Hutchinson, C.M., Warren, M. and Lands, S. 2006. *Controlled-release fertilizers for commercial potato production in Florida*. UF/IFAS Extension.

Ma, L., Zhang, M., Chen, J.Q., Kong, F.M. and Yang, Y. 2006. Effect of coated controlled-release nitrogen fertilizers on yield increase of corn. *Scientia Horticulturae* 21(4): 12-14.

Maene, L.M., Tong, K.C., Ong, T.S. and Mokhtaruddin, A.M. 1979. *Surface wash under mature oil palm*. Proc Symp. On Water in Malaysian Agriculture. MSSS, Kuala Lumpur. pp. 203-216.

Malaysia Oil Palm Board (MPOB). 2014. Economics and Industry Development Division.http://bepi.mpob.gov.my/index.php/statistics/production/118production-2013/608-production-trend-2013.html. Retrieved 20 February 2014.

Marschner, H. 1997. *Mineral Nutrition of Higher Plants* (2nd Ed.) Stuttgart-Hohenheim, Germany.

Martínez, D.E. and Guiamet, J.J. 2003. Distortion of the SPAD 502 chlorophyll meter readings by changes in irradiance and leaf water status. *Agronomie* 24: 41-46 41.

Martínez-Murillo JF, Nadal-Romero E, Regüés D, Cerdà A, Poesen J. 2013. Soil erosion and hydrology of the Western Mediterranean badlands throughout rainfall simulation experiments: a review. *Catena* 106: 101-112.

McAllister, C.H., Beatty, P.H and Good, A.G. 2012. Engineering nitrogen use efficient crop plants: The Current Status. *Plant Biotechnology Journal* 10: 1011-1025.

Mikkelsen, R.L., Williams, H.M. and Behel, A.D., Jr. 1994. Nitrogen leaching and plant uptake from controlled-release fertilizers. *Fertilizer Research* 37: 1 43-50.

Milne, R.M., Haynes, R.J., 2004. Soil Organic matter, microbial properties, and aggregate stability under annual and perennial pastures. *Biology and Fertility of Soils* 39: 172-178.

Minolta Camera Co. Ltd., 1989. *Chlorophyll meter SPAD-502. Instruction Manual*. Radiometric Instruments Divisions, Osaka, Minolta, pp. 22.

Mohammed, M.A.A., Salmiaton, A., Wan Azlina, W.A.K.G. and Amran, M.S.M. 2011. Gasification of empty fruit bunch for hydrogen rich fuel gas production. *Journal of Applied Sciences* 11: 2416- 2420.

Morgan, K.T., Cushman, K.E. and Sato, S. 2009. Release mechanisms for slow- and controlled-release fertilizers and strategies for their use in vegetable production. *HortTechnology* 19(1): 10-12.

Motavalli, P.P., Goyne, K.W. and Udawatta, R.P. 2008. Environmental impacts of enhanced-efficiency nitrogen fertilizers. *Crop Management*. Doi: 10.1094/CM-2008-0730-02-RV.

MPOB. 2014. Monthly FFB Yield: Economics and Industry Development Division. Malaysian Palm Oil Board. (http://bepi.mpob.gov.my/index.php/statistics/yield/123-yield-2013/655-yield-2013.html. Retrieved 6 March 2014.

Murphy, D.J. 2014. The future of oil palm as a major global crop: opportunities and challenges. *Journal of Oil Palm Research* 26(1): 1-24.

Mutchler, C.K., C.E. Murphree, and K.C. McGregor. 1994. Laboratory and field plots for erosion research. In *Soil Erosion Research Methods* (R. Lal, Ed.), 2nd ed. Soil and Water Conservation Society, Ankeny, IA, pp. 11–37.

Mutert, E. 1999. Suitability of soils for oil palm in Southeast Asia. *Better Crops International* 13(1): 36- 38.

Nash, J.E. and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models. Part I: a discussion of principles. *Journal of Hydrology* 10: 282-290.

Nearing, M.A. 1998. Why soil erosion models over-predict small soil loss and under-predict large soil losses. *Catena* 32: 15-22.

Nelson, K.A., Scharf, P.C., Bundy, L.G. and Tracy, P. 2008. Agricultural management of enhanced-efficiency fertilizers in the North-central United States. *Crop Management*, doi:10.1094/CM-2008-0730-03-RV.

Ng, S.K. and Thong, K.C. 1985. Nutrient requirements for exploiting yield potentials of major plantation tree crops in the tropics. In *Potassium in the Agricultural System of the Humid Tropics.* 19th Coll. Int. Potash Inst. Bangkok, Thailand: 81-95.

Ng, S.K. 1977. A review of oil palm nutrition and manuring: Scope for greater economy in fertilizer usage. *Oleagineux* 32: 197-209.

Nieuwolt, S., Zaki, M.G and Gopinathan, B. 1982. *Agro-ecological regions in Peninsular Malaysia*. MARDI, Serdang. pp. 20.

Oberthür, T., Cock, J., Donough, C.R., Rahmadsyah., Abdurrohim, G., Indrasuara, K., Lubis, A. and Dolong, T. 2012. *Best management practices (BMP) in oil palm fertilization for sustainable intensification*. Presented at International Oil Palm Conference, Cartagena, Colombia.

Obi, J.C. and Udoh, B.T. 2012. Nutrient budget for optimal oil palm (*Elaeis guineensis* Jacq.) yield on coastal plain sands soils of Akwa Ibom State Nigeria. *Open Journal of Soil Science* 2: 289-298.

Obreza, T.A. and Sartain, J.B. 2010. Improving nitrogen and phosphorus fertilizer use efficiency for Florida's Horticultural Crops. *HortTechnology*, 20(1): 23-33.

Obreza, T.A. and Rouse, R.E. 2006. Long-term response of 'Hamlin' orange trees to controlled-release nitrogen fertilizer. *HortScience* 41: 423-426.

Obreza, T.A., Rouse, R.E. and Sherrod, J.B. 1999. Economics of controlled-release fertilizer use on young citrus trees. *Journal of Production Agriculture* 12(1): 69-73.

Obreza, T.A., and Rouse, R.E. 1993. Fertilizer effects on early growth and yield of 'Hamlin' orange trees. *HortScience* 28: 111-114.

Oenema, O. and Roest, C. 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. *Water Science Technology* 37: 19-30.

Oertli, J.J. and Lunt, O.R. 1962. Controlled release of fertilizer minerals by encapsulating membranes: II. Efficiency of recovery, influence of soil moisture, mode of application, and other considerations related to use. *Soil Science Society of America, Proceedings* 26: 584-587.

Oil World. 2008. *Oil World Annual.* Vol. 2 Up to 2007/08, Eds. ISTA Mielke GmbH Mielke T., Hamburg, Germany.

Oil World. 2013. Palm oil. http://www.oilworld.biz/app.php?fid=310&fpar=YToyOntzOjI6IklkIjtzOjQ6IjYzMTQiO3M6NDoicGNpZCI7czoyOiIxMiI7fQ%3D%3D&isSSL=0&aps=0&blub=26bc92353fe185973450e4160e44224d&ista=apdxujfvn. Retrieved 20 February 2014.

Omoti, U., Ataga D.O. and Isenmila, A.E. 1983. Leaching losses of nutrients in oil palm plantations determined by tension lysimeters. *Plant Soil* 73: 365-376.

Orewa, S.I. 2008. Designing agricultural development projects for the small scale farmers: Some lessons from the World Bank assistance small holder oil palm development scheme in Nigeria. *Journal of Applied Science* 8: 295-301.

Otero, J.D., Figueroa, A., Muñoz, F.A., and Peña, M.R. 2011. Loss of soil and nutrients by surface runoff in two agro-ecosystems within an Andean paramo area. *Ecological Engineering* 37(12): 2035-2043.

Pack, J.E., Hutchinson, C.M., Simonne, E.H. 2006. Evaluation of controlled release fertilizers for Northeast Florida chip potato production. *Journal of Plant Nutrition* 29:1301-1313.

Pakiam, R. 2013. "Malaysia Keeps Palm Oil Export Tax Unchanged to Spur Shipments". Bloomberg News. http://www.bloomberg.com/news/2013-09-17/malaysia-keeps-palm-oil-export-tax-unchanged-to-spurshipments.html. Retrieved 22 September 2013.

Pandey, A., Chowday, V.M., Mal, B.C. and Billib, M. 2008. Runoff and sediment yield modeling from a small agricultural watershed in India using the WEPP model. *Journal of Hydrology* 348: 305-319.

Paramananthan, S. 2000. *Soils of Malaysia: Their Characteristics and Identification. Academy of Sciences Malaysia*.

Paramanathan, S. 2003. General Oil Palm Nutrition. In *Oil Palm: Management for Large and Sustainable Yields* (T. Fairhurst and R. Härdter, Eds.), pp. 191-230. PPI/PPIC and IPI, Singapore.

Pavinato, P.S., Mondardo, J.T., Marangon, R.J., Herrera, W.F.B., Brun, E.J. and Martin,T.N. 2014. Growth and nutrient uptake by slash pine seedlings under phosphate fertilizer sources. Brazilian Journal of Agricultural Sciences 9(1): 103-109.

Percival, G.C., Keary, I.P. and Noviss, K. 2008. The potential of a chlorophyll content SPAD meter to quantify nutrient stress in foliar tissue of sycamore (*Acer pseudoplatanus*), English oak (*Quercus robur*), and European beech (*Fagus sylvatica*). *Arboriculture and Urban Forestry* 34(2): 89-100.

Perez-Bidegain, M. 2007. *Modeling phosphorus transport using the WEPP model*. PhD. Dissertation, Iowa State University Ames, Iowa, U.S.A.

Pieri, L., Bittelli, M., Wu, J.Q., Dun, S., Flanagan, D.C., Pisa, P.R., Ventura, F. and Salvatorelli, F. 2007. Using the Water Erosion Prediction Project (WEPP) model to simulate field-observed runoff and erosion in the Apennines mountain range, Italy. *Journal of Hydrology* 336: 84-97.

PORIM. 1994. *Environmental impacts of oil palm plantations in Malaysia*. Palm Oil Research Institute of Malaysia.

Povilaitis, A., Robichaud, P., Dumbrauskas, A., Tumas, R. and Ruseckas, J. 1995. Erosion prediction in the republic of Lithuania with the WEPP model. In *Proc. Water Quality Modeling*, 333-340. Orlando, FL. St Joseph, MI: American Society of Agricultural Engineers.

Prasad, R. 2009. Efficient fertilizer use: The key to food security and better environment. *Journal of Tropical Agriculture* 47(1-2): 1-17.

Prasertsak, P., Freney, J.R., Saffiga, P.G., Denmead, O.T., and Prove, B.G. 2001. Fate of urea nitrogen applied to a banana crop in the wet tropics of Queensland. *Nutrient Cycling in Agroecosystems* 59: 65-73.

Prochnow, L. I. 2008. Optimizing nutrient use in low fertility soils of the tropics. *Better Crops* 92(3): 19- 21.

Pudasaini, M., Shrestha, S. and Riley, S. 2004. *Application of Water Erosion Prediction Project (WEPP) to estimate soil erosion from single storm rainfall events from construction sites*. Super Soil 2004: 3rd Australian New Zealand Soils Conference, 5-9 December 2004, University of Sydney, Australia. Published on CD-ROM. www.regional.org.au/au/asssi/.

Rahman, M.H., Das, B.K., Miah, M.A.J. and Ahmad, H. 2009. Fixation of urea to polyacylic acid and nitrogen release behavior of the product (Polyurea) – A comparison with urea and control (without Nitrogen Fertilizer). *Asian Journal of Crop Science* 1(1): 6-14.

Rankine, I.R. and Fairhurst, T.H. 1999. *Field handbook – Oil palm series*, Vol. 3, Mature. Potash and Phosphate Inst., Singapore, pp.8-11.

Rasouli, S., Whalen, J.K. and Madramootoo, C.A. 2014. Review: Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: Best management practices, policies and perspectives. *Canadian Journal of Soil Science* 94: 109-127

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. and Yoder D.C.. 1997. *Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. Agricultural Handbook No. 703. 384 p. U.S. Department of Agriculture, Washington D.C., USA.

Richards, R.P. 2002. The Lake Erie Agricultural Systems for Environmental Quality Project: An Introduction. *Journal of Environmental Quality* 31: 6-16.

Rietze, E. and Seidel, W. 1994. An adequate supply of coated slow-acting fertilizers reduces nitrate leaching. *Gartenbau Magazine* 3(7): 32-33.

Roberts, T.L. 2007. Right product, right rate, right time, and right place. The foundation of best management practices for fertilizer. In *Fertilizer Best Management Practices: General Principles, Strategy for Adoption and Voluntary Initiatives vs. Regulations* (A, Krauss, K, Isherwood, P, Heffer, Eds.). International Fertilizer Industry Association, Paris, France, pp. 29–32.

Roberts, T.L. 2010. *Nutrient Best Management Practices: Western Perspectives on Global Nutrient Stewardship*. Paper presented at the 19th World Congress of Soil Science: Soil Solutions for a Changing World, Brisbane. Australia 1-6 August 2010.

Roberts, T.L. 2009. The Role of Fertilizer in Growing the World's Food. *Better Crops* 93(2): 12-15.

Romero-Díaza, A., Marín-Sanleandro, P. and Ortiz-Sillab, R. 2012. Loss of soil fertility estimated from sediment trapped in check dams, South-eastern Spain. *Catena* 99: 42–53.

Römheld, V. and Kirkby, E.A. 2010. Research on potassium in agriculture: needs and prospects. *Plant Soil* 335: 155-180.

Rosliza, S., Ahmed, O.H and Majid, N.M. 2009. Controlling ammonia volatilization by mixing urea with humic acid, fulvic acid, triple superphosphate and muriate of potash. *American Journal of Environmental Sciences* 5 (5): 605-609.

Ryan, J., Sommer, R. and Ibrikci, H. 2012. Fertilizer best management practices: A perspective from the dryland West Asia–North Africa Region. *Journal of Agronomy & Crop Science* 198: 57-67.

Sabri, M.A. 2009. *Evolution of fertilizer use by crops in Malaysia: Recent trends and prospects*. Proceedings of the International Fertilizer Industry Association (IFA) Crossroads Asia-Pacific 2009 Conference, December 8-10, 2009, Kota Kinabalu, Malaysia, pp. 1-40.

Sartain, J.B., Hall, W.L., Littell, R.C. and Hopwood, E.W. 2004. New tools for the analysis and characterization of slow-release fertilizers. In *Environmental impact of fertilizer on soil and water*. Amer. Chem. Soc. Symo. Ser. 872. Washington. DC. pp. 180-195.

Sempeho, S.I., Kim, H.T., Mubofu, E. and Hilonga, A. 2014. Meticulous overview on the controlled-release fertilizers. *Advances in Chemistry* Volume 2014, Article ID 363071, 16 pages, doi:10.1155/2014/363071.

Shamshuddin, J. and Anda, M. 2012. Enhancing the productivity of Ultisols and Oxisols in Malaysia using basalt and/or compost. *Pedologist* 55(3): 382-391.

Shao, L., Zhang, M., Chen, X.S. and Wang, L.X. 2007. Effects of Controlled-release nitrogen fertilizer on yield and nitrogen content of soil and apple tree (Chinese). *Acta Horticulturae Sinica* 34(1): 43-46.

Shaviv, A. 2005. *Controlled Release Fertilizers*. IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt. International Fertilizer Industry Association Paris, France.

Shaviv, A. 2001. Advances in Controlled-release Fertilizers. *Advances in Agronomy*, 71: 1-49.

Shaviv, A. and Mikkelsen, R.L. 1993. Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation- A review. *Fertilizer Research* 35: 1-12.

Sheil, D., Casson, A., Meijaard, E., Van Noordwijk, M., Gaskell, J., Sunderland Groves, J., Wertz, K. & Kanninen, M. 2009. *The impacts and opportunities of oil palm in Southeast Asia. What do we know and what do we need to know?* Jakarta: CIFOR, VIII, 67 p. (CIFOR Occasional Paper, 51). Center for International Forestry Research (CIFOR), Bogor.

Shen, Z.Y., Gong, Y.W., Li, Y.H., Hong, Q., Xu, L and Liu, R.M. 2009. A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the three Gorges Reservoir Area. *Agricultural Water Management* 96: 1435-1442.

Shoji, S. 2005. Innovative use of controlled availability fertilizers with high performance for intensive agriculture and environmental conservation. *Science in China Series C*: *Life Sciences* 48: 912- 920.

Shoji, S., Delgado, J., Mosier, A. and Miura, Y. 2001.Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Communications in Soil Science and Plant Analysis* 32: 1051-1070.

Sierra, G. 1994. *Less nutrients and more growing power with Osmocote Plus*. Publisher: Grace Sierra International B.V., De Meern, The Netherlands.

Simonne, E.H. and Hutchinson, C. 2005. Controlled release fertilizers for vegetable production in the era of best management practices: teaching new tricks to an old dog. *HortTechnology* 15(1): 36-46.

Smil, V. 1999. Nitrogen in crop production: An account of global flows. *Global Biogeochemical Cycles* 13(2): 647-662.

Smith, K.A., Jackson, D.R. and Pepper, T.J. 2001. Nutrient losses by surface run-off following the application of organic manures to arable land: 1. Nitrogen. *Environmental Pollution* 112: 41-51.

Smith, R.E., Goodrich, D.C., Woolhiser, D.A. and Unkrich, C.L. 1995. KINEROS - A kinematic runoff and erosion model, Chapter 20. In *Computer Models of Watershed Hydrology* (V.P. Singh, Ed.), Water Resources Publications, Highlands Ranch, CO, pp. 697-732.

Stewart, W.M. and Roberts, T.L. 2012. Food security and the role of fertilizer in supporting it. *Procedia Engineering* 46: 76-82.

Sorte, B. 2011. *A Summary overview: Controlled-release fertilizer and Oregon's Agricultural Industry: Challenges and Potential. Oregon Agricultural Experiment Station*. Oregon State University, January 2011.

Tachibana, M. 2007. Chissoasahi Fertilizer Co., Ltd: Personal report.

Tajudeen, A. I., Azmi, Y., AbdulRashid, M. S. and Samsuzana, A. A. (2013). An RFID-based Variable Rate Technology Fertilizer Applicator for Tree Crops. *Journal of Applied Sciences* 13: 409-415.

Tan, K.H. 2005. *Soil Sampling, Preparation and Analysis (2nd Ed.).* Taylor and Francis/CRC Press, Boca Raton, FL.

Tarmizi, A.M. 2001. Nutritional requirements and efficiency of fertilizer use in Malaysian oil palm cultivation. In *Advances in Oil palm Research* (Y, Basiron, Jalani, B.S. and K.W. Chan, Eds.). Vol. 1. Malaysian Palm Oil Board, Ministry of Primary Industries, Malaysia, ISBN-13: 9789679610819, pp: 411-440.

Tegedera, M. and Rentsch, D. 2010. Uptake and partitioning of amino acids and peptides. Molecular *Plant* 3(6): 997-1011.

Teh, C.B.S. and Talib, J. 2006. *Soil Physics Analyses.* Volume 1. Serdang: Universiti Putra Malaysia Press. pp.11-24.

Teoh, K.C. and Chew, P.S. 1988. Use of rachis analysis as an indicator of K nutrient status in oil palm. In: *International Oil Palm/Palm Oil Conferences: Progress and Prospects* (H.A.H, Hj Hassan, P.S, Chew, B.J, Wood and E.Pushparajah, eds.). Conference 1: Agriculture. Kuala Lumpur, 23-26 `June 1987. PORIM, ISP, pp. 262-271.

Thomas, G.W. 1982. Exchangeable Cations. In Page, A.L., Miller, R.H. and Keeny, D.R: Methods of Soil Analyses. American Society of Agronomy, Madison, WI 159-165.

Thomas, P. 1987. Nitrogen losses from urea - techniques and means for their control. pp. 321-328.

Tinker, P.B. and Nye, P.H. 2000. Solute movement in the rhizosphere. Oxford University Press, Oxford, United Kingdom: pp. 444.

Tiwari, A.K., Risse, L.M. and Nearing. M.A. 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. *Transactions of the ASAE* 43(5): 1129-1135.

Torres-Netto.A., Campostrini, E., Oliveira, J.G. and Smith, R.E.B. 2005. Photosynthetic pigments, nitrogen, chlorophyll a fluorescence and SPAD-502 readings in coffee leaves. *Scientia Horticulturae* 104(2): 199-209.

Tossell, R.W., Dickinson, W.T., Rudra, R.P. and Wall, G.J. 1987. A portable rainfall simulator. *Canadian Agricultural Engineering* 29(2) 155-162.

Toy, T.J., Foster, G.R. and Renard, K.G. 2002. *Soil erosion: processes, prediction, measurement and control*. Wiley, New York.

Trenkel, M.E. 2010. *Slow- and controlled-release and stabilized fertilizers: an option for enhancing nutrient use efficiency in agriculture* (2nd ed.) International Fertilizer Industry Association (IFA) Paris, France, October 2010.

Trenkel, M.E. 1997. *Improving fertilizer use efficiency. Controlled-release and stabilized fertilizers*. International Fertilizer Industry Association, Paris.

Truman, C.C., Strickland, T.C., Potter, T.L., Franklin, D.H., Bosch, D.D. and Bednarz, C.W. 2007. Variable rainfall intensity and tillage effects on runoff, sediment, and carbon losses from a loamy sand under simulated rainfall. *Journal of Environmental Quality* 36(5): 1495-1502.

USDA 2012. Malaysia: stagnating palm oil yields impede growth. Commodity Intelligence.Report.http://www.pecad.fas.usda.gov/highlights/2012/12/Malaysia/. Retrieved 20 December 2012.

USDA-FAS, 2013. *Oilseeds World Markets and Trade*. Circular Series. US Department of Agriculture –Foreign Agricultural Service, Washington, DC.

Valavan, P.S. and Kumaresan, K.R. 2006. Relative efficiency of controlled release and water soluble fertilizers on the yield and quality of Chilli (*Capsicum annuum* Linn.). *International Journal of Soil Science* 1: 264-268.

von Uexküll, H.R. and Fairhurst, T.H. 1991. *Fertilizing for High Yield and Quality*. The Oil Palm. IPI, Bern, pp. 79.

Wachal, D.J., Harmel, R.D., Banks, K.E. and Hudak, P.F. 2008. Evaluation of WEPP for runoff and sediment yield prediction on natural gas well sites. American Society of *Agricultural and Biological Engineers* 51(6): 1977-1986.

Wallace, C.B,. Burton, M.G., Hefner, S.G. and DeWitt, T.A. 2013. Effect of preceding rainfall on sediment, nutrients, and bacteria in runoff from biosolids and mineral fertilizer applied to a hayfield in a mountainous region. *Agricultural Water Management* 130: 113-118.

Wen, G., Mori, T., Yamamoto, T., Chikushi, J. and Inoue, M. 2001. Nitrogen recovery of coated fertilizers and influence on peanut seed quality for peanuts grown on sandy soil. *Communication in Soil Science and Plant Analysis* 32: 3121-3140.

Williams, J.R., Jones, C.A. and Dyke. P.T. 1984. A modeling approach to determining the relationship between erosion and soil productivity. *Transactions of the ASAE* 27(1): 129-144.

Wischmeier, W.H. and D.D. Smith. 1978. *Predicting rainfall erosion losses - A guide to conservation planning*. USDA Agricultural Handbook No. 537.

Wood, S., K. Sebastian and S. J. Scherr. 2000. *Pilot analysis of global ecosystem: agroecosystems*. International food policy research institute and world resource institute, USA.

Woolhiser, D.A., Smith, R.E. and Goodrich, D.C. 1990. *KINEROS, A Kinematic Runoff and Erosion Model: Documentation and User Manual*. U.S Department of Agriculture, Agricultural Research Service, ARS-77, pp. 130.

World Bank. 2010. *World Development Report 2010: Development and Climate Change*. Washington DC.

Yan, X., Jin, J. yun, He, P. and Liang, M. 2008. Recent advances on the technologies to increase fertilizer use efficiency. *Agricultural Sciences in China* 7(4): 469-479.

Yang, W.Y., He, M.R., Wang, Y.J., Wang, X.Y., Zhang, B. and Wu, C.P. 2005. Effect of controlled-release urea combined application with urea on nitrogen utilization efficiency of winter wheat. *Plant Nutrition and Fertilizer Science* 11(5): 627-633.

Zekri, M. and Koo, R.C.J. 1991. Evaluation of controlled-release fertilizers for young citrus trees. *Journal of the American Society for Horticultural Science* 116(6): 987-990.

Zema, D.A., Bombino, G., Denisi, P., Licciardello, F. and Zimbone, S.M. 2012. Prediction of surface runoff and soil erosion at watershed scale: analysis of the AnnAGNPS Model in different environmental conditions. Doi: 10.5772/50427.

Zemenchik, R A. 2002. Bio-available phosphorus in runoff from alfalfa, smooth bromegrass, and alfalfa-smooth bromegrass. *Journal of Environmental Quality* 31: 280-286.

Zhang, X.C., Nearing, M.A., Risse, L.M. amd McGregor, K.C. 1996. Evaluation of runoff and soil loss predictions using natural runoff plot data. *Transactions of the ASAE* 39: 855-863.

Zheng, F.L., He, X.B., Gao, X.T., Zhang, C.E. and Tang, K.L. 2005. Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. *Agriculture, Ecosystems & Environment* 108: 85-97.

Ziadat, F.M. and Taimeh, A.Y. 2013. Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment. *Land Degradation and Development* 24: 582-590.

Zvomuya, F., Rosen, C.J., Russelle, M.P., Gupta, S.C. 2003. Nitrate leaching and nitrogen recovery following application of polyolefin coated urea to potato. *Journal of Environmental Quality* 32: 480-489.