Landscape-scale assessment of soil properties, water quality and related nutrient fluxes under oil palm cultivation: A study case in Sumatra, Indonesia

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Landscape-scale assessment of soil properties, water quality and related nutrient fluxes under oil palm cultivation: a case study in Sumatra, Indonesia

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April, 2013

A thesis submitted to McGill University
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Abstract

The rapid expansion of oil palm cultivation in Southeast Asia raises environmental concerns, necessitating a critical evaluation of the impacts of this production system on ecological health. Oil palm growers in Indonesia are faced with the challenge of sustaining high yields to keep pace with the growing global demand for oil and fats, while reducing the environmental impacts of oil palm cultivation. Environmental impacts associated with the deforestation at the initial phase of an oil palm plantation establishment are well documented, however the impacts of mature oil palm plantation on water quality remain poorly investigated. Oil palm is a perennial crop (25-30 years) cultivated predominantly on weathered tropical soils, so high fertilizer input is necessary to sustain high yields, which is expected to endanger neighboring aquatic ecosystems when excess nutrients are carried out to waterways. In Indonesia, 39 % of oil palm planted area is owned by smallholder farmers, who rely on mineral fertilizers to support oil palm production, and 52 % are large private plantations operated by private industries. In addition to mineral fertilizers, industrial plantations also apply mill byproducts as organic fertilizers in the plots surroundings the mill (due to transportation costs). Soil characteristics and fertilizer management in oil palm plantations (i.e. mineral vs. organic fertilizer applications) were expected to alter the soil fertility status and nutrient loads to waterways. Due to the fact that oil palm plantations generally extend over thousands of contiguous hectares, crossing several watersheds and covering different soil types, the effect of fertilizer management on the soil response and nutrient loads to waterways requires landscape-scale studies accounting for soil variability and long-term fertilization sequences across the plantation. The first objective of the thesis was to (i) perform a literature review that provides an overview of the agricultural practices in oil palm plantations as well as hydrological processes involved in the nutrient transfers from those agroecosystems to waterways. Then I aimed to (ii) assess the effect of long term mineral and organic fertilizer sequences on the soil response, considering different soil types, (iii) characterize the dominant hydrological processes involved in the nutrient fluxes to waterways in oil palm plantations, and

(iv) assess the effect of fertilizer management and soil characteristics on groundwater quality and nutrient fluxes to streams. The study area was located in the Petapahan area, Central Sumatra, Indonesia, which has a tropical humid climate (annual rainfall > 2000 mm) and weathered soils (Ferralsols). The study area was a landscape (100 km^2) including a 4000 ha industrial plantation and a 1500 ha smallholder plantation using rational fertilizer programs. Low-fertility Ferralsols responded significantly to continuous applications of organic fertilizers, with greater improvement in loamy-sand uplands than in loamy-lowlands, compared to repeated applications of mineral fertilizers. I proposed that spatial fertilizer management at the landscape-scale should complement the current plot-scale fertilizer management to get higher nutrient use efficiency and improve soil fertility in an oil palm plantation. One year (2009-2010) multi-site monitoring of stream water quality showed nutrient concentrations below Indonesian standards for water quality. In this case study, mature oil palm cultivation did not contribute to the eutrophication of aquatic ecosystems. This was ascribed to nutrient dilution in streams from the high rainfall as well as high nutrient demand by oil palm that was met with a rational fertilizer program. Assessment of nutrient fluxes from baseflow showed that loamy-sand uplands were more sensitive to nutrient losses than loamy lowlands, and organic fertilization helped to reduce nutrient losses to streams. The study also showed high dissolved organic matter content in streams, likely from natural sources. Oil palm agroecosystems in the study area are characterized by fast groundwater renewal indicating the potential for inputs to be quickly transported from soils to the streams. This may be of concern when unbalanced fertilizer management leads to over-application of nutrients or persistent agrochemicals like pesticides bind to dissolved organic matter, since they will be susceptible to contribute to nonpoint source pollution in streams.

Résumé

La rapide expansion de la culture du palmier à huile en Asie du Sud-Est soulève maintes interrogations sur ses impacts environnementaux. Les planteurs indonésiens doivent désormais assurer de hauts rendements pour répondre à une demande mondiale croissante d'huile de palme, tout en minimisant leurs impacts. Les impacts environnementaux associés à la déforestation lors de la phase initiale d'établissement d'une plantation sont déjà bien documentés. En revanche, les impacts d'une plantation mature sur la qualité de l'eau a été très peu étudiée. Le palmier à huile est une culture pérenne (25-30 ans) généralement cultivée sur des sols tropicaux peu fertiles d'où la nécessité de forts apports de fertilisants, apports susceptibles de menacer les écosystèmes aquatiques quand les nutriments en excès sont transportés vers les rivières. En Indonésie, les petits planteurs villageois détiennent 39 % des surfaces plantées en palmier à huile et n'utilisent que des fertilisants minéraux pour assurer leur production. Les industriels privés possèdent 52 % des surfaces, et appliquent, en plus des fertilisants minéraux, des fertilisants organiques issus des rejets de leurs usines. Ces fertilisants organiques sont généralement appliqués dans les parcelles à proximité de l'usine pour réduire les coûts de transport. Les caractéristiques du sol et la gestion de la fertilisation (i.e. fertilisants minéraux vs. organiques) des palmeraies sont susceptibles d'influer sur la fertilité du sol et sur les transferts de nutriments vers les rivières. Etant donné que les plantations s'étendent généralement sur plusieurs milliers d'hectares d'un seul tenant, couvrant plusieurs bassins versants et différents types de sol, l'effet de la gestion de la fertilisation sur la réponse du sol et les transferts de nutriments vers les rivières nécessite des études à l'échelle du paysage. Celles-ci doivent tenir compte tant de la variabilité du sol au sein de la plantation que de la variabilité des séquences de fertilisation pluriannuelles. Le premier objectif de cette étude est (i) de réaliser une revue de littérature sur les pratiques agricoles utilisées dans les palmeraies ainsi que sur les processus hydrologiques impliqués dans les transferts de nutriments dans ce type de contexte, (ii) d'évaluer l'effet de séquences pluriannuelles de fertilisation minérale et organique sur la réponse du sol, tenant compte de la variabilité des sols au sein de la plantation, (iii) de

caractériser et quantifier les processus hydrologiques dominants impliqués dans le transfert de nutriments depuis la palmeraie vers les rivières, (iv) et enfin d'évaluer l'effet de la gestion de la fertilisation et des caractéristiques du sol sur la qualité des eaux souterraines et sur les flux de nutriments vers les rivières. La zone d'étude est située dans la région de Petapahan, dans le centre de Sumatra, en Indonésie. Le climat y est tropical humide (précipitations annuelles > 2000 mm) et les sols peu fertiles (Ferralsols). Il s'agit d'un paysage de 100 km² incluant une plantation villageoise de 1500 ha et une plantation industrielle de 4 000 ha, pratiquant une gestion raisonnée de la fertilisation. Cette étude a montré une amélioration significative des propriétés chimiques des sols suite à des applications continues de fertilisants organiques, avec une amélioration encore plus sensible sur les sols sablo-limoneux que sur les sols limoneux. Une gestion spatiale de la fertilisation à l'échelle de la plantation serait plus efficace et devrait compléter la gestion à la parcelle pour une meilleure stratégie d'application des fertilisants adaptée à la variabilité des sols sur les milliers d'hectares de la plantation. Le suivi multi-site sur un an de la qualité des eaux de surface dans le paysage a montré des niveaux de concentrations de nutriments en deçà des limites maximales recommandées par les standards indonésiens. Dans cette étude de cas, la culture d'une palmeraie mature ne semble pas avoir contribué à l'eutrophisation des cours d'eaux. Les raisons en seraient la dilution du système par la forte pluviosité locale, et la pratique d'une fertilisation raisonnée. L'évaluation des flux de nutriments a montré que les sols sablo-limoneux étaient plus sensibles que les sols limoneux aux pertes de nutriments et que la fertilisation organique pouvait réduire significativement ces pertes. De fortes teneur en matières organiques ont été observées dans les rivières, mais probablement dues à des causes naturelles. Le renouvellement rapide des eaux souterraines induit une grande réactivité du système aux intrants qui peuvent être rapidement drainés vers les cours d'eau. Des apports massifs de nutriments (fertilisation non raisonnée) ou des pesticides liés à la matière organique dissoute pourraient donc entraîner un risque de pollution en aval de l'agrosystème.

Preface and contribution of authors

This thesis is composed of three chapters, preceded by a general introduction. The first chapter is a literature review that summarizes the body of knowledge surrounding this thesis and outlines the objectives of this research project. Connecting paragraphs between these chapters show the progression from one manuscript to the next. Finally, the general conclusions and contributions to knowledge highlight the key findings of this thesis and suggest areas for further research.

All manuscripts are co-authored by the candidate, François Colin, Olivier Grünberger, Joann Whalen and Jean-Pierre Caliman. François Colin, Olivier Grünberger and Joann Whalen provided guidance and editorial assistance with the manuscripts. Jean-Pierre Caliman (from SMARTRI) provided technical and financial support in field work, data collection and laboratory analysis. Financial support was also provided by the CIRAD and the NSERC. Chapter 2 is modified from the original manuscript that was also co-authored by Stéphane Follain due to his implication in data analysis and editorial assistance and. The candidate was fully responsible for designing and conducting the field work, analyzing the data and writing the manuscripts. The manuscripts that compose the body of this thesis are in the following order:

Chapter 1. Comte, I., Colin,F., Whalen, J.K., Grünberger, O., 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, vol. 116, pp 71-124. DOI: 10.1016/B978-0-12-394277-7.00003-8

Chapter 2. Comte, I., Colin, F., Grünberger, O., Follain, S., Whalen, J.K., Caliman, J.-P. Landscape-scale assessment of soil response to long-term organic and mineral fertilization in an industrial oil palm plantation, Indonesia (Agriculture, Ecosystems & Environment, vol. 169, pp.58-68. DOI: http://dx.doi.org/10.1016/j.agee.2013.02.010).

Chapter 3. Comte, I., Colin, F., Grünberger, O., Whalen, J.K., Caliman, J.-P., Widoyo R. Multi-site assessment of water quality in oil palm agroecosystems and influence of soil types and fertilizer management on nutrient fluxes to streams.

Contributions to Knowledge

The research conducted in this thesis provides the following important contributions to knowledge:

- The literature review provides an overview of current agricultural practices in oil palm plantations and compiles information regarding the complete hydrological cycle in oil palm plantations and the implications for nutrient export to water bodies, pointing out the research gaps regarding the assessment of nutrient transfer from mature oil palm agroecosystems to waterways at the watershed-scale.
- Chapter 2 is the first study to assess the soil response to long term organic and mineral fertilizer applications, at the landscape-scale within a 4000 ha industrial mature oil palm plantation (>15 yr old). An original landscape-scale approach was built to cope with unavailable historical soil data, variability in fertilization sequences and diverse soil classes across the plantation, an approach that can be transferred to understand soil-fertilizer interactions in other large-scale perennial cropping systems.
    - Results indicate that low-fertility Ferralsols responded significantly to continuous organic fertilization, with greater improvement on the loamy-sand uplands than loamy lowlands. Regular organic fertilizer applications to loamy-sand uplands are recommended to sustain soil fertility.
    - The study opened the way to the idea that a higher level of spatial consideration, both towards smaller scale (intra block scale) but also landscape scale, should be considered by agronomists, as well a higher integration of organic and mineral fertilizers, to improve a the quality of nutrition management, and minimizing any risk on the environment.
- Chapter 3 is a ground-breaking study that provides us information with first report about the state of water quality in streams running through oil palm agroecosystems. It is the first large-scale hydrological study carried out across several watersheds in industrial and smallholder oil palm agroecosystems that include various soil types and fertilizer management.

- The study proposes a survey approach to assess annual nutrient exports to streams based on multi-site monitoring (16 watersheds) and methods of reconstituting daily hydrochemical time series from bi-monthly monitoring.
- Results indicate that the hydrological behavior occurring in the study area is dominated by stream flow (annual ratio stream flow / rainfall = 60 %) and that stream flow is mainly fed by baseflow from shallow groundwater. Observations suggested a high renewal rate of the groundwater leading to short residence time.
- Stream water was generally acidic with low nutrient concentrations that did not exceed Indonesian water quality standards. High organic matter content was measured, likely from natural sources (peatsoil patches across the landscape).
- The study showed that soil types played a major factor in nutrient transfers to waterways, with loamy-sand uplands being more sensitive to nutrient losses than loamy soils. The soil effect was tempered by the fertilizer management. It was demonstrated that organic fertilizers applications helped to reduce nutrient losses, especially DIN and TP, to waterways.
- I concluded that mature oil palm agroecosystems do not pose eutrophication risks in streams even on fast-draining soils, (i) when managed suitably through a rational fertilizer program, (ii) and in humid climatic conditions that dilute nutrient concentrations in water outflows.
- As the mill location is the main factor in the long term strategy for applying organic fertilizers (due to transportation costs), managers should also consider whether local soils are more sensitive to nutrient losses and benefit more from repeated organic fertilizers applications to improve soil fertility when they choose a location for the mill, during the establishment phase of the plantation.

Acknowledgments

I sincerely thank my supervisor, Joann Whalen, for providing sound advice and constant encouragement. I have greatly appreciated her timely comments and incredible rapidity in relying, which made us overcome the geographical distance.

I am grateful to my co-supervisor, François Colin, for providing excellent guidance, generous support and trust since the beginning of this work. I appreciated his “positive attitude”, especially in most difficult times.

I thank Olivier Grünberger for his kind support throughout the duration of this work. He has always been patiently available to help, despite his many responsibilities.

I’d like to express my thanks for my collaborators Jean-Pierre Caliman for providing agronomic advice and effective field support, and Stéphane Follain for editorial assistance. I do not forget Jacques Ranger, Patrick Giraudoux and Laurent Gazull. I thank also Laurent Prévot for his helpful skills using “R” and François Garnier for teaching me how to use a currentmeter!

I thank the CIRAD, the NSERC and SMARTRI for financial support. Especially, I thank Robert Habib, Marcel de Raissac, Jean-Luc Battini and Eric Gohet for providing me the means to achieve this work. And I am grateful to the LISAH (Marc Voltz and Jérôme Molénat) for receiving me in Montpellier, France.

I would also like to thank Pak Abdullah, Pak Prapto, Pak Rio for field work assistance. Very special thanks to Pak Rudy for his skills, professional care and patience towards the many favors I’ve asked to him. This work would have been impossible to achieve without him. Impossible also without Pak Cipto and especially Pak Adi and Heri for their great job in the field. I greatly appreciated their good mood, their patience towards my Indonesian and their professional care in sampling soil and water. I do not forget the laboratory staff, the drivers and all others at SMARTRI who have all contributed to carry out this work.

Julie Wohlfahrt, Julie Andru, Nafi Diop, Amélie Février, thank you for your pleasant company in Indonesia. Special thanks to Crystèle Leauthaud, Lai Ting Pak, Jésus Fernandez, Armand Crabit, and all others at LISAH for all the good times. Sylvain, thank you for your good vibes!

I deeply thank my Love for his valued presence and unwavering support. I’d like to express my heartfelt thanks to my family, my brother Elric, my sister Lauranne and my beloved parents who have supported and believed in me throughout my studies.

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List of Abbreviations

Abbreviation	Significance
Al	Aluminum
AMSL	Above mean sea level
AS	Ammonium sulfate
B	Bore
BMP	Best management practice
BOD	Biological Oxygen demand
BS	Base saturation
C	Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
CF	Clayey floodplain soil class
cm	Centimeter
COD	Chemical Oxygen demand
CPO	Crude oil palm
Cz	Contributive zone
DAP	Diammonium phosphate
DIN	Dissolved inorganic Nitrogen
EC	Electrical conductivity
EFB	Empty fruit bunch
ET	Evapotranspiration
FAO	Food and agriculture organization
Fe	Iron
FFB	Fresh fruit bunch
FSV	Fertilizer sequence value
GHG	Greenhouse gaz
h	Hour
H	Hydrogen
ha	Hectare
HGFB	High-grade fertilizer borate
Ind	Industrial oil palm plantation
IPM	Integrated pest management
K	Potassium
kg	Kilogram
KMgCa	Sum of Potassium, Magnesium and Calcium
L	Liter
LCC	Leguminous cover crop
LL	Loamy lowland soil class
LSU	Loamy-and upland soil class

LU	Land use
m	Meter
Mg	Magnesium
mg	Milligram
Min	Mineral fertilizer application
mm	Millimeter
MOP	Muriate of potash
N	Nitrogen
n	Number of observations
Na	Sodium
NGO	Non governmental organization
NH4	Ammonium
NO2	Nitrite
NO3	Nitrate
OC	Organic Carbon
Org	Organic fertilizer application
P	Phosphorous
p	Probability
Pl	Plasma oil palm plantation
PNG	Papua New Guinea
POME	Palm oil mill effluent
Q	Discharge
R	Rainfall
Rh	Hydraulic radius
RP	Rock phosphate
RSPO	Roundtable on sustainable palm oil
S(t)	Storage
Sh	Independent smallholder oil palm plantation
SRTM	Shuttle radar topography mission
TA	Total Alkalinity
TDS	Total dissolved solids
TN	Total Nitrogen
TOC	Total organic Carbon
TP	Total Phosphorus
TSP	Triple superphosphate
UTM	Universal Transverse Mercator
WGS	World Geodetic System
WY	Water yield
yr	Year
α	Drainage coefficient
µS	Microsiemens

General introduction

Oil palm (*Elaeis guineensis*) is one of the most rapidly expanding crops in the tropics, especially in Indonesia, which is now the top producer in the world with about 7.5 million ha cultivated for oil palm. Smallholders grow oil palm on almost 3 million ha, which represents 39 % of Indonesian oil palm plantations, the remaining 4.5 million ha being on larger private (53 %) and government-owned (8 %) plantations (IMA, 2010). Consequently, oil palm cultivation provides food and employment for several million people and contributes to the development of poor countries like Indonesia. Continued expansion of the oil palm crop is forecasted due to growing global demand for palm oil as a source of fats and oil for human consumption, nonedible products, and biofuel (Bangun, 2006; Tan et al., 2009). However, there is concern from socio-environmental non-governmental organizations (NGOs) about the environmental impacts resulting from the rapidly expanding oil palm sector, which were widely covered by the media. Thus, the Roundtable on Sustainable Palm Oil (RSPO), an international organization of producers, distributors and socio-environmental NGOs was created to promote sustainable palm oil production. The RSPO recommends that growers undertake a full assessment of the environmental impact of oil palm cultivation and encourages them to follow best management practices (BMP) (Lord and Clay, 2006). To date, most of the attention and research related to the environmental impact of oil palm cultivation has focused on deforestation and its consequences (loss of biodiversity, GHG emissions, etc.) during the initial phase of oil palm plantation establishment. Much less attention has been paid to the environmental impacts of established oil palm plantations, particularly the risk of water pollution.

Oil palm is cultivated predominantly on weathered tropical soils, which are generally highly acidic with low buffering capacities (Harter, 2007). Due to the low inherent fertility of these soils and the high nutrient removal in tree products, high fertilizer input is necessary to sustain high yields and typically constitutes 40-65% of total field upkeep costs (Ng, 2002; Caliman et al., 2001). However, mineral fertilizers applications can contribute to soil acidification, which causes a further decline in pH and reduces the buffering capacity of these low-fertility tropical soils (Barak et al., 1997; Nelson et al., 2010; Oim and Dynoodt, 2008). High fertilizer applications on low-buffered soils may also result in substantial nutrient loading in water bodies and contribute to eutrophication of aquatic ecosystems (Turner and Rabalais, 1994). Among the BMP proposed by RSPO was the use of palm oil mill byproducts such as empty fruit bunches (EFB) and palm oil mill effluent (POME) as a substitute for mineral fertilizers. Research underway since the 1980s demonstrated that EFB and POME improve soil fertility significantly at the plot-scale; however the risk of nutrient losses from these fertilizers to water bodies remains under-investigated. Given the number of factors involved in assessing how oil palm cultivation could impact nutrient transfers to waterways, a review of peer-reviewed literature was required to provide an overview of fertilizer use and other agronomic practices in oil palm agroecosystems, as well as the hydrological processes that may be altered and therefore affect nutrient export from these agroecosystems to waterways.

Commercial oil palm plantations in Southeast Asia commonly extend over thousands contiguous hectares with distinct topographical positions and soil classes. Many studies reported differences in soil response to fertilizer applications related to their inherent physico-chemical characteristics (Heriansyah). For example, Loong et al., (1987) reported higher yields of fresh fruit bunches (FFB) in Inland (Rengam series) than in Coastal (Briah series) soils in oil palm plantations with EFB mulching. A number of studies demonstrated that the soil texture influences the organic matter dynamics (Bosatta and Ǻgren, 1997; Krull et al., 2001). Also, nutrient inputs are expected to vary according to the growth stage of an oil palm tree, with higher oil palm nutrient requirement during the mature stage (FAO, 2005). Thus, perennial crops like oil palm that are productive for 25 to 30 years and grown throughout the landscape in large-scale agroecosystems require both spatial and long term fertilization management across the plantation that accounts for soil variability to optimize yields. Since organic fertilizers are in limited supply and costly to handle and apply, relative to mineral fertilizers, producers need to know where to deploy organic fertilizers and how frequently to improve soil fertility. Thus, a landscape-scale assessment of the soil response to fertilization in an oil palm plantation is a crucial first step to understand the nutrient use efficiency throughout the plantation and assess the potential for excess nutrients to be exported to water bodies. Within a commercial plantation, fertilizer management is carried out at the plot-scale, resulting in a high variability in long term fertilizers application sequences across the plantation landscape, with some fields receiving mineral fertilizers only, organic fertilizers only or a mixed sequence of both fertilizer types. However, both long-term and landscape-scale field studies assessing the soil response to fertilization in oil palm plantations are scarce. Most of these studies were carried out at the plot-scale (10-30 hectares) as agronomic trials comparing applications of mineral fertilizer only to organic fertilizer only over relatively short (3-5 yr) study periods (Cristancho et al., 2011; Dolmat et al., 1987; Kheong et al., 2010), and were performed on a single soil class rather at larger spatial scales and across multiple soil classes, which is more representative of the conditions in industrial plantations (Abu Bakar et al., 2011; Budianta et al., 2010; Loong et al., 1987).

In the same way, assessing the risk of nutrient export from oil palm plantations to waterways requires the assessment of hydrochemical dynamics at the watershed-scale, accounting for variation in fertilizer applications and soil properties across the plantation. However, hydrochemical dynamics and nutrient outflows from oil palm plantation are far from being fully assessed and understood. Few studies have evaluated how fertilizer use in oil palm agroecosystems impact nutrient loading and water quality in nearby waterways (Ah Tung et al., 2009). Most hydrological studies in oil palm plantations were carried out at the plot scale (i.e., a few hectares), although a watershed-scale study by Yusop et al. (2008) quantified runoff processes on a small watershed of 8.2 ha, and a study by DID (1989) assessed nutrient exports at the watershed-scale after forest clearing and during the first year of oil palm cultivation. It is difficult to extrapolate from these studies to large scale mature oil palm plantations, accounting for spatial variability of soil properties and fertilizer use (e.g., organic vs. mineral fertilizers, which vary in space and time). I am not aware of studies that provided an integrated view of hydrological processes or have taken account of the intrinsic spatial variability of an oil palm plantation in relation to water quality in streams and groundwater. Consequently, the link between agricultural practices and water quality, especially nutrient loading, from oil palm plantations remains tenuous.

This study is part of the general research effort to sustain high oil palm yields while mitigating environmental impacts of oil palm cultivation on aquatic ecosystems. The objectives of this thesis were : (i) to review the fertilizer use and agronomic management of oil palm plantations in Southeast Asia and the hydrological processes leading to nutrient export to waterways; (ii) to assess the soil response to long term fertilization sequences (mineral vs organic fertilizer applications) in a 4000 ha mature (> 15 year old) industrial oil palm plantation, and (iii) to characterize the hydrological processes and (iv) assess nutrient fluxes and relate these to stream water quality in a landscape including mature (> 15 year old) industrial and smallholder oil palm plantations using balanced fertilizer program. This research effort involved the design of a spatially-explicit measurement protocol to sample soil, stream water and groundwater and the development of analytical methods to cope with highly heterogeneous data.

CHAPTER 1. Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review

1.1 Abstract

Rapid expansion of oil palm (*Elaeis guineensis* Jacq.) cultivation in Southeast Asia raises environmental concerns about deforestation and greenhouse gas emissions. However, less attention was paid to the possible perturbation of hydrological functions and water quality degradation. This work aimed to review : i) the agricultural practices commonly used in oil palm plantations, which potentially impact hydrological processes and water quality, and ii) the hydrological changes and associated nutrient fluxes from plantations. Although many experimental trials provide clear recommendations for water and fertilizer management, we found that few studies investigated the agricultural practices actually followed by planters. Our review of hydrological studies in oil palm plantations showed that the main hydrological changes occurred during the first years after land clearing and seemed to dissipate with plant growth, as low nutrient losses were generally reported from plantations. However, most of those studies were carried out at the plot scale and often focus on one hydrological process at a single plantation age. So, there is insufficient information to evaluate the spatio-temporal fluctuations in nutrient losses throughout the entire lifespan of a plantation. Furthermore, few studies provided an integrated view at the watershed-scale of the agricultural practices and hydrological processes that contribute to nutrient losses from oil palm plantations and the consequences for surface and ground water quality. Future research efforts need to understand and assess the potential of oil palm plantations to change hydrological functions and related nutrient fluxes, considering agricultural practices and assessing water quality at the watershed-scale.

1.2. Introduction

Oil palm (*Elaeis guineensis*) is one of the most rapidly expanding crops in the tropics. Since the early 1980s, the global land area under oil palm production has more than tripled, reaching almost 15 million hectares in 2009 and accounting for almost 10 % of the world's permanent crop land (FAOSTAT, 2011 ; Sheil et al., 2009) Most of this increase has taken place in Southeast Asia. Together, Malaysia and Indonesia account for almost 85 % of the 46.5 million tonnes of crude oil palm produced in the world, Indonesia being the top producer since 2007 (Oil World, 2011; USDA, 2007). The area covered by smallholder plantations in Indonesia increased nearly 1000-fold between 1979 and 2008, reaching almost 3 million ha, i.e. 39 % of current total Indonesian oil palm plantations, the remaining 4.5 million ha being large private (53 %) and government owned (8 %) plantations (IMA, 2010).

Although oil palm cultivation is a strong driver of economic development in Indonesia, providing jobs and incomes to millions of people (USDA, 2007), it is strongly denigrated for its environmental impacts. Many media and NGOs accuse oil palm plantation development in Southeast Asia of triggering deforestation, loss of biodiversity, peatland degradation and high greenhouse gas (GHG) emissions (Greenpeace, 2011; WWF, 2011). In the scientific community, there is controversy about the positive and negative aspects of the expanding oil palm cultivation and potential environmental risks, which has been discussed at length in the scientific literature (Basiron, 2007; Lamade and Bouillet, 2005; Nantha and Tisdell, 2009; Sheil et al., 2009). The development of oil palm plantations, which frequently cover tens of km^2 in Southeast Asia, involves land clearing, roads and drainage network construction, and sometimes earthworks such as terracing on undulating areas. The use of agro-chemicals, such as fertilizers and pesticides might represent a potential risk for the sustainability of aquatic ecosystem and hydrological functions, when agricultural practices are not optimized. In particular, oil palm growers usually apply large amounts of commercial fertilizer, and thus are among the largest consumers of mineral fertilizers in Southeast Asia (Härdter and Fairhurst, 2003). However, hydrological processes within oil palm plantations are still not fully understood and few studies have examined the impacts of agricultural practices on terrestrial hydrological functions and water quality in nearby aquatic ecosystems (Ah Tung et al., 2009), although "*aspects that impact on water quality are by far the largest component of an environmental risk register accounting for nearly 50 % of all entries in oil palm plantations" (*Lord and Clay, 2006).

This review aims to document the current state-of-knowledge of agricultural practices in oil palm plantations that potentially impact hydrological functions and water quality in surface waters, with a focus on nutrient loading of surface waterways, and to highlight research gaps in the understanding of these processes. This work focuses on the situation in Indonesia, with examples from other oil palm producing countries in the humid tropics as appropriate**.** First, the expansion of oil palm cultivation in Indonesia, relevant environmental issues and polemics will be presented. Next, typical agricultural practices in industrial and smallholder oil palm plantations will be discussed, focusing on nutrient, soil and water management. Finally, the last section gives the state-of-the-art knowledge of hydrological changes and associated nutrient fluxes from oil palm plantations compared to tropical rainforests, which were the dominant natural ecosystem prior to oil palm plantation establishment. Relevant processes in the hydrological cycle, their magnitude and relevance in oil palm plantations will be explained in this section, but we do not provide an in-depth discussion of hydrological processes in rainforests, as a number of reviews were already published on this topic (Bruijnzeel, 1991; Bruijnzeel, 2004; Elsenbeer, 2001).

1.3. Expansion of oil palm cultivation in Indonesia and environmental stakes

1.3.1. Expansion of oil palm cultivation

1.3.1.1. Palm oil utilization

Palm oil is derived from the plant's fruit, which produces two types of oils: crude palm oil (CPO), which comes from the mesocarp of the fruit, and palm kernel oil, which comes from the seed in the fruit. Most CPO is used for food products, while most palm-kernel oil is used in non-edible products such as detergents, cosmetics, plastics, as well as a broad range of other industrial and agricultural chemicals (Wahid et al., 2005). The oil palm is the highest productive oil crops in terms of oil yield per hectare and resource use efficiency due to its high efficiency at transforming solar energy into vegetable oil. The average yield of palm oil is approximately 4.2 t ha^{-1} yr^{-1}, with yields exceeding 6.0 t ha^{-1} yr^{-1} in the best managed plantations, greatly exceeding vegetable oils such as rapeseed and soybean that produce only 1.2 and 0.4 t ha^{-1} yr^{-1}, respectively (Fairhurst and Mutert, 1999). In addition, little fossil fuel energy is used, as most of the energy required by the oil palms mill for processing of the fruits is provided by burning the palm by-products (shells and fibers). Consequently, the energy balance, expressed as the ratio of outputs to inputs, is higher for oil palm (9.6) than other commercially grown oil crops (e.g. rapeseed : 3.0; soybean : 2.5), making oil palm the most attractive candidate for biofuel production (Fairhurst and Mutert, 1999).

1.3.1.2. Extent of oil palm cultivation in Indonesia: 1911 to present

The first commercial plantation was developed in Sumatra in 1911 and the area planted in Indonesia increased from about 31600 ha by 1925 to 7.3 million ha by 2008 (Corley and Tinker 2003; IMA, 2010). Since 2007, Indonesia has been the world's largest and most rapidly growing producer. Its production rose from 168 000 tonnes in 1967 to 22 million tonnes by 2010 (IMA, 2010). Crude palm oil and kernel oil prices have been rising, encouraging investors to develop plantations on the large areas of suitable land in the islands of Sumatra, Indonesia (Figure 1.1) then, new developments occurred, mainly on the island of Borneo (USDA, 2007).

1.3.1.3. Expected future expansion of oil palm cultivation

Continued expansion of oil palm plantations is forecast due to growing global demand for palm oil as a source of fats and oil for human consumption, non-edible products and biofuel to keep pace with human population growth, expected to reach 8.9 billion in 2050 (Bangun, 2006; Tan et al., 2009; UN, 2004). Present plans are to increase production up to 40 million tonnes of CPO by 2020 (IMA, 2010; Rist 2010). According to USDA (2007), the availability of land in Indonesia, coupled with other factors - high seed sales, record energy prices, and high vegetable oil prices – ensure that Indonesia will continue to lead the world in palm oil production for years to come. However, few developments generate as much controversy as the rapid expansion of oil palm in developing countries such as Indonesia (Koh and Wilcove 2008; Nantha and Tisdell, 2009). Negative consequences reported by environmental groups include deforestation, loss of biodiversity, peatland degradation, GHG emissions and water pollution.

1.3.2. Environmental stakes

1.3.2.1. Deforestation and loss of biodiversity

The most contentious environmental issue facing the oil palm industry is deforestation as huge tracts of tropical rainforest are converted to plantations (Germer and Sauerborn, 2008; Wakker, 1999). Indonesian tropical forested area ranks third behind Brazil and the Democratic Republic of Congo, and harbors numerous endemic or rare species (Koh and Wilcove, 2008; WRI, 2002). Many sources are claiming that virgin tropical forests are being cleared for oil palm plantations, leading to natural habitat loss for many endangered species and biodiversity reduction. For instance, it was reported that Sumatran orangutans (*Pongo abelii*) and Bornean orangutans (*Pongo pygmaeus*) face extinction due to plantation expansion (Nantha and Tisdell, 2009; Nelleman et al., 2007; Tan et al., 2009). Herds of elephants, tigers and rhinos are reported to be critically threatened due to this expansion (Danielsen et al., 2008; WRI, 2002). Studies in oil palm frontier areas on the island of Sumatra concluded that oil palm plantations result in a significant reduction in biodiversity if plantations replace natural forests, secondary forests, agroforests, or even degraded forests and scrubby unplanted areas (Gillison and Liswanti, 1999; Sheil et al., 2009). However, others mentioned that the expansion of oil palm plantations is only one of the factors contributing to herd displacement and local extinction, as other anthropogenic activities like illegal logging, forest fires and illegal hunting are also problematic for large mammals (Nelleman et al., 2007; Tan et al., 2009). According to Koh and Wilcove (2008), at least 56 % of the oil palm expansion in Indonesia during the period 1990-2005 occurred at the expense of primary, secondary, or plantation forests, and 44 % was on cropland area. Deforestation in Southeast Asia cannot be attributed solely to oil palm production. According to the World Rainforest Movement (WRM, 2002), the immediate causes of rainforest destruction in Southeast Asian countries are logging by commercial companies, shifting agriculture, monoculture plantations (e.g. rubber in Thailand), cattle ranching, fuelwood harvesting, hydro-electric dams, mining and oil exploitation, and colonization schemes.

1.3.2.2 Peatland degradation

Peatland formation

Southeast Asia has an estimated 27.1 million ha of peatlands, most of which are located in Indonesia (22.5 million ha), representing 12 % of its land area (Hooijer et al., 2006). Peatlands develops in depressions or wet coastal areas when the rate of biomass deposition from adapted vegetation (i.e., mangroves, swamp forest) is greater than the rate of decomposition. The accumulation of organic matter that degrades very slowly, over a period of hundreds of years, makes peat soil. This is due to the presence of a permanently high water table that prevents aerobic microorganisms from decomposing the plants debris (Mutert et al., 1999; Wieder et al., 2006). A soil is considered to be peat when it includes an organic layer thicker than 40-50 cm (USDA, 2006). In Southeast Asia, all low-lying peatlands are naturally forested with an average canopy height of 40 m and emergent trees of up to 50 m (WI, 2010). In the Eastern coast of the island of Sumatra, Indonesia, peat deposits are usually at least 50 cm thick but can form a deep profile that extends up to 20 m (CAAL, 2011).

Peatland ecological functions

Peatlands regulate water flow by capturing rainwater during the wet season and slowly releasing it, over a period of months, during the dry season. Consequently, peatlands help to prevent floods and droughts (Clark et al., 2002; Tan et al., 2009). In addition, peatlands are an important carbon (C) sink in the global C cycle because they cover nearly 3 % (some 4 million km^2) of the earth's land area and store about 528 000 Mt C, which is equivalent to one-third of global soil C and 70 times annual global emissions from fossil fuel burning (Hooijer et al., 2006; Tan et al., 2009). Peatland attributes also include biological diversity, since tropical peatlands are important genetic reservoirs of certain animals and plants. Tropical peatlands have long provided goods and services for local communities to fulfill their daily, basic requirements, for example, hunting grounds and fishing areas, food, medicines, and construction materials (Rieley, 2007).

Peatland conversion to oil palm

Peat swamp forests have remained relatively undisturbed until recently, as they were unattractive for agriculture. But the increasing international demand for biofuel and the current lack of available land on mineral soils has accelerated the conversion of peatlands to oil palm plantations especially in Indonesia (Kalimantan, Sumatra and West Papua) where nearly 25 % of all oil palm plantations are located on peatlands (Sheil et al., 2009; Tan et al., 2009). However, oil palms cannot survive in undrained waterlogged peatlands. Drainage for oil palm growth in peatlands is installed between 40 and 80 cm, but the water table could recede below 80 cm during an extended drought (WI, 2010). Many authors reported that there is a direct relationship between the depth of the water table and the rate of peat subsidence and thus the sustainability of the peat (Strack and Waddington, 2007; Wösten et al., 1997; Wösten et al., 2008). Drainage results in rapid peat subsidence and compaction, leading to various changes in its physical properties including greater bulk density and less total porosity, oxygen diffusion, air capacity, available water volume and water infiltration rate (Rieley et al., 2007). Drainage ultimately destroys the sponge effect of peat swamps and their reservoir function (Andriesse, 1988). In addition, the exploitation or removal of the overlying forest resource further reduces the ability of the ecosystem to hold rainfall and water is flushed more quickly into the rivers, increasing flooding in the rainy season and drought in the dry season (Rieley, 2007; Rieley and Page, 1997). Moreover, the drainage of C-rich peatlands leads to aeration of the peat material and hence to the oxidation (or aerobic decomposition) of peat material resulting in massive CO_2 gas emissions to the atmosphere (Schrevel, 2008; Hooijer et al., 2006). Although the exploitation of peat swamp forests also provides employment, local income, new jobs and business opportunities, contributing to poverty alleviation of the country, it is at the expense of the ecosystem and the environment (Rieley et al., 2007).

1.3.2.3 Greenhouse gas emissions and carbon storage

As mentioned in previous sections, establishment of oil palm plantations requires deforestation or peatland conversion, which irreversibly alters the greenhouse gas balance. Before 1998, most of the deforestation in Southeast Asia involved burning, which caused numerous, large and persistent fires and consecutive GHG emissions (Tan et al., 2009). In 1997-98, these fires were particularly devastating due to a severe drought caused by the El-Niño climatic phenomenon. In Indonesia, the total area damaged or destroyed by the 1997-98 fires was estimated at nearly 10 million ha and the overall economic cost of fire and haze in the region at \$9 billion (Glastra et al., 2002). Globally, peatlands emit 2000 Mg CO_2 equivalents (CO_{2eq}) yr^{-1}, equal to almost 8 % of global emissions from fossil fuel burning, and more than 90 % of this annual emission originates from Indonesia. Establishment of oil palm plantation requires removal of other vegetation. Due to GHG emissions from forest burning and peatland conversion, Indonesia is in fourth place in the global CO_2 emission ranking (Barnett, 2007).

Nevertheless, some authors suggested that oil palm plantations may act as a C sink as they assimilate more CO_2 and release more oxygen (O_2) than tropical forest (Lamade and Bouillet, 2005). Henson (1999) reported oil palm CO_2 uptake at 25.71 t ha^{-1} yr^{-1} and O_2 production at 18.70 t ha^{-1} yr^{-1} compared to 9.62 t ha^{-1} yr^{1} and 7.00 t ha^{-1} yr^{-1} respectively in tropical forest. According to several studies reported by Henson (1999), the total dry matter production in oil palm stands was from 19.1 to 36.5 t ha^{-1} yr^{-1}, and the total dry matter production recorded in a

Malaysian forest reached 25.68 t ha^{-1} yr^{-1}. While a new oil palm plantation may grow faster and sequester C at a higher annual rate than a naturally regenerating forest, ultimately, the oil palm plantation will store less C (50-90 % less over 20 years) than the original forest cover (Henson, 1999; Germer and Sauerborn, 2008). This is due to the wide spacing between oil palm trees and control of the understory vegetation to avoid competition with the trees, whereas a natural forest has a plant community that is stratified horizontally and vertically to maximize primary production on a given acreage. Germer and Sauerborn (2008) estimated that forest conversion to oil palm causes a net release of approximately 650 Mg CO_{2eq} ha^{-1} on mineral soils and more than 1 300 Mg CO_{2eq} ha^{-1} on peatlands, during the first 25-year cycle of oil palm growth (e.g. an average net release of 26 t ha^{-1} yr^{-1} and 52 t ha^{-1} yr^{-1} for forest and peatland conversion, respectively). However, Germer and Sauerborn (2008) also reported that if tropical grassland (instead of forest or peatlands) is converted to oil palm plantation, C fixation in plantation biomass and soil organic matter not only neutralizes emissions caused by grassland conversion, but also results in the net removal of about 135 Mg CO_{2eq} ha^{-1} from the atmosphere.

1.3.2.4 Water pollution

Runoff and sedimentation, leaching of nutrients from fertilizer, pesticides and other agrochemicals, effluent discharge and sewage from the worker population, all are potential factors that could affect water quality and can be significant impacts of oil palm cultivation (ECD, 2000; Lord and Clay, 2006). The consequences of poor water quality will be borne by much of the Indonesian population: at the beginning of the 21^{st} century, at least 80 % of the Indonesian population (250 million) had no access to piped water while in 2002, 66.2 % of the population used river water for washing and bathing, and 22.5 % relied on it for drinking water (WEPA, 2011).

Runoff water can transport eroded soil particles from fields to water bodies. Suspended particles contribute significantly to water turbidity, which reduces light penetration, impairs photosynthesis, alters oxygen levels and reduces the food supply for certain aquatic organisms (Bilotta and Brazier, 2008). Sediment clogs streams, reducing their water holding capacity and can cover spawning beds, destroying fish populations (Kemp et al., 2011).

Mineral fertilizer application can lead to a marked increase in the nutrient concentrations of water draining from the fertilized areas (ECD, 2000). Of greatest importance for water quality are N and P exported from agroecosystems to waterways. Nitrogen is mainly applied to agroecosystems as ammonium sulphate or urea. Both ammonium compounds and urea are eventually converted into nitrate in the soil under well-drained conditions. Nitrate in water promotes undesirable growth of aquatic microflora in surface water bodies and concentrations exceeding 10 mg $NO_{3.}$ L^{-1} are not recommended in drinkable water (WHO, 2008). Phosphorous in the form of orthophosphate (PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^{-}$) has a similar eutrophication effect in surface water as nitrate, causing excessive growth of cyanobacteria, blocking sunlight and oxygen diffusion to aquatic life in deeper water (Schindler et al., 1971; Turner and Rabalais, 1994).

Pesticides, including herbicides, are commonly used in oil palm plantations, despite their adverse impacts on human beings and the environment (Sheil et al., 2009). As rainfall can easily exceeds 2500 mm yr^{-1} in Indonesia, herbicides can be washed into streams and rivers that are the only water source for all household needs - including drinking water - in villages around the plantations and contaminating fishing grounds (DE, 2005). Yet the risk of water pollution from pesticides originating from oil palm plantations is probably low, as the Malaysian Environmental Conservation Department (ECD, (2000) noted that biological control methods can be quite effective. However, to our knowledge, there has been no study on the impact of pesticide use on water quality within oil palm plantations.

Finally, palm oil production generates large amounts of waste that can pollute local waterways when disposed incorrectly. For instance, in 2001, Malaysia's production of 7 million tonnes of CPO generated 9.9 million tonnes of solid oil wastes, palm fiber, and shells. Moreover, 10 million tonnes of palm oil mill effluent (POME), a polluted mix of crushed shells, water, and fat residues, was produced and often returned without treatment to natural watercourses downstream from the mill (Lord and Clay, 2006), leading to the degradation of the aquatic ecosystems (Briggs et al., 2007; Kittikun, 2000; Sheil et al., 2009). The POME is an acidic colloidal suspension characterized by high concentration of suspended solids, with a Biological Oxygen Demand (BOD) of 25 000 ppm, and a Chemical Oxygen Demand (COD) of 60 000 ppm (Jacquemard, 1995; Olaleye and Adedeji, 2005). According to Olaleye and Adedeji (2005), riparian rivers and streams receiving untreated mill effluent are expected to be heavily polluted. Fortunately, technologies have been developed to treat and reclaim drinking water from the POME (Ahmad et al., 2006; Rupani et al., 2010; Singh et al., 2010; Yi Jing et al., 2010), and they need to be widely implemented to protect downstream waters. Sewage from the worker population in the plantation is another waste byproduct that is expected to elevate COD, BOD and fecal coliform levels in waterways.

1.3.2.5 Agricultural policies

The pressing environmental and social issues associated with the palm oil industry were the impetus for dialogue between palm oil stakeholders and NGO representatives regarding methods to achieve sustainable palm oil production and use, including better management practices (BMP) for agronomists and planters working with this industry (Darussamin, 2004). Thus, the Roundtable on Sustainable Palm Oil (RSPO), an international organization of producers, distributors, environmental NGOs and social NGOs, was created and defines sustainable palm oil production as *a legal, economically viable, environmentally appropriate and socially beneficial management and operations* (Tan et al., 2009). RSPO has recently established a set of Principles and Criteria for the management of oil palm plantations and palm oil mills and encourages the planters to follow BMP (Lord and Clay, 2006). These practices are environment-friendly approaches like zero burning for land clearing, conservation of wildlife and habitat, Integrated Pest Management (IPM) and waste minimization and recycling. For example, IPM in plantations relies on barn owls or snakes to reduce rat populations instead of pesticides (Hansen, 2007; Sheil et al., 2009). Planting leguminous cover crops (LCC) to minimize soil erosion and maintain soil fertility and the recycling of palm oil empty fruit bunches (EFB) and POME as fertilizer in the plantation are also promoted. These environmentally-friendly practices could reduce the use of mineral fertilizers (Tan et al., 2009) and improve water quality.

The Indonesian government also has recently started to encourage planters to improve the sustainability of their plantations. The Indonesian Sustainable Palm Oil (ISPO) was launched in 2010 by the government of Indonesia, and will be compulsory in the coming years for all oil palm growers, while RSPO is still a voluntary process. In addition, Indonesia government has recently edited a guideline on oil palm cultivation on peatland "*to manage the peatland in a sustainable way considering the ecological function of peatland*". It stipulates, among other things, that the land clearing will be done without burning (since 1998, zero burning is compulsory in Indonesia) and an intensive and quick process of drying is not allowed, to avoid irreversible shrinkage. The decree also lays down that oil palm cultivation on peatland must be restricted to: a) areas in which the peat extended less than three m below the surface; b) areas where the subsoil under the peatland is not silica sand or acid sulfate soil to avoid the toxic effects of the oxidation of the pyrite and accumulation of sulfuric acid, due to the drop in water table level (Zaidel'man, 2008); c) areas with mature peat soils, classified as sapric (the most decomposed) or hemic (somewhat decomposed); and (d) areas with eutropic peatlands (Ministerial Decree on Agriculture, 2009).

1.3.2.6 Implications for future research

To date, most of the attention and research related to the environmental impact of oil palm cultivation has focused on deforestation and its consequences (loss of biodiversity, GHG emissions from burning, etc.) during the initial phase of oil palm plantation establishment. Much less attention has been paid to the environmental impacts of established oil palm plantations, in particularly hydrological changes and water pollution. Understanding and assessing the activities in oil palm plantations that impact hydrological functions and associated nutrient fluxes requires a good knowledge of all agricultural practices followed throughout the entire life cycle of the plantation. In the next section, we describe the preferred growing conditions for oil palm (climate, soils) and agronomic considerations (site preparation, tree spacing), with emphasis on nutrient, soil and water management in different production systems (industrial and smallholders).

1.4. Oil palm cultivation

1.4.1 Climate and soil conditions

The African oil palm (*Elaeis guineensis*, Family Arecaceae) is a tropical forest palm native to West and Central African forests. Oil palm needs humid equatorial conditions (1780–2280 mm annual rainfall and a temperature range of 24–30°C) to thrive, and so conditions in Southeast Asia are ideal (Corley and Tinker, 2003). Palm productivity benefits from direct sunshine: the lower incidence of cloud cover over much of Southeast Asia is thought to be one reason why oil palm yields are higher there than in West Africa (Dufrêne et al. 1990). Oil palm is tolerant of a wide range of soil types, as long as it is well watered. Seasonal droughts at higher tropical latitudes greatly reduce yields (Basiron, 2007). The oil palm is cultivated predominantly on tropical soils Ultisol, Oxisol, and Inceptisol. These soils are highly acidic with low buffering capacities (Ng, 2002) as a consequence of cation leaching (Caliman et al., 1987). Once the pH drops below 5.5, aluminum and manganese soil compounds start to dissolve, which may cause root deterioration (Godbold et al., 1988). However, oil palm is adapted to acidic soil conditions (Omoti et al., 1983), and with appropriate management, oil palm plantations can also be productive on ‘problem soils’ such as acid sulfate soils, deep peat and acidic high aluminum soils, where few other crops are successful (Corley and Tinker, 2003).

1.4.2 Production systems: industrial versus smallholder plantations

Oil palm growing areas in Indonesia are distributed among three production systems: government holdings, private companies and smallholders. In 2010, the Indonesian Ministry of Agriculture estimated that of almost 8 million ha under oil palm cultivation, private companies held 53 %, smallholders had 39 %, and the remaining 8 % belonged to government plantations. Private and governmental estates typically range in size from 3000 to 20 000 ha (Sheil et al., 2009), while the smallholders are defined as family-based enterprises producing palm oil from less than 50 ha of land, often about 2 ha (Vermeulen and Goad 2006). When the price of palm oil in the international market was exceptionally high (around US$ 700 per ton in 1974), efforts were made to increase production. The government established a strategy called the Nucleus Estate Scheme (NES), where state-owned or private plantation companies (*nucleus*) helped smallholder farmers to grow oil palm on 2-3 ha of land in the surrounding area, called the *plasma* (Bangun, 2006; IEG, 1993; Zen et al., 2005). Smallholders working under contract to the plantation companies received seedlings of high-yielding cultivars, technical assistance for land preparation and planting, agrochemical inputs (fertilizers and pesticides), management assistance and loan access (Bangun, 2006; Vermeulen and Goad, 2006). The estates benefited through their fees for services and returns from milling smallholder fruit into CPO (Zen et al., 2005). In contrast to smallholders working under the NES, independent smallholders cultivate oil palm without direct assistance from government or private companies. They sell their crop to local mills directly or through buyers (Vermeulen and Goad, 2006).

1.4.3 Land clearing and site preparation

Many authors provide recommendations for the establishment of an oil palm plantation including land clearing, roads and drainage network construction, caring for pre-nursery and nursery stages, planting, management of immature and mature trees until replanting. Among the most popular agronomic handbooks for oil palm cultivation are Corley and Tinker (2003), Jacquemard (1995), Rankine and Fairhusrt (1998a, 1998b, 1998c), and Hartley (1988).

Once the site is selected, establishment of the oil palm plantation starts with land clearing. At present, mechanical methods are used in all major oil palm-growing countries with chainsaws, winches and bulldozers. Then, the felled vegetation is either burnt or allowed to rot. The issue of whether or not to burn the felled vegetation has remained a subject of controversy for years (Corley and Tinker, 2003) due to environmental impacts of burning: smoke, haze and large nutrient losses through volatilization and ash carried away (Mackensen et al., 1996). Since the massive fires in Kalimantan and Sumatra in 1997, the Indonesian government prohibited burning (Corley and Tinker, 2003). However, according to some media, laws to limit agricultural burning are poorly enforced and burning still continues (Mongabay Editorial, 2006).

The general layout of a plantation is decided by the topography, the drainage, the position of the mill and the distance to transport fresh fruit bunches (FFB) to the nearest road. Hartley (1988) recommends a gap of 320 m between roads, the density being 33 m roads ha^{-1}, i.e. 3 % of the land area. In hilly areas, the road density should increase, with distances between roads not exceeding 200 m, due to the difficulty of transporting FFB across platforms and terraces. With terraces, the distance should be 125 m, the density being 80 m roads ha^{-1}. A typical road layout in hilly estates has to be arranged in relation to the drainage lines and streams. If the roads can run parallel to streams, this reduces the number of bridges needed and helps to avoid crossing over swampy areas (Corley and Tinker, 2003). Steps for the establishment and exploitation of an oil palm plantation on a typical private estate are summarized in Figure 1.2.

1.4.4 Water and soil management

Water management is a crucial aspect of oil palm cultivation as deficit or excess of water stresses oil palm trees and are highly detrimental for crop yields. Water management mainly aims at minimizing impacts of drought and floods, and optimizing the use of rainwater and fresh water from streams by drainage, irrigation and soil moisture conservation practices. Corley and Tinker (2003) provided detailed information on irrigation in oil palm plantations. In Indonesia, rainfall is generally well distributed over the year so irrigation is not common in oil palm plantations, except in South Sumatra where yield-limiting water deficits may occur during the dry season.

Drainage systems are common in Indonesian oil palm plantations, particularly in flat areas with a high water table where drainage is compulsory to remove excess water and promote oil palm root proliferation in deeper soil layers. Indeed, optimum depth of water table for oil palm growth is 50 to 75 cm (APOC; Goh and Chew, 1995). To achieve this, a good outlet with sufficient capacity to discharge excess water is needed (Corley and Tinker, 2003). Another possibility is to install controlled drainage systems that retain subsurface water in the drains prior to dry periods. Generally, the drainage system consists of an inter-connected network of collection and main drains of varying dimensions depending on the hydrological and rainfall characteristics of the area (Othman et al., 2010). The slope, intensity and dimension of drains depend largely on the expected amount of water to be removed during wet periods. To achieve the desired water level, the minimum drain intensity is at least one drain for every eight rows of palm and the intensity could be further increased to one in every four or even to one in every two rows of palms. Higher drainage intensity is adopted on clayey soils compared to sandy soils, which naturally have better drainage (Cheong and Ng, 1974 quoted by Goh and Chew, 1995).

Water management is more critical on undulating, hilly or inland soils because growers need to maintain soil moisture and minimize soil erosion and nutrient losses. The American Palm Oil Council (APOC) recommends: 1) digging of silt-pits and foothill drains to trap water sediments from surface runoff, 2) stacking fronds across the slope to minimize the velocity of water runoff downhill slopes and to conserve water through mulching, 3) planting LCC, which not only helps to replenish soil organic matter stock, but also reduces the velocity of soil and water movement. The LCC commonly established in oil palm estates include *Mucuna Bracteata, Pueraria phasesloides* and *Calopogonium cearuleum*. In steep terraced areas, deep rooting *Vetiver* grass can be used to prevent soil erosion and regulate water excess.

However, water management and soil conservation are not practiced by all planters. Plasma smallholders may benefit of drainage network implemented by large companies involved in the Nucleus-Plasma scheme, whereas independent smallholders may not have the financial and technical means to dig and maintain a drainage network within their plantations, nor the knowledge of soil moisture and soil conservation practices. Despite abundant literature and recommendations for water management, studies investigating actual and current water management practices in oil palm plantations, especially in smallholdings are almost nonexistent.

1.4.5 Nutrient demand assessment

Despite the absence of mineral elements in the palm oil, large quantities of nutrients are required by the palm tree to support its vegetative growth and fruit production, which cannot be provided by inland and upland soils in Sumatra and Borneo due to their low fertility status (Goh and Härdter, 2003). Thus, mineral fertilizers are compulsory to supplement the low indigenous soil nutrient supply and to ensure suitable yields. Fertilizers account for 50–70 % of field operational costs and about 25 % of the total cost of production (Caliman et al., 2007; Goh and Härdert, 2003). Understanding the factors that contribute to efficient fertilizer use are crucial to maximize yields and enhance economic returns (Goh and Härdert, 2003). Consequently, the Indonesian oil palm industry has invested millions of dollars in research and development to improve fertilizer use. Many trials have been conducted on a wide range of soil types, climate and tree ages in order: i) to determine the ecophysiological nutrient demand of oil palm for targeted yields (Tarmizi and Mohd, 2006); ii) to determine input levels to achieve an economically optimum production (income vs costs of production) (Breure, 2003; Caliman et al., 1994; Caliman, 2001; Goh and Härdter, 2003) including recommended types, rates and timing of fertilizer applications to minimize nutrient losses (Goh and Chew, 1995); and also iii) to develop agricultural practices aiming at minimizing chemical fertilizers inputs such as the establishment of a LCC during the immature stage (Agamuthu and Broughton, 1985), recycling of pruned fronds and male inflorescences (Ng and Thamboo, 1967), mulching of empty fruit bunches (EFB) (Caliman et al., 2001; Chiew and Rahman, 2002; Loong et al., 1987) and POME spreading (Rupani et al., 2010;

Wood et al., 1979). These studies led to an abundant literature on recommendations for optimum nutrient management in oil palm plantations (Corley and Tinker, 2003; Fairhurst et al., 2005; Kee and Goh, 2006).

Fertilizer management in oil palm plantation is based on nutrient balance principle, which estimates the total demand of the palm and matches it with the nutrient supply in the oil palm plantation and from supplemental fertilizers (Goh et al., 1999). Nutrient demand can be divided in two categories: nutrient uptake and nutrient losses from soil through processes such as runoff, leaching and gaseous emissions. Within nutrient uptake, we distinguish nutrient stocks exported by harvesting (FFB) and nutrients immobilized in the palm biomass (for growth) (Goh and Härdter, 2003; Goh, 2004). Some authors also calculate nutrients recycled from pruned fronds and male inflorescences because they are usually returned to the soil (Tarmizi and Mohd, 2006). The nutrient requirements of oil palm vary widely, depending on the target yield, genetic potential of the planting material used and numerous environmental factors such as tree spacing, palm age, soil fertility, groundcover conditions, climate (Fairhurst and Mutert, 1999; Goh and Härdter, 2003; Tarmizi and Mohd, 2006). Table 1.1a compares the total nutrient stocks in standing biomass of oil palm plantation and tropical forest, illustrating that one hectare of forest generally contains more nutrients in plant biomass than a plantation. Table 1.1b shows nutrient uptake and allocation for production, immobilization in palm biomass and recycling, based on data from trials in Southeast Asia. Generally, a larger proportion of nutrient uptake is needed for FFB than for immobilization. For example, Ng et al. (1999) reported, for a target yield of 25 t ha^{-1} yr^{-1}, the annual nutrient uptake in FFB was 2.3 fold greater than nutrients immobilized in new biomass.

The soil nutrient supply in an oil palm plantation comes from dissolved nutrients in atmospheric deposition, including precipitation, nutrients recycled from pruned fronds and male inflorescences when these are returned to the soil, nutrients leached by rainfall from the leaf canopy (leaf wash), nutrient returns from LCC, available nutrients present in the soil, and fertilizer applications (Goh et al., 1999; Goh and Härdter, 2003; Goh, 2004, Tarmizi and Mohd, 2006). As an example, the potassium fluxes in oil palm plantation are illustrated in Figure 1.3.

Some research groups developed complex models, based on the nutrient balance principle, to assess nutrient requirements, taking account of the commodity price and fertilizer cost. Corley and Tinker (2003) reported on three of these models, which are summarized below:

1) The Applied Agriculture Research group in Malaysia developed a linked group of models for oil palm management, which include a model to assess site-specific yield potential (ASYP), a model for predicting the fertilizer requirements, the Integrated Site Specific Fertilizer Recommendation System (INFERS), and expert systems for determining best month for fertilizer application, and the timing and allocation of different fertilizers (Kee et al., 1994; Kok et al., 2000).

2) Leaf analysis is the most common diagnostic tool to determine the nutritional status of oil palm and estimate the appropriate fertilizer rates because of significant relationship between leaf nutrient concentration and FFB yield (Foster and Chang, 1977; Goh, 2004). It is largely used by the International Cooperation Centre in Agronomic Research for Development (CIRAD), which carries out leaf analysis of palms located on important soil types within the plantation and uses response curves of the leaf analysis results to determine the critical level corresponding to the economically optimal fertilizer rate (Caliman et al., 1994; Caliman, 2001).

3) The Foster system (PORIM fertilizer recommendation system) involves two basic approaches: i) the use of site-specific characteristics to determine yield without fertilizer, fertilizer need and the efficiency of response to fertilizer (Foster et al., 1986; Foster, 1995); and ii) leaf analysis data (Foster and Chang, 1977; Foster et al., 1988).

1.4.6 Fertilizer management

1.4.6.1 Chemical fertilizer

The dominant fertilizers produced and used in Indonesia are urea (46 % N), triple superphosphate (TSP, 46 % P_2O_5), rock phosphates (RP, 27-34 % P_2O_5), ammonium sulfate (AS, 21 % N and 24 % S), potassium chloride, also called muriate of potash (KCl or MOP, 60 % K_2O), magnesium sulphate, also called kieserite (17 % Mg, 23 % S), and blended NPK, NP and PK fertilizers (FAO, 2005). Table 1.2 shows some recommended fertilizer application rates, which vary according to climatic conditions, soil type, age of palms and palm yield potential. The optimal frequency of fertilizer application depends on crop requirements, tree age, ground conditions, types of fertilizer available and rainfall. For example, frequent application of fertilizer at low rates is preferred for sandy or sloped land where the risk of nutrient losses through runoff or drainage is great. In such areas, a single annual application of water insoluble rock phosphate is recommended, whereas soluble fertilizers would be applied in low doses several times a year. More frequent fertilizer application is also advised for immature trees (Goh and Chew, 1995). Some authors recommend fertilizers applications close to the tree base in the initial years, and to be gradually extended to the tree avenues when the canopy overlaps and good root development is reached (Goh and Chew, 1995; Goh et al., 2003). Moreover, the timing of fertilizer application should account for the rainfall pattern to avoid substantial nutrient losses (Goh and Chew, 1995; Goh et al., 2003). Thus, the general guideline is to avoid fertilizer applications during period with high rainfall, such as during months with more than 250 mm month^{-1}, months with high rainfall on more than 16 days month^{-1}, and months with high intensity rainfall events of more than 25 mm day^{-1} (Goh and Chew, 1995).

1.4.6.2. Organic fertilizer

The value of oil palm residues such as pruned fronds and other wastes from processing mills for mulch and organic manure is well documented (Haron et al.,, 2000; Dolmat, 1987; Loong, 1987). According to Fairhurst (1996), field palms yielding 30 t FFB ha^{-1} in West Sumatra return to the soil about 10 t ha^{-1} yr^{-1} dry matter from pruned fronds, which contain 125 kg N, 10 kg P, 147 kg K and 15 kg Mg. Also, both EFB and POME contain substantial amounts of nutrients and organic matter that can replenish the soil fertility and help to meet the nutrient requirements for oil palm. According to Tailliez (1998), mulched EFB can reduce the need for chemical fertilizers by more than 50 % in immature stands and by 5 % in mature stands. Application of 40-60 t EFB ha^{-1} yr^{-1} or 750 m^3 POME ha^{-1} yr^{-1} is recommended to add organic matter and improve soil fertility on poor inland soils (Goh et al., 1999).

1.4.7 Synthesis

Industrial and smallholder planters do not have the same resources to ensure optimum nutrient management. Specifically, independent smallholders do not benefit from techniques such as leaf diagnosis and soil analysis (Fairhurst and Mutert, 1999; Pushparajah, 1994) to assess the nutrient requirements of their plantations. In many smallholdings, low productivity palms are planted unevenly without terracing, fertilizer use is inadequate and unbalanced (urea applied alone) (FAO, 2005; Zen et al., 2005, Webb et al., 2011). Some smallholders observe and copy the industrial plantations in recycling pruned fronds and male inflorescences, but not all. Moreover, they do not benefit from organic inputs of EFB and POME, which are available only in industrial or governmental estates where the mills are located. Unfortunately, few data are available on actual fertilization practices in most oil palm plantations in Indonesia. Some authors provide estimates of average yields of palm oil from the different management groups, which are generally higher for private plantations than smallholdings, although the FAO estimated similar yields for these two groups (Table 1.3). However, these estimates should be interpreted with caution as they do not take in account of the high variability of cultural practices among planters. Although some private producers have recorded high yields of 6.5 to 8.0 t ha^{-1} on individual plantations, the gap between yields on smallholdings and private estates is inexplicably low, given the tremendous advantages that private estates show in capital, land management abilities, fertilizer availability, and access to high-yielding varieties (USDA, 2009). Two possibilities to explain this discrepancy are: (1) producers on private estates have seriously under-invested in soil fertility and fertilizer use efficiency, as they have the financial resources to manage nutrients for higher yields; or (2) producers on private estates have not been motivated to manage their trees intensively, as they already achieve sufficient profit margins (USDA, 2009).

Abundant recommendations exist for soil, water and nutrient management on oil palm plantations, especially for large plantations, but smallholder farms are generally not large enough for trials to be implemented (Webb et al., 2011). Moreover, there is scant or no data available from study cases on the actual management practices and fertilizer use in industrial plantations, let alone smallholdings. However, these practices have a high potential to impact hydrological processes and associated nutrient fluxes from oil palm plantations.

1.5. Hydrological processes and associated nutrient transfers in oil palm plantations

Replacing a natural forest with an oil palm plantation is expected to *drastically* change the existing characteristics of the area and to modify the hydrological cycle, shown in Figure 1.4 (Henson, 1999). The activities related to the oil palm plantation establishment and exploitation (e.g. complete clearing of forested area, construction of roads and drainage networks, fertilizer and agro-chemical use, wastewaters release from mill and worker residences) are expected to cause problems related to water flow (e.g. flooding incidents downstream) and increase nutrient and sediment delivery to streams, causing deterioration in water quality (ECD, 2000; Goh et al., 2003). This section aims to : (1) compare hydrological processes in naturally forested watersheds with those under oil palm plantation, including the hydrological changes occurring during oil palm development (immature vs. mature plantations), and (2) highlight gaps in literature regarding the understanding of hydrological processes in oil palm plantations and the consequences for water quality. We do not review hydrological processes in tropical forests as a number of detailed reviews were already published (Bruijnzeel, 1990, 2004; Douglas, 1999; Elsenbeer, 2001), but will refer to those data to illustrate the magnitude of change in hydrological processes occurring in oil palm plantations.

1.5.1 Precipitation in Indonesia

Indonesia's humid tropical climate is characterized by seasonal changes in rainfall largely determined by monsoons winds, due to its location in the equatorial zone, between the Asian and Australian landmasses. Typically, the northwest monsoon brings rain from December through March, followed by the southeast monsoon, which brings drier weather from June through September (Galdikas, 2009). Rainfall patterns in Indonesia vary from one region to another (Aldrian and Dwi Susanto, 2003). Annual rainfall in lowland areas is between 1800 and 3200 mm, increasing with altitude to an average of 6100 mm in some mountainous regions. In the lowlands of Sumatra and Kalimantan, the annual rainfall averages 3000 to 3700 mm.

1.5.2 Interception

Studies of hydrological processes in tropical rainforests indicate the importance of interception by the leaves and branches (canopy) of plants. In his review, Bruijnzeel (1990) concluded that forest interception was between 4.5 and 22 % of the rainfall incident on the canopy, with an average value of 13 %. Compared to natural forest vegetation, a lower proportion of rainfall is expected to be intercepted by palms as a result of lower Leaf Area Index (LAI), even in mature oil palm plantations (Henson, 1999) due to clearing of most understory vegetation. Dufrêne (1989) reported less than 5 % rainfall was intercepted following a 30 mm precipitation event and lower values were recorded at higher rainfall intensity. However, Squire (1984) found interception was 17-22 % of precipitation in oil palm plantation, the amount varying with palm age, erectness of canopy and rainfall intensity.

In tropical forests, only a small amount of rain falls directly on the ground or into water bodies, as most of the rainfall will reach the soil via throughfall and stemflow, which are responsible for transferring nutrients from the canopy to the soil. Some Malaysian studies found throughfall transferred 70-78 % of rainfall in mature oil palm plantations (Kee et al., 2000). In Papua New Guinea where rainfall is higher, Banabas et al. (2008) found that 83 % of the rain reached the ground as throughfall. These values are the same order of magnitude as those reported by Bruijnzeel (1990) for lowland rainforest: 77-93 % of incident rainfall (on average 85 %) was transported by throughfall. There is insufficient published data on throughfall, stemflow and rainfall interception by immature oil palm when the canopy has not yet closed.

1.5.3 Evapotranspiration

A number of evapotranspiration (ET) studies were carried out in tropical forests (Tanaka et al., 2008; Zulkifli et. al., 1998; Noguchi et al., 2004). In three catchments in Selangor, Malaysia with more than 94 % forest cover, Low and Goh (1972) found ET accounted for half of the 2 162 to 2 482 mm annual rainfall when estimated as the difference between measured rainfall and water outflow from the catchment. In a study in the Sungai Tekam Experimental Basin, Malaysia (DID, 1989) that received average annual rainfall of 1 878 mm for the period 1977/78 to 1985/86, the actual ET of a forested catchment averaged 1500 mm yr^{-1} (range: 1374-1583 mm yr^{-1}), which represents 99% of the potential ET, on average 1515 mm yr^{-1} (range: 1449-1567 mm yr^{-1}) based on the Penman & Thornwaite method of estimation. In his review, Bruijnzeel (2004) reported ET typically ranged from 1000 to 1800 mm yr^{-1} in lowland and hill *dipterocarp* forests in Peninsular Malaysia.

There have been few ET studies in oil palm plantations (Yusop et al., 2008). Micrometeorological measurements in mature oil palm on a Malaysian coastal site showed that ET accounted for 83% of rainfall and was close to potential ET calculated by the Penman equation (Henson, 1999). A study of oil palm on volcanic soils in Papua New Guinea gave an estimated ET of 1334 to 1362 mm yr^{-1}; Banabas et al. (2008) noted that water deficit was unlikely to limit transpiration in this area, which had average annual rainfall between 2398 and 3657 mm. Radersma and de Ridder (1996) estimated oil palm ET of 1018 to 1051 mm yr^{-1} from literature data. We know of one published report on ET in immature oil palm plantations. Yusop et al. (2008) estimated ET in three catchments where oil palm ages ranging from 2 yr to 9 yr, using Short Time Period Water Budget and Catchment Water Balance. Surprisingly, they found higher values (1405 and 1365 mm yr^{-1} for the two methods, respectively) in the 2 yr old plantation than the 9 year old plantation (927 and 1098 mm yr^{-1}, respectively), as higher transpiration is expected in mature plantation. They concluded that ET values in the older plantation were underestimated. Overall, these literature reports suggest high rates of ET in mature oil palm plantations in Southeast Asia, ranging about 1000-1300 mm yr^{-1}, which is similar to ET in tropical rainforests. However, few studies report ET in immature oil palm plantation and the difference in ET of different age plantations remains to be fully investigated.

1.5.4. Soil infiltration, leaching and ground water quality

1.5.4.1 Soil infiltration

Water reaching the ground may either infiltrate into the soil or flow directly to the stream through surface runoff. Partitioning between surface runoff and infiltrated water essentially depends on soil infiltrability and rainfall intensity. Once infiltrated, water can either percolate downward as vertical flow or reach the stream through lateral (downslope) subsurface flow, depending on soil hydraulic conductivity gradient. In rainforests, water moves within the soil as matrix flow or more rapidly through bypass or preferential flows (roots channels, macropores) in both vertical and lateral directions (Noguchi et al., 1997a). It is well known that soil infiltration capacity depends on soil texture (FAO, 1988) and on land use (Chorley, 1984; Osuji et al., 2010). Many studies showed that tropical forest soils have high infiltration capacities (Bruinjnzeel, 1990), due to dense vegetation (increases water uptake and ET from the system) and high soil organic matter content that improves the soil structure and enhances its porosity. For example, high infiltration rates of 200–250 mm h^{-1} were found in two tropical forest soils of western Nigeria under bush fallow (natural regrowth) (Wilkinson and Aina, 1976). According to Bruinjnzeel (2004), about 80-95% of incident rainfall infiltrates the soil in a mature tropical rainforest. However, some studies showed that hydraulic conductivities decrease rapidly with soil depth in forested land, leading to shallow subsurface flow from the nearly saturated topsoil and contributing to stormflow generation (Bidin et al., 1993; Malmer, 1996; Noguchi et al., 1997b). This phenomenon was also observed by Yusop et al. (2006) in forested catchments in Malaysia due to positive hydraulic pressure at 10 cm depth during storms, despite high hydraulic conductivity (169 - 1485 mm h^{-1}).

Deforestation can affect infiltration capacity of soils in a number of ways. According to DID (1989), removal of forest reduces transpiration and increases soil moisture storage, which resulted in soils reaching field capacity earlier during rainfall events. Infiltration rates will also be reduced immediately following deforestation when soils are compacted by heavy machinery. However, DID (1989) showed that infiltration rates return to pre-disturbance levels following the establishment of crops due to improvement in soil structure under vegetative ground cover.

According to Banabas (2007), soils under mature oil palm typically have high infiltrability (80 to 8500 mm hr^{-1}, depending on soil texture). However, the infiltrability of the soil is highly variable due to the ordered structure of vegetation in oil palm plantations. A study in West Sumatra on 10 year-old oil palms demonstrated significant spatial variability when comparing water infiltration rates in soil beneath the palm circle, harvest path and frond piles. Infiltration rate increased in the order path < circle < frond pile (Fairhurst, 1996). In Papua New Guinea, Banabas et al. (2008) recorded similar results (Table 1.4). They attributed the highest values in the frond pile zones to the macroporosity-enhancing effect of the organic matter present in this zone. They ascribed the lower values found in the weeded circle and harvest-path zones to topsoil compaction from falling bunches in the weeded circle, wheel and foot traffic in the harvest paths, and sparse understory vegetation.

Thus, apart from its high dependence on soil texture, infiltrability will vary temporally and spatially in oil palm plantation. After a strong decrease due to soil compaction after land clearing, infiltrability in oil palm plantation may partly recover due to plant growth and organic matter addition to the soil. Yet, infiltrability will remain low along roads, harvest pathways and in weeded circles.

1.5.4.2 Leaching and ground water quality

Leaching losses are generally assumed to be higher in the humid tropics than temperate areas due to the frequent and intense rain storms, higher temperature and high carbonic acid content in soil (Ah Tung et al., 2009; Johnson et al., 1975). Depending on the amount of water draining out of the rooting zone, leached solutes may simply accumulate in a deeper layer of the soil profile or may reach the underlying groundwater (Ah Tung et al., 2009). Table 1.5 summarizes results from Bruinjzeel (1991), including estimates of annual runoff and nutrient losses in drainage water from tropical rainforests. The author also reported that forest clear-cutting often increased nutrient losses to streams. Brouwer and Riezebos (1998) compared nutrient leaching in closed and logged tropical rainforest in Guyana. Logging clearly increased leaching, which they ascribed to an increased percolation of water through the soil (2800 mm after 22 months logging compared to 1800 mm in closed forest), and increased solute concentrations in the percolating water. They found that Ca, K and Mg concentrations were 2-10 times greater in the gaps after logging than in closed forest, with the greatest increase in concentration for NO_3 (10-20 times greater than closed forest). The major pulse of leaching occurred during the first year after logging and most solute concentrations in percolating soil water remained higher up to 15 months after logging. However, vegetative regrowth reduced leaching losses as plants absorbed soluble nutrients and immobilized them in standing stock biomass.

Large nutrient losses are expected in oil palm plantations (Goh et al., 2003). According to Ng et al. (2003), most of the oil palm root biomass is found within 1 m of the soil but the distribution of oil palm active roots favors the nutrient uptake in the upper 30 cm, which may increase the potential risk of nutrient leaching. Omoti et al. (1983) measured amounts of nutrients leached under immature (4 years) and mature (22 years) oil palms, distinguishing between the loss of native nutrients and the loss of applied nutrients (fertilizers). The losses of native nutrients from closed and logged tropical forest on one hand, and in immature and mature oil palm plantations on the other hand are summarized in Table 1.6. To our knowledge, there is no chronological study comparing the amounts of nutrient leached under natural forest and oil palm plantation established on the same site after forest clearing, nor between forested and oil palm catchments with similar climatic and soil conditions. This makes it difficult to quantify the impact of oil palm plantation establishment on native nutrient leaching. The most complete study to assess the impact on hydrological processes of forest conversion to tree crop and oil palm plantations (DID, 1989) did not evaluate leaching, leaving a considerable gap in our knowledge of this process in plantations at the catchment scale.

Despite the paucity of large-scale data on leaching processes, many plot-scale studies investigated the percentage of applied fertilizers lost through leaching in oil palm plantations, some of them comparing young and mature oil palm stands (Chang and Zakaria, 1986; Foong et al., 1983 Maena et al., 1979). For example, a field lysimeter study conducted on Munchong series soil in Malaysia found higher fertilizer losses when the palm was 1-4 yr old (17 % for N and 10 % for K), which declined to 2.1 % of applied fertilizer N and 2.7 % of fertilizer K when the palm was 5-14 yr old (Foong, 1993). Higher nutrient losses through leaching from immature palm implies less plant nutrient uptake, whereas older palms have more extensive root system that can absorb applied and indigenous soil nutrients, a greater nutrient demand and a higher transpiration rate that lowers water loss via leaching. However, a field-scale study on Orlu and Algba series (Rhodic Paleudult) soils in Nigeria showed no significant differences in nutrient leaching from applied fertilizers between the immature (4 yr) and mature plantations (22 yr) (Omoti et al., 1983). According to some authors, the adult stage poses a high risk of nutrient losses because ground vegetation is sparse due to poor light penetration through the closed oil palm canopy (Breure, 2003). Moreover, the LCC dies off at canopy closure, releasing a large amount of N from the decomposing legume biomass and increasing the risk of N loss via leaching (Campiglia et al., 2010; Goh et al., 2003). According to Goh and Chew (1995), leaching losses also depends on soil texture and greater losses were recorded in sandier soils, as summarized in Table 1.7. In general, leached P losses are low due to the relative immobility of P in acidic, weathered tropical soils (Omoti et al., 1983; Goh et al., 2003).

A plot-scale study by Ah Tung et al. (2009) is the only one to our knowledge that investigated leaching losses of inorganic N and K and measured their concentrations in groundwater. They found leaching losses of inorganic N represented between 1.0 and 1.6 % of applied N fertilizer and the K losses were between 2.4 and 5.3 %, depending on fertilizer application rates. The concentration of N and K in the soil solution decreased with soil depth, which they explained by nutrient removal and uptake by palm roots, resulting in lower nutrient concentrations in the soil solution with depth. However, another explanation they did not mention is that fertilizers are applied near the soil surface, so the topsoil layers have a higher concentration of nutrients in soil solution; this naturally declines with depth because there was no fertilizer injection deeper in the soil profile. The measured concentrations of NH_4-N, NO_3-N and K in groundwater ranged from 0.23-2.7, 0.07-0.25 and 0.63-9.54 mg L^{-1}, respectively, which did not exceed the water quality standards, set by the World Health Organization (WHO, 2008). The authors did not specify the distance of groundwater sampling wells from the palm circles where the fertilizers were applied. However, they mentioned the possibility of groundwater pollution when excessive N fertilizer was applied or if NO_3-N leached from the soil profile into groundwater in the inter-tree spaces between palms. This supposition is supported by Schroth et al. (2000), who reported pronounced spatial pattern of NO_3-N concentrations within the plantation. Low NO_3-N concentrations were measured in the soil profile within 1m of palm trees, indicating efficient absorption of mineral N by the palms, whereas soil NO_3-N concentrations increased with increasing distance from palm trees. At 4 m away from the trees, the vertical NO_3-N concentration gave clear evidence of NO_3-N leaching into the deeper subsoil as concentrations almost doubled from surface soil to 175 cm depth (6 μg g^{-1} to 11.5 μg g^{-1}, respectively). They concluded that much of the soil volume in the plantation was apparently not accessed by palm roots, leaving surplus N at risk of leaching loss (Schroth et al., 2000).

Thus, nutrient leaching in oil palm plantations may be impacted by soil type and rainfall intensities (that both influence infiltration rates), oil palm age, agricultural practices such as LCC establishment, water management that impacts the water table level and subsequently increases the possibility of leaching, fertilizer types and rate applications, etc. In oil palm plantations receiving chemical fertilizer, low nutrient losses via leaching and nutrient concentrations in ground water quality were generally reported. Higher nutrient losses (as % of fertilizer application) are expected in immature plantations due to lower nutrient uptake by palm roots. However, higher fertilizer applications are recommended in mature plantations, which may lead to higher losses in absolute terms. The link between nutrient leaching and groundwater quality is clearly not fully investigated or understood. A shortcoming of the current literature is the reliance on plot-scale studies with lysimeters installed close to the trees, despite high spatial heterogeneity in the structure of the oil palm plantation that affects soil infiltration rates, distribution of vegetation and root growth in the soil profile. Although organic fertilizer applications (POME and EFB) also supply nutrients than could potentially leach, impacting groundwater quality, work on oil palm plantations amended with these residuals has focused on soil properties rather than groundwater quality (Okwute and Nnennaya, 2007).

1.5.5 Surface runoff and erosion

In rainforest watersheds, surface runoff may occur as infiltration excess overland flow and/or saturated overland flow. Malmer (1996) reported that infiltration excess overland flow was more likely than saturated overland flow across the sloping uplands of a tropical forested catchment, whereas areas close to the stream are susceptible to saturated overland flow or return flow. However, infiltration excess overland flow in forests is regarded as a rare phenomenon, as vegetation plays an important role in holding and absorbing rainfall (Bonnell, 2005; Bruijnzeel, 1990; Zhang et al., 2007). Noguchi et al. (1997a) concluded that neither saturation overland flow nor infiltration excess overland flow are likely to occur at Bukit Tarek Experimental Watershed, a forested watershed in Peninsular

Malaysia. Data on annual runoff, soil and nutrient losses in tropical rainforests, reviewed by Bruijnzeel (1990), are summarized in Table 1.8. Although surface runoff is rare in forests, it is likely in oil palm plantations during short-term high intensity rainfall events because of the high intrinsic variability in soil infiltrability (Banabas et al., 2008). When runoff does occur, it would be initiated mainly from the weeded circle (where stem flow causes the highest local water inflows and the infiltrability is quite low) and the harvest path zone (where infiltrability is lowest due to soil compaction) (Table 1.9).

While erosion is never excessive (i.e. greater than the rate of soil formation) in forests, soil loss can be pronounced at particular stages in an oil palm plantation. Many studies reported highest erosion rates immediately after land-clearing**,** resulting from increased exposure of the soil surface to erosion and surface runoff losses (Bruinjzeel, 1990, 2004; Douglas, 1999; Goh et al., 2003). According to Clay (2004), bare soil resulting from road construction and other infrastructure such as bridges, culverts and drains increases soil erosion in oil palm plantations. DID (1989) showed that deforestation activities such as timber harvesting, construction of roads and preparation of land for crop planting account for as much as 91% of all the sediment exported from the catchments. Results from erosion plots on two soil types revealed 5-7 times more erosion from deforested land than forested lands during the first year after planting the LCC. However, once the ground cover was established, erosion was greatly reduced but not eliminated (DID, 1989). In mature plantations, erosion still occurs from harvest paths, roads and localized areas of steep elevation. Clay (2004) reported that in Papua New Guinea, every 100 m of road has the potential to produces as much sediment as each ha of oil palm, but this is not unrelated as there are 50 linear m of road for every ha of oil palm planted.

Some authors estimated contribution of rainfall to runoff and associated nutrient losses, usually expressed as percentage of applied fertilizers, carrying out plot-scale studies in oil palm plantations. Some of them computed nutrient losses, via runoff and/or sediment transport to be large, accounting for up to 10% of applied fertilizers (Maena et al., 1979). They observed greater losses from surface runoff in the uncovered soil in the harvest path, compared to the interrows, where pruned fronds provide soil cover (Goh et al., 2003; Fairhurst, 1996; Maena et al. 1979). Others reported low losses of nutrient via runoff in oil palm plantation (Banabas et al., 2008). Results from key papers are summarized in Table 1.10. Moreover, runoff losses of applied fertilizers also depend on the lagtime between application and the subsequent rainfall. While Chew et al. (1995) showed that high rainfall prior to fertilizer application resulted in substantial nutrient loss, Kee and Chew (1996) found that the first rain event following fertilizer application in a wet month gave N concentrations in runoff water of 89 mg kg^{-1} and 135 mg kg^{-1} for 65 kg N ha^{-1} and 130 kg N ha^{-1} rates respectively, compared to 4 mg N kg^{-1} in the unfertilized control plot. Thus, the amount of fertilizer nutrients lost through runoff and sediment transport depends on the soil texture, the age of the oil palms, the local topography and infiltrability, and on the lag time between fertilizer application and rainfall (Banabas et al., 2008). The continual compaction of harvest pathways and roads, and the disappearance of understory cover (including LCC) due to canopy closure may also contribute to soil and nutrient losses via runoff and erosion within a mature oil palm plantation (Table 1.10).

1.5.6 Stream flow and stream water quality

1.5.6.1. Stream flow

Hydrological changes observed at the plot-scale will have consequences on stream flow and water quality. It is well known that total stream flow increases following clearance of forest cover and conversion to other types of land use (Bruijnzeel, 1990). The absence of vegetation allows a greater proportion of direct rainfall to reach the forest floor, and reduced ET rates (due to absence of plants) translate into a greater volume of water leaving the catchment. When land use change increases the amount of disturbed and compacted surfaces, there will be an associated increase in surface runoff and stream flow. This increase may be permanent when converting natural forest to grassland or shallow rooted agricultural crops, or temporary in the case of conversion to tree plantations (Abdul Rahim and Harding, 1992; Bruijnzeel, 1990).

Hydrological studies carried out in oil palm plantation at a watershed scale are scarce, except those of Sungai Tekam Experimental Basin in Pahang by DID (1989). They observed an increase in total flow immediately in response to deforestation (+ 85 to 157 % for the first three years after deforestation), which declined gradually with the planting of LCC and tree crops. Total flow increase was due to greater baseflow rather than more runoff. The authors ascribed the large increase in baseflow to rising water table level due to reduced ET and ponding effects immediately after deforestation, as felled logs and debris were left in the stream channels for long period acting as debris dams. However, in Bruijnzeel's review (2004), other authors reported a decrease in baseflow following deforestation, especially during the dry season because more surface runoff from compacted soils decreased the groundwater recharge and the subsequent release of baseflow. Soil compaction following land clearing triggers a shift from dominant subsurface flow to overland flow, increasing peak flow during storm events (Bruijnzeel, 2004). DID (1989) observed also that peak discharge increased after deforestation and that time-to-peak decreased significantly from 3 hr to 1 hr immediately after deforestation. Although this study provides insight into short-term hydrological changes when oil palm plantations are established, it was stopped before the oil palm plantation reached maturity (Hui, 2008). Further study of the mature plantation would be helpful to determine whether older oil palm plantations continue to experience more surface runoff and higher peak flows during storms than undisturbed forest, leading to higher stream flow in the watershed. A study in a small oil palm catchment (8.2 ha) on a coarse sandy clay loam Ultisol in the upstream of Skudai River in Johor, Malaysia showed a high proportion of baseflow, approximately 54 % of the total runoff and rapid responses to rainfall with a short time (6-48 min) to peak flow (Yusop et al., 2007). However, baseflow can be higher in forested catchments and reach as much as 70 % of the total annual flow (Abdul Rahim and Harding, 1992; Yusop et al., 2007).

1.5.6.2 Stream water quality

It is clear that oil palm plantations have different hydrological characteristics from natural forests at the plot-scale, which may impact the quality of receiving waters at a watershed-scale. The increase of surface runoff loaded with eroded soil particles, the use of agro-chemical (fertilizers and pesticides) and the release of POME in the streams are expected to affect the aquatic life and drinkable water quality of the receiving water bodies (ECD, 2000; Sheil et al., 2009)**.** However, **c**atchment-scale studies on water quality and nutrient losses in tropical areas have focused primarily on forested areas and the impacts of rainforest disturbances (Malmer, 1996; Malmer and Grip, 1994). In Malaysia, some researchers reported slightly acidic stream water, low levels of electrical conductivities and solute concentrations from forested catchments (DID, 1989; Yusop et al., 2006) and in a catchment with diversified land uses, including oil palm plantation (15 %), forest (50 %), mining and urbanized area (Gasim et al., 2006) (Table 1.11). As expected, deforestation greatly increased outflow of sediment loads and nutrients after clearing (e.g. EC (+16%), Ca (+26 %) and Mg (+37 %) by DID (1989); turbidity (x 9) and suspended solids (x 12) by Zulkifli et al., 1987). Temporal variations of stream water quality. at the storm event-scale were noted by Yusop et al. (2006), in particular higher export of nitrates (x3) and suspended solids in stormflow than in baseflow but greater export of SiO_2 during baseflow, suggesting that low flow removed solutes associated with soil weathering processes. At the seasonal scale, Gasim et al. (2006) observed higher values for most water quality parameters in the wet season than the dry season, while DID (1989) observed higher values for turbidity, suspended solids and iron in wet season and higher values of conductivity, pH, Mg and Ca during dry months.

In large oil palm plantations, POME is released directly to streams, sometimes without treatment, which is expected to cause water pollution. To our knowledge, the study by Olaleye and Adedeji (2005) is the only one published in the peer-reviewed literature to assess the water quality of a river impacted by POME release from oil palm plantations. They ascribed the near absence of zooplankton in a large Nigerian river to the deleterious effect of POME discharge in the stream. Pesticides originating from oil palm plantations are expected to have a strong impact on water quality according to NGOs, while oil palm managers expect low impact due to low application rates. The absence of data on this topic in the peer-reviewed literature is a major knowledge gap.

Despite the potential risk of water pollution expected from oil palm plantation activities, there have been very few studies at the watershed-scale to assess water quality in streams within a plantation at different development stages (i.e. immature vs. mature palms).

1.5.7 Synthesis

There is an abundance of literature on hydrological processes in tropical rainforest ecosystems, immediate and short-term impacts of rainforest disturbance (logging, clearing), as depicted in Figure 1.5. It is generally accepted that natural regrowth in tropical forests leads to a relatively fast return to previous levels of soil infiltrability, streamflow, water budget and soil nutrient stocks. However, the impact of oil palm establishment on changes to hydrological processes and associated nutrient losses, and their evolution during oil palm growth are much less investigated, documented and understood.

Table 1.12 summarizes the evolution of hydrological processes and associated nutrient losses occurring from forested land to mature oil palm plantation stage, based on observed or expected outcomes and highlights research gaps in the understanding of these processes. We compare consecutive stages (cleared land vs. tropical forest; immature plantation vs. cleared land; mature vs. immature plantation) and also compare both immature and mature stages to forest, the original land cover. Expected trends for each stage are described qualitatively because observations were often made for a specific plantation age (without long term monitoring to cover all stages) across areas with a broad range of climatic and soil conditions. The impacts of forest clearing rely on many studies reviewed by Bruijnzeel (1990, 1991) that generally reported strong impacts of complete forest clearing. Information regarding the immature oil palm stage are based on the study by DID (1989), that represents, to our knowledge, the only chronological study focused on the evolution of hydrological process dynamics from forest to oil palm plantation establishment, at both plot-scale and watershed-scale. Unfortunately it was stopped before oil palms reached maturity and did not investigate leaching process at the plot-scale. It concluded that after clearing, the growth of oil palm (with LCC) tends to counteract the negative impacts of clearance, without always returning to pre-disturbance levels. Runoff and erosion remain high in compacted areas such as roads, harvest paths and weeded circles. Due to the high nutrient uptake rate and large evaporative demand of the palms, low nutrient losses via leaching were generally reported in oil palm plantations in Southeast Asia despite high rainfall intensities.

Few studies compared the water and nutrient budgets between young and mature oil palm stands, although leaching losses at the plot-scale were examined by Foong et al. (1983) and Omoti et al. (1983) and ET was measured by Yusop et al. (2008). In mature plantations, data were available from a number of plot-scale focusing on single hydrological processes, such as runoff or leaching, with the exception of Banabas et al. (2008). Investigating water budget in a mature plantation, including ET, soil water storage, runoff and leaching losses, authors demonstrated that nutrient losses occurred primarily from leaching rather than from runoff. Few studies have taken in account the spatial heterogeneity of the plantation. Finally, hydrological studies carried out at the watershed-scale in mature oil palm plantation are almost nonexistent, with the exception of Yusop et al. (2008) who quantified runoff processes on a small oil palm watershed (8.2 ha). The only research on stream water quality within oil palm plantations agroecosystems comes from DID (1989) for immature plantations. Thus, hydrological process dynamics and magnitude (e.g. total water yields, dry season baseflow, stormflow dynamics) and nutrient outflows from oil palm plantation are far from being fully assessed and understood.

1.6. Conclusion

Since the 1960s, research effort focused on plot-scale trials in Southeast Asia to provide agronomic recommendations for plantation managers that would increase productivity and economic returns for the palm oil industry. Growing awareness of environmental impacts from the rapidly expanding oil palm sector, driven by media and socio-environmental NGOs, led to the creation of RSPO to promote a sustainable palm oil production. This organization encourages planters to assess the environmental impacts of oil palm cultivation and develop eco-friendly agricultural practices. Although RSPO encourages an evaluation of oil palm plantation activities impacting water quality and hydrological processes, this review demonstrated that the topic remains largely under-investigated. First of all, the actual agricultural practices for nutrient and water management currently used in Southeast Asian oil palm plantations are poorly described, especially in smallholdings. Assessing actual agricultural practices is challenging as high variability likely occurs not only between large companies and smallholders, but also among both production systems, due to variable access to knowledge, technical and financial means. Another constraint is that palm oil is produced in developing countries, which may lack the resources to monitor the impact of oil palm plantation on hydrological functions at different stages throughout its long lifespan (about 25 yr). Indeed, most of hydrological studies in oil palm plantations were carried out at the plot scale (i.e. a few ha), whereas oil palm plantations can reach thousands contiguous ha across several watersheds. Few studies provided an integrated view of hydrological processes or have taken account of the intrinsic spatial variability of an oil palm plantation. Spatio-temporal variation in surface water quality and groundwater quality within oil palm plantations have been very poorly investigated, and the link to agricultural practices remains tenuous. Therefore, study cases that include a survey of actual agricultural practices, water quality assessment and hydrological processes investigation at the watershed-scale are needed to better understand and assess the potential risk to waterways of oil palm plantations. In the end, this information will help planters to manage their oil palm plantations more sustainably.

Table 1.1a. Standing stock biomass in oil palm plantation and topical forest

Vegetal cover	Mean biomass	Total stocks in standing biomass (kg ha^{-1})					Source
		N	P	K	Mg	Ca	
Oil palm, 14 years	94 t ha^{-1} for 136 palms ha^{-1}	588	58	1112	151	173	Ng et al., 1968
Rainforest (5 studies range)	385 t ha^{-1}	1067-2980	33-315	340-3163	161-595	476-4168	Anderson and Spencer, 1991

(adapted from Henson, 1999).

Table 1.1b. Nutrient uptake in different components of oil palm plantations

Oil palm components		Target yield (t FFB* ha^{-1} yr^{-1})	Nutrient contents in oil palm biomass (kg ha^{-1} yr^{-1})					Source
			N	P	K	Mg	Ca	
Production								
	Harvested fruit bunches	24	72.5	12.1	93.2	20.7	-	Ng and Thamboo 1967, Ng et al., 1968
		25	73.2	11.6	93.4	20.8	19.5	Ng et al., 1968
		30	97.6	10.0	105.4	18.2	-	Tarmizi and Mohd, 2006
		30	99.1	15.6	129.3	33.3	-	Ng et al. 1999
Immobilized								
	trunk	30	42.4	4.1	121.6	10.2	-	Ng et al. 1999
	roots	-	16.6	1.1	2.8	0.42	-	Corley et al., 1971
	Trunk & roots	30	18.5	2.4	61.9	3.8	-	Tarmizi and Mohd, 2006
	Immobilized in new biomass	25	40.0	3.1	55.7	11.5	13.8	Ng et al., 1968
Recycled								
	Pruned fronds & male inflorescences	24	78.4	11.3	102.1	28.1	-	Ng and Thamboo 1967, Ng et al., 1968

*FFB= Fresh Fruit Bunch

Table 1.2. Recommended fertilizer applications for oil palm in South East Asia

Smallholder	Industrial		Source
	Government	Private	
1.8	3.7	1.7	FAO, 2005 (in 2002)
3.3 (5)	4.2 (7)	4.1 (7)	USDA, 2009 (in 2008)
2.34		3.04-5.52	Bangun, 2006

Table 1.3. Average yields of palm oil production for the different production systems in Indonesia (t ha^{-1}).

Fertilizer applications (kg ha^{-1} yr^{-1}*)						Source
Notes	N	P	K	Mg	B	
Immature oil palm						
	45	24	108	28	0.6	FAO, 2005
	35-105	42-56	42-420	8.4-35	1.4	Goh et al., 2003
	50-120	22-48	54-216	7-24	1.2-3.7	von Uexküll
Mature oil palm						
	120	22	286	24	0.6	FAO, 2005
	35-245	56-98		42-105	2.1-4.9	Goh et al., 2003
	120-200	30-87	183-581	0-36	2.5-5.6	von Uexküll

*Assuming 140 palms ha^{-1} when recommendations were expressed as kg $palm^{-1}$

Table 1.4. Soil infiltrability (mm hr^{-1}) for major soil types and at specific locations in oil palm plantations

Soil	Frond piles	Between zones	Weeded circles	Harvest path	Source
Typic Hapluland, sandy clay to clay loam	1351	997	270	265	Banabas et al., 2008
Typic Udivitrand, sandy loam to sand	7350	1230	340	60	Banabas et al., 2008
Typic Hapludult	2050	−	−	175	Maena et al., 1979

Table 1.5. Catchment studies of annual rainfall, annual runoff and nutrient losses in drainage water from South East Asian tropical forests (modified from Bruijnzeel, 1991).

Location	Type of forest	Soil	Watershed area (ha)	Annual rainfall R (mm)	Annual runoff Q (mm)	Q/R %	Nutrient losses (kg ha^{-1} yr^{-1})					Sources quoted by Bruijnzeel (1991)
							Ca	Mg	K	P	N	
Ulu Gombak, Malaysia	Partly disturbed *Dipterocarp* forest	Oxisol	31	2500	750	30	2.1	1.5	11.2	-	-	Kenworthy (1971)
Bt. Berembun, Malaysia	Undisturbed *Dipterocarp* forest	Deep Ultisols and Oxisols	29.6	2005	225	11	5.8	3.6	8	-	-	Abdul Rahim and Zulkifli (1986) ; Zulkifli (1989) ; Zulkifli et al. (1989)

Table 1.5. (Continued)

Location	Type of forest	Soil	Watershed area (ha)	Annual rainfall R (mm)	Annual runoff Q (mm)	Q/R	Nutrient losses (kg ha^{-1} yr^{-1})					Sources quoted by Bruijnzeel (1991)
						%	Ca	Mg	K	P	N	
Watubelah, Indonesia	Plantation forest of *Agathis dammara*	Andesitic tuffs	18.7	4670	3590	77	29	30.5	22	0.7	10.6	Bruijnzeel (1983a,b, 1984)
Kinta Valley, Malaysia	Lowland rainforest	Limestone (karst terrain)	-	2845	1605	56	795	90	76	-	-	Crowther (1987a,b)
Ei Creek, Papua	Colline rainforest	Basaltic volcanic agglomerates	16.25	2700	1480	55	24.8	51	14.9	-	-	Turvey (1974)
Gua Anak Takun, Malaysia	Lowland rainforest	Limestone	-	2440	1255	51	764	45	20	-	-	Crowther (1987a,b)

Table 1.6. Nutrient leaching losses in undisturbed forest, highly disturbed forest and oil palm plantations.

	Amount of element leached (kg ha^{-1} yr^{-1})									Source
	Ca	K	Mg	Na	Cl	NH_4-N	NO_3-N	N-total	SO_4-S	
Closed tropical rain forest, Guyana*	2	5	1	24	25	1	3	4		Brouwer and Riezebos, 1998
Large gap sikkder zone, Guyana*	14	23	16	65	56	1	90	91		Brouwer and Riezebos, 1998
Unfertilized young oil palm (4 yr), Nigeria	165	3	32	−	53	−	−	32	53	Omoti et al., 1983
Unfertilized adult oil palm (22 yr), Nigeria	123	29	32	−	30	−	−	65	83	Omoti et al., 1983

*annual average on 1030 days

Table 1.7. Nutrient leached as percentages of applied fertilizers in immature (1 to 4 yr) and mature (> 4 yr) oil palm plantations

Location	Soil	Annual rainfall (mm)	Palms ha^{-1}	Age of palm (yr)	Nutrient losses of applied fertilizer (%)							Notes	Source
					N	P	K	Mg	Ca	S	Cl		
Nigeria	Rhodic Paleudult	1923	150	4 and 22	34	-	18	172	60	14	141		Omoti et al., 1983
Sabah, Malaysia	Typic Hapludults	> 2500		26	1-1.6	-	2.4-5.3	-	-	-	-		Ah Tung et al., 2009
Malaysia	Typic Hapludox	1909	145	1	26.5	trace	19.5	169	-	-	-	Rainfed	Foong et al., 1983
		1495		2	10.9	trace	3.4	8.4	-	-	-	Rainfed	
		2729		3	12.2	1.4	10.4	53.6	-	-	-	Irrigated	
		2787		4	16.8	5.8	5.6	47.6	-	-	-	Irrigated	
		2391		5	2.7	1.7	1.9	5.4	-	-	-	Irrigated	
		2193		6	4.8	1.4	3.3	6.6	-	-	-	Irrigated	

Table 1.7. (Continued)

Location	Soil	Annual rainfall (mm)	Palms per ha	Age of palm (yr)	Nutrient losses of applied fertilizer (%)							Source
					N	P	K	Mg	Ca	S	Cl	
Malaysia	Typic Paleudult (Serdang series)	2352	-	-	10.4	-	5.1	-	-	-	-	Chang and Zakaria, 1986
Malaysia	Typic Hapludox (Munchong series)	-	-	1 to 4	16.6	1.8	9.7	69.8	-	-	-	Foong et al., 1993
				5 to 8	1.2	1.6	2.5	11.5	-	-	-	
				9 to 14	3	1.5	2.9	15.5	-	-	-	

Table 1.8. Runoff, soil erosion, dissolved solutes and sediment losses via runoff in Southeast Asian rainforest

Location	Soil	Study scale	Annual rainfall (R) mm	Runoff (Q) mm	Q/R (%)	Soil erosion	Dissolved loss ($t\ ha^{-1}\ yr^{-1}$)	TSS outflow ($t\ ha^{-1}\ yr^{-1}$)	Notes	Source
Central Kalimantan, Indonesia	Red-yellow podsol	plot 2x10 m	2862 - 3563	2.50	0.5	0.41 g m^{-2}	-	-	Period 27/3 to 6/6/98 ; rainfall 495 mm	Hartanto et al., 2003
				2.50	0.8	1.35 g m^{-2}	-	-	Period 28/12/97 to 21/2/98 ; rainfall 316 mm	
Sabah, Malaysia	Gleyic podsol	runoff plot 50-200 m^2; catchment scale	1950	56.55	2.9	38 kg $ha^{-1}\ yr^{-1}$	0.16	0.3	excluding valley bottom	Malmer, 1996

Table 1.9. Soil erosion and nutrient losses in surface runoff water from spatial components of an oil palm plantation on a Typic Hapludult in Malaysia (after Maena et al., 1979; Goh et al., 1999).

Fertilizer placement	Average annual runoff (% of rainfall)	Soil erosion ($t\ ha^{-1}\ yr^{-1}$)	Nutrient losses (% of applied fertilizer)					
			N	P	K	Mg	Ca	B
Oil palm row	20.2	7.47	13.3	3.5	6.0	7.5	6.8	22.9
Harvest path	30.6	14.92	15.6	3.4	7.3	4.5	6.2	33.8
Frond pile	2.8	1.1	2.0	0.6	0.8	2.7	0.8	3.3
Frond pile/harvest path	−	−	6.6	1.4	3.5	2.2	3.4	12.5
Average for the field	−	−	11.1	2.8	5.0	5.6	5.2	20.7
Fertilizer nutrients applied ($kg\ ha^{-1}$)			90.2	52.0	205.9	32.8	78.9	2.4

Table 1.10. Nutrient losses through runoff and eroded sediment in mature oil palm plantations (plot-scale studies)

Location	Soil	Age of oil palm plantation	Annual rainfall (mm)	Annual runoff (% of rainfall)	Annual nutrient losses kg ha^{-1} yr^{-1} (% of applied fertilizers)					Transport	Source
					N	P	K	Mg	Ca		
Malaysia	Orthoxic Tropudult	11	1426	2.8-30.6 %	9.93 (11.1 %)	1.43 (2.8 %)	10.40 (5.0 %)	1.82 (5.6 %)	4.04 (5.2 %)	in runoff	Maena et al., 1979
					5.57 (6.2 %)	3.63 (7.0 %)	8.79 (0.0 %)	21.10 (64. %)	7.40 (9.4 %)	in eroded sediment	
Malaysia	Typic Paleudult				4.5 - 7.2 (4.4-7.2%)	0.7 - 1.1 (0.5-0.8%)	20.8 - 33.0 (9.7-15.4%)	3.6 - 6.8 (4.0-7.6%)	-	in runoff	Kee and Chew, 1996
					0.5 - 0.8 (0.5-0.9%)	0.5 - 1.3 (0.3-0.9%)	Trace	0.1 (0.1 %)	-	in eroded sediment	

Table 1.10. (Continued)

Location	Soil	Age of oil palm plantation	Annual rainfall (mm)	Annual runoff (% of rainfall)	Annual nutrient losses kg ha^{-1} yr^{-1} (% of applied fertilizers)					Transport	Source
					N	P	K	Mg	Ca		
PNG*	Typic Hapluland	Mature (135 palms ha^{-1})	2398 ± 374	6 (0-44 for individual events)	2.2	-	-	-	-	in runoff	Banabas et al., 2008
PNG*	Typic Udivitrand	Mature (135 palms ha^{-1})	3657 ± 682	1.4 (0-8 for individual events)	0.3	-	-	-	-	in runoff	

*Papua New Guinea

Table 1.11. Water quality in streams as impacted by oil palm plantation, managed and natural forest catchments in Southeast Asia.

Land use	Soil	Annual rainfall (mm)	Notes	pH	EC	K	Ca	Mg	Na	NH_3	NO_3	PO_4	Cl	SO_4	SiO_2	Source
					(µs cm^{-1})	mg L^{-1}										
Variously vegetated with 50 % forest and 15% oil palm	−	2235		3.2-6.3	14.3-85.7					0.007-0.57	0.7-2.9	0.0-0.50		0.0-2.0		Gasim et al., 2006
Two forested catchments (~30 ha)	Araceneous series	2348-3169	low flow	5.6	7.3-7.5	0.34-0.38	0.17-0.19	0.32-0.35	0.25-0.28	0.03	0.08-0.10	0.1	0.4-0.5	0.005	9.2	Yusop et al., 2006
			storm flow	5.1-5.2	10.2-11.6	0.83-0.92	0.20-0.24	0.37-0.45	0.2-0.21	0.04	0.23-0.32	0.1	0.6	0.005	5.2-6.3	

Table 1.11. (Continued)

Land use	Soil	Annual rainfall (mm)	Notes	pH	EC	K	Ca	Mg	Na	NH_3	NO_3	PO_4	Cl	SO_4	SiO_2	Source
					(µs cm^{-1})	mg L^{-1}										
Forested control catchment (56 ha)	Tropeptic Harplothox	1878	6 years average	6.9	55.7	1.48	6.81	2.48	3.36		1.29				26.5	DID, 1989
Cleared catchment for oil palm (97 ha)	Tropeptic Harplothox	1878	6 years average	7	83.6	2.56	9.04	3.83	2.94		1.55				20.49	DID, 1989

Table 1.12. Qualitative description of the expected change in hydrological processes and associated nutrient losses from forest clearing to mature oil palm plantation, compared to undisturbed tropical forest

Hydrological process	Clearance (bare soil)	Immature oil palm plantation		Mature oil palm plantation	
	vs forest	vs clearance	vs forest	vs immature	vs forest
Plot-scale					
Infiltration rate	↘[a, b]	↗[b]	↑[b]	–	↕[f,g]
Leaching	↗[a]	↘e[a]	↑e[5]	↘[d] or =[e]	↑[h,i]
Actual Evapotranspiration	↘[a]	↗ e[b]	↓e[a,c]	–	=[a,f]
Runoff & erosion	↗[a,b]	↘[b]	↑[b]	–	↑ e[h]
Catchment-scale					
Water yields	↗[b]	↘[b]	↑[b]	–	–
Dry season flow	↘[a]	–	–	–	–
Stormflow	↗[a]	↘[a,b]	↑e[a]	–	↑e[h]
Peakflow	↗[b]	↘[b]	↑[b]	–	↑e[h]
Time to peak	↘[b]	↗[b]	–	–	–
Ntrient outflow	↗[a,b]	↘[b]	↑[b]	–	↑e[h]
Sediment loads in stream	↗[b]	↘[b]	↑[b]	↘ e[a,b]	↑ e[h]

[a]Bruijnzeel, 1990 ; [b]DID, 1989 ; [c]Ling et al., 1979 (quoted by Bruijnzeel, 1990) ; [d]Foong et al., 1993 ; [e]Omoti et al., 1983 ; [f]Banabas et al., 2008 ; [g]Maena et al., 1979; [h]ECD, 2000 ; [i]Schroth et al., 2000

↘ decrease, ↗ increase, ↑ higher, ↓lower, ↕ variable, e= expected, = similar

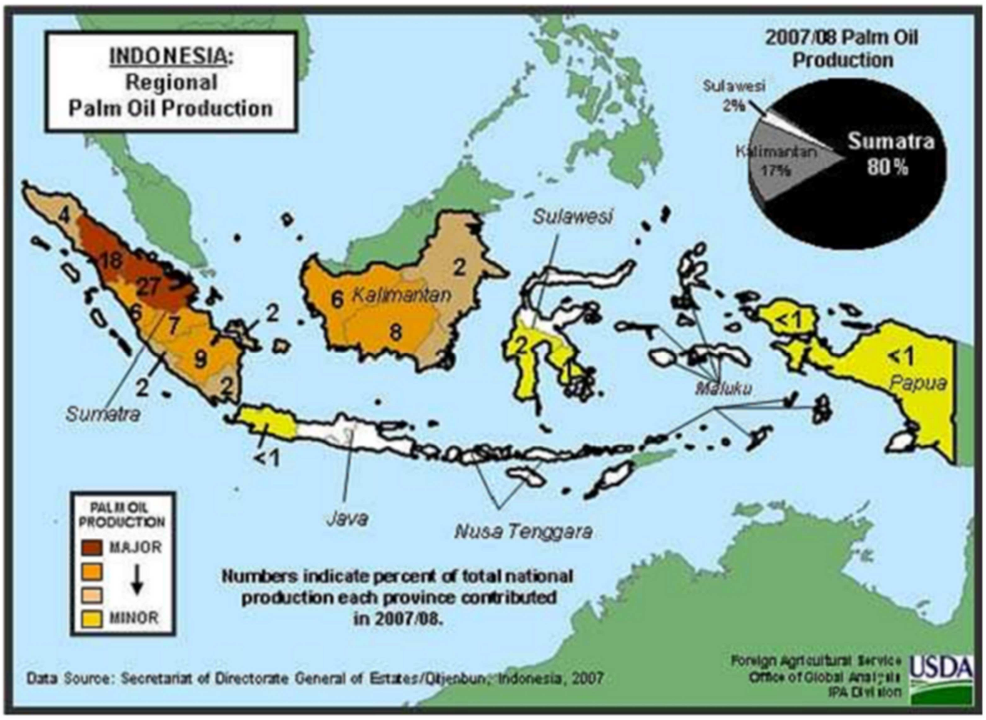


Figure 1.1. Map of Indonesian oil palm production in 2007/2008 (from U.S. Department of Agriculture, Foreign Agricultural Service, Office of Global Analysis, International Production Assessment Division, 2009).

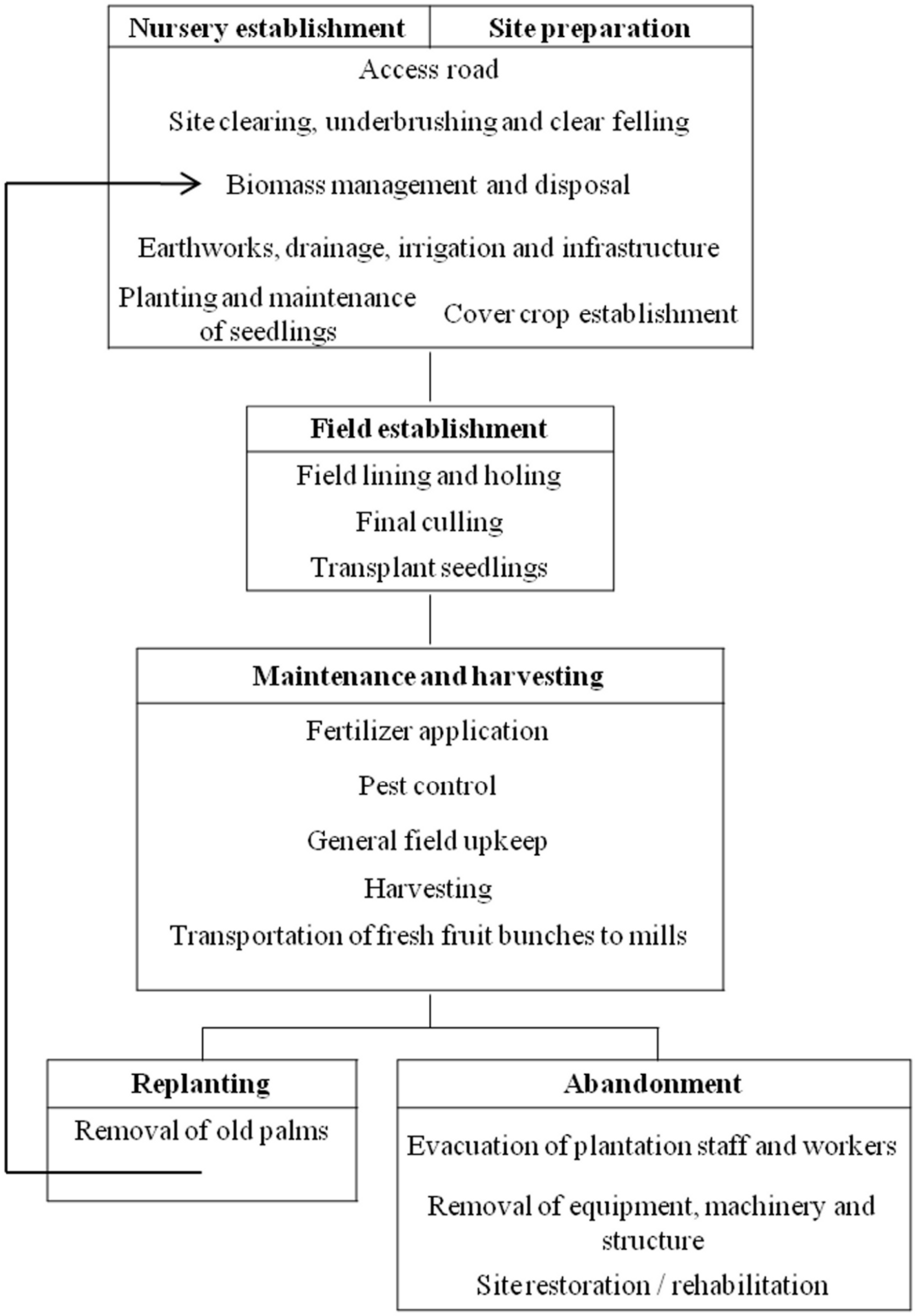


Figure 1.2. Typical oil palm plantation development activities (adapted from ECD, 2000).

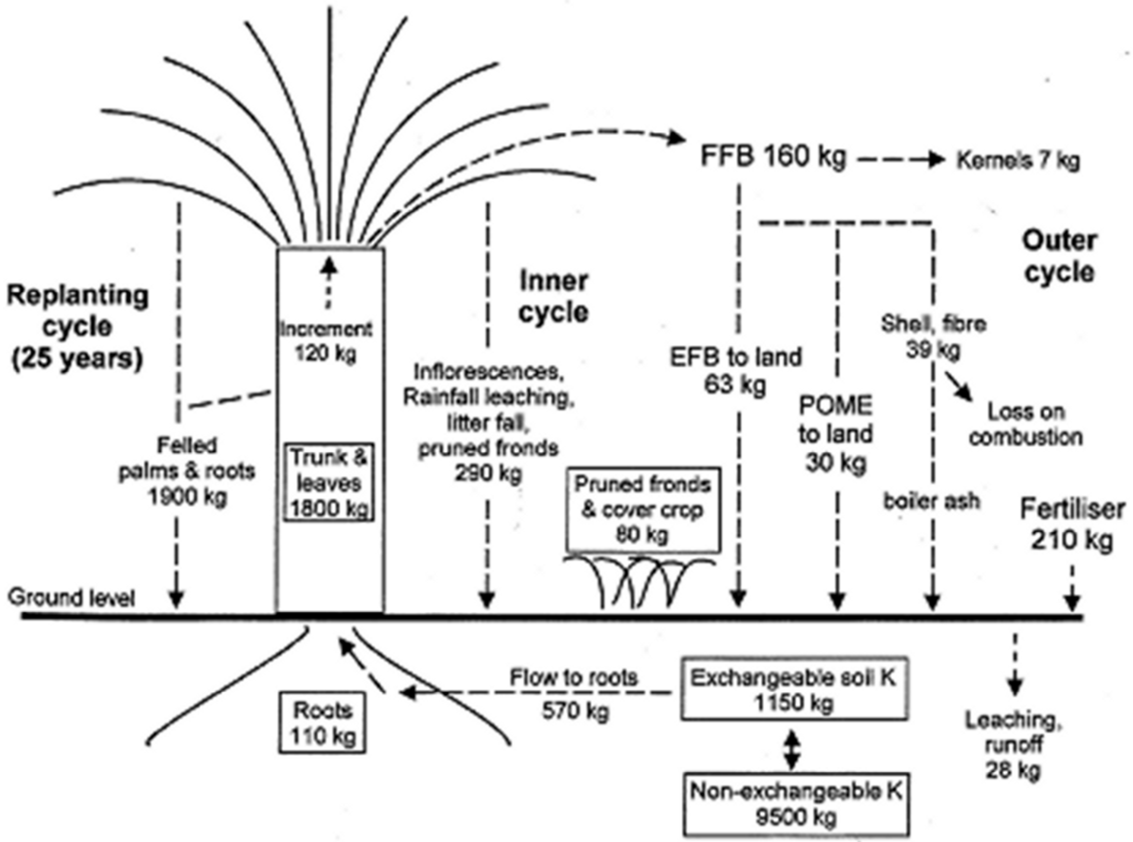


Figure 1.3. Total demand and sinks for potassium in an oil palm plantation with 30 tonnes FFB yield (from Henson, 1999; Corley and Tincker, 2003). EFB= Empty Fruit Bunch; FFB= Fresh Fruit Bunch; POME= Palm Oil Mill Effluent.

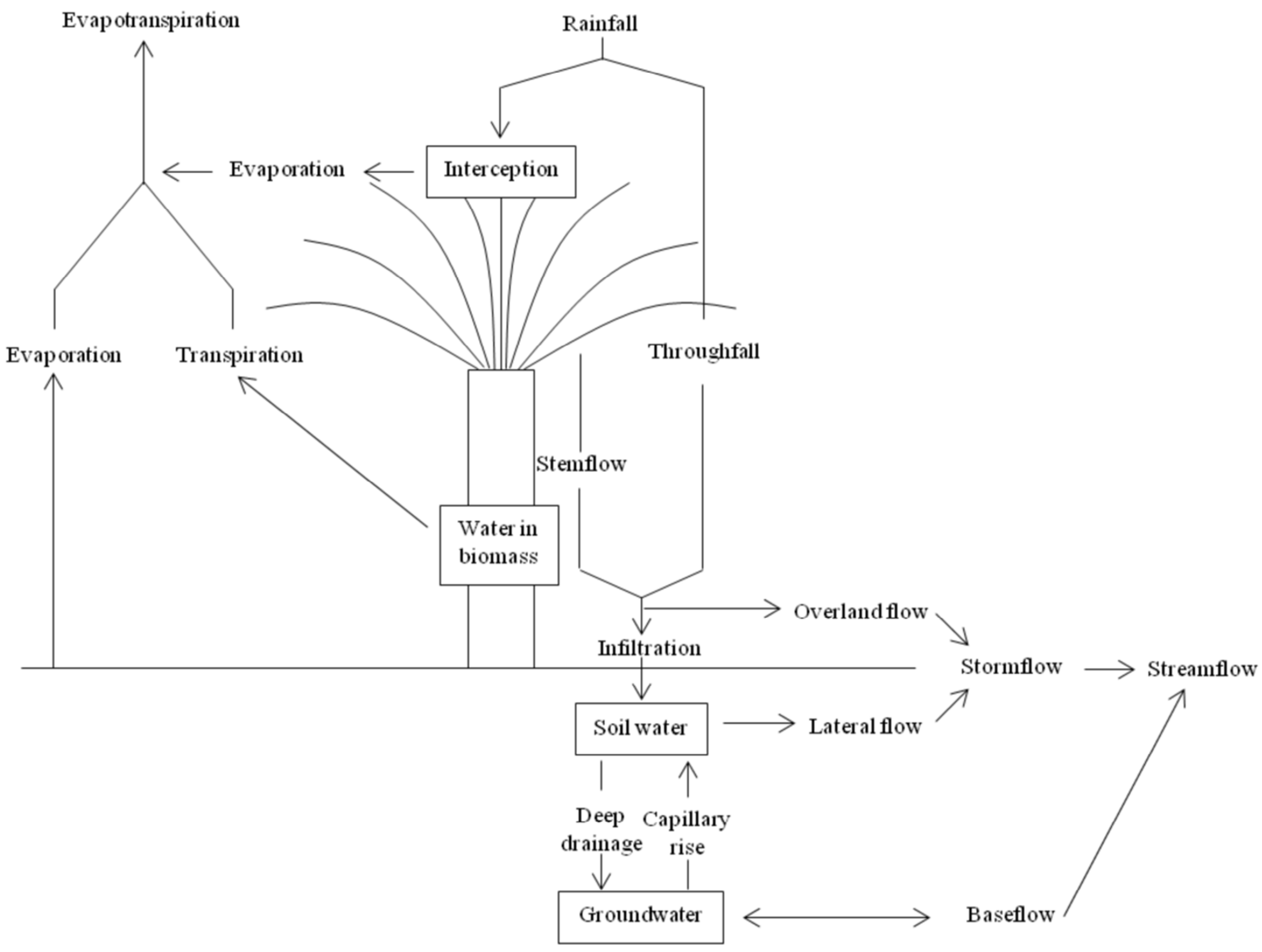


Figure 1.4. The hydrological cycle in oil palm plantation. Boxes indicate storage pools, arrows indicate fluxes.

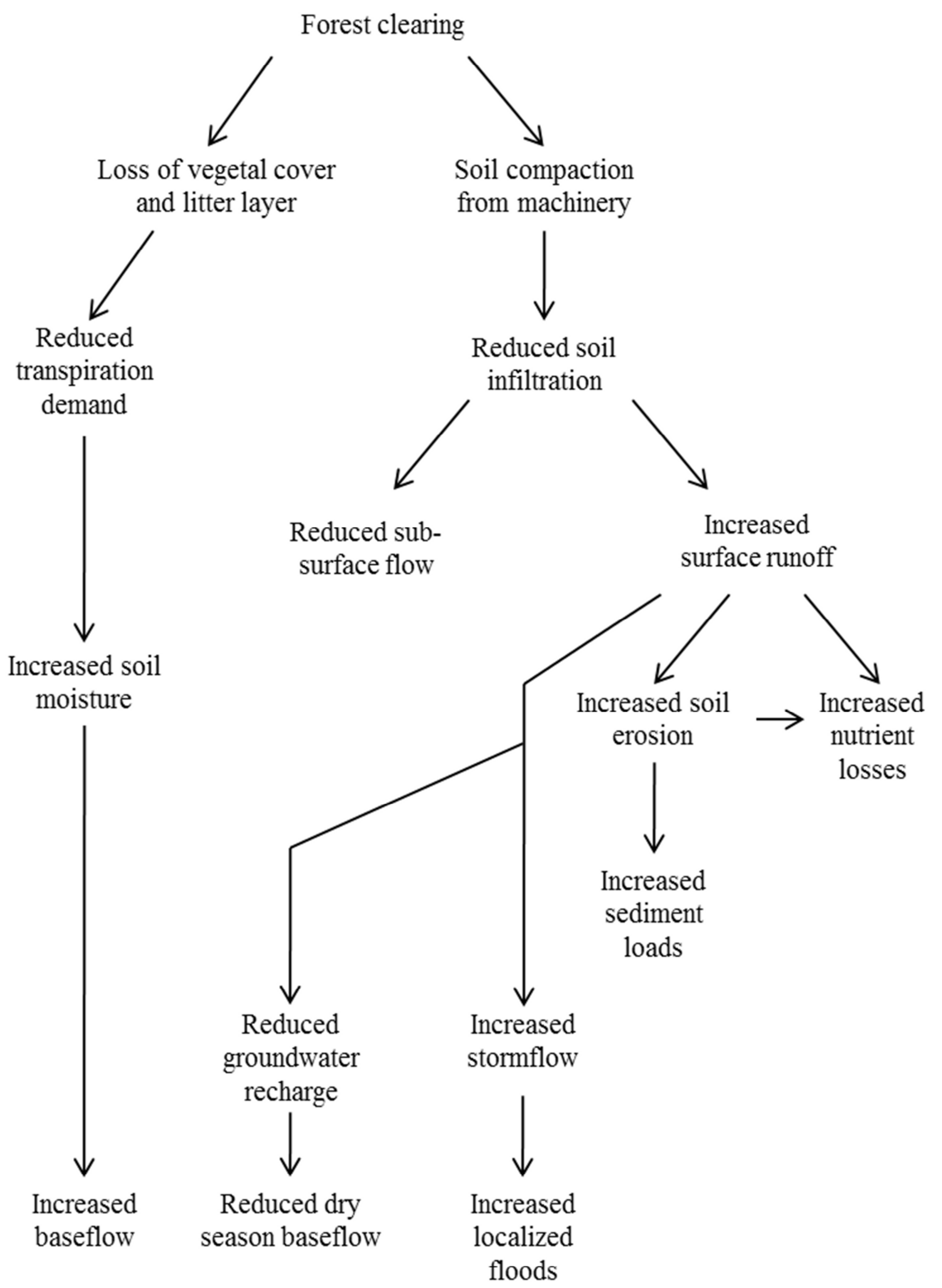


Figure 1.5. Hydrological impacts of forest clearing (modified from Henson, 1999)

Connecting Paragraph to Chapter 2

The literature review highlighted the environmental issues raised by the expansion of oil palm plantations in Southeast Asia. Oil palm planters have to ensure high yields to keep pace with the growing demand for oil and fats, while mitigating environmental impacts. The review showed that the risk of nutrient export to streams and its relationship to fertilizer applications and/or soil characteristics was poorly understood, and needs further investigation.

The literature review described the fertilizer practices generally followed in commercial oil palm plantations in Southeast Asia. Plot-scale fertilization management, which is the norm in commercial plantations, does not take account of soil variability throughout the plantation landscape, especially in devising a long term strategy for applying organic and mineral fertilizers for high nutrient use efficiency and soil fertility improvement.

I chose to work at the landscape-scale in an oil palm plantation characterized by soil variability (due to the large scale) to assess the response of diverse soil types to long term (> 7 years) fertilizer management (sequences with organic fertilizer only, mineral fertilizer only, or a combination of the two). Working with data from 4000 ha area allowed me to develop a landscape-scale approach to assess the effect of fertilization practices on soil properties in a large-scale, heterogeneous perennial agroecosystem. Then, in the next Chapter I will assess the stream water quality and the influence of fertilizer practices and soil types on nutrient fluxes in streams.

CHAPTER 2. Landscape-scale assessment soil response to long-term organic and mineral fertilizer applications in an industrial oil palm plantation in Indonesia

2.1 Abstract

Organic fertilizers improve soil fertility in oil palm plantations, based on small-scale (< 30 ha), short-term (3-5 yr) studies, but the response is not equal across soil classes. Since organic fertilizers are costly to handle and apply, relative to mineral fertilizers, producers need to know where and how frequently to apply organic fertilizers to improve soil fertility. This study assessed the soil response to long-term mineral and organic fertilizer applications in an industrial oil palm plantation. A landscape-scale approach was developed to cope with unavailable historical soil data, variability in fertilizer application sequences and diverse soil classes across the plantation. Soil response to fertilizer application was inferred from (i) a one-off soil survey, (ii) record of fertilizer sequences, and (iii) knowledge of the biogeochemical processes underlying the measured soil response. Low-fertility Ferralsols responded significantly to continuous organic fertilizer application, with greater improvement of some soil chemical parameters in the loamy-sand uplands (pH: + 0.48 unit, base saturation: + 150 %, sum of bases; + 220 %) than in the loamy lowlands (pH: + 0.35 unit, base saturation: + 8 %, sum of bases; + 16 %). In the loamy-sand uplands, discontinuing organic fertilizer applications significantly decreased the organic carbon concentration without reducing the pH, base saturation or nutrient concentrations, but organic carbon was protected from mineralization by slower drainage and fine texture in the loamy lowlands. We conclude that organic fertilizers should be applied regularly to loamy-sand uplands to sustain soil fertility.

Key Words: oil palm, soil chemical properties, long-term fertilizer application, organic and mineral fertilizers, landscape-scale approach

2.2. Introduction

Since the 1960s, the rapid expansion of oil palm (*Elaeis guineensis*) cultivation in Southeast Asia has provided food and employment for several million people and contributed to the development of poor countries. However, it has also raised environmental concerns regarding deforestation, loss of biodiversity, greenhouse gas emissions, and the degradation of soil and water quality (Sheil et al., 2009; Tan et al., 2009). Soil degradation is of concern because oil palm is cultivated predominantly on tropical soils that are highly acidic and have low buffering capacities (Harter, 2007). Due to the low inherent fertility of these soils and the high nutrient removal in harvested products, fertilizer input is necessary to sustain high yields and typically constitutes 40-65 % of total field upkeep costs (Caliman, pers. com). When mineral fertilizers are utilized, they can contribute to soil acidification, which causes a further decline in pH and reduces the buffering capacity of these low-fertility tropical soils (Barak et al., 1997; Nelson et al., 2010; Oim and Dynoodt, 2008).

There are two sources of organic fertilizer available to commercial oil palm plantations that operate a processing mill. Palm oil mill effluent (POME) is the wastewater emitted from the mill, which contains organic carbon (including oil and fat), nutrients, suspended solids and microorganisms. For every 1 tonne of crude palm oil produced, 2.7 tonnes of POME are generated (Caliman, pers. com). Empty fruit bunches (EFB) are another mill byproduct, generated at a rate of 1 tonne per tonne of crude palm oil produced. Research underway since the 1980s demonstrates that POME and EFB can be substituted for mineral fertilizers to sustain oil palm yields and soil fertility by significantly increasing the soil pH, water holding capacity, organic carbon content, total nitrogen content, cation exchange capacity (CEC), available phosphorus content and exchangeable non acidic cations (Abu Bakar et al., 2011; Okwute and Isu, 2007; Teh Boon Sung et al., 2011; Thambirajah et al., 1995; Zaharah and Lim, 2000). These positive responses are attributed to an improvement in the soil moisture regime, soil structure, organic matter content and microbial activity, as well as addition of nutrients and a reduction in soil erosion and nutrient losses (Lim and Chan, 1987;

Caliman et al., 2001; Chiew and Rahman, 2002). For this reason, organic fertilizer application is an important practice for oil palm cultivation.

Fertilizer management in an oil palm plantation requires an annual plan for each block (25-30 ha) within the plantation for the duration of the tree's lifespan (25 years). Thus, each block receives a specific fertilizer sequence. On a multiannual period, blocks receive mineral fertilizers only, organic fertilizers only (a uniform fertilizer sequence), or they receive alternating mineral and organic fertilizer applications (called a mixed fertilizer application sequence). Generally, mineral fertilizers are applied throughout the entire plantation, whereas the organic fertilizers tend to be applied to blocks in close proximity to the mill due to the limited supply and the higher cost to transport over long distances, relative to mineral fertilizers. These constraints result in POME and EFB application based on transportation costs, which ignores the fact that the soil response to fertilizer applications differs according to the soil type (texture, buffering capacity) (Salomon, 1999; Wrona, 2006),

Industrial oil palm plantations in Southeast Asia commonly extend over thousands of contiguous hectares with distinct topographical positions and soil classes. Assessing the soil response to fertilizer applications in this large, perennial cultivation system requires both long-term and landscape-scale field studies, which are scarce. Agronomic trials have compared applications of mineral fertilizer only to organic fertilizer only over relatively short (3-5 yr) study periods (Cristancho et al., 2011; Dolmat et al., 1987; Kheong et al., 2010). Soil responses to mixed fertilizer sequences in industrial oil palm plantations are largely unknown. Moreover, agronomic trials often focused on oil palm yields, were conducted on the plot-scale (10-30 ha) and were performed on a single soil class rather at larger spatial scales and across multiple soil classes, which is more representative of industrial plantations (Abu Bakar et al., 2011; Budianta et al., 2010; Loong et al., 1987).

Research results from classical, small plots of homogeneous soils often proved to be of limited relevance when applied to non-level, heterogeneous landscapes. Advances made in landscape-scale soil research (mainly due to the integration of breakthroughs from relevant disciplines such as hydrology, geomorphology and geology) have allowed pedologists to focus on soil properties and processes that cannot be understood apart from their spatial and temporal context (Pennock and Veldkamp, 2006). This implies consideration of land forms and land use to understand how soils change through space and time (e.g. Veldkamp et al., 2001; Follain et al., 2007).

Previous studies showed that organic fertilizer applications significantly improved soil fertility status at the plot-scale. Plantation managers wishing to make better use of organic fertilizers need to know how long-term fertilizer applications (uniform and mixed fertilizer sequences) affect soil responses across the landscape, considering the inherent soil variation within the oil palm plantation. This requires landscape-scale soil studies, which were rarely carried out in large oil palm plantations in South-East Asia. The present study aims to assess the soil response to fertilizer management as a function of soil spatial heterogeneity and through time, to understand the variability in soil fertility status at the plantation-scale. This study hypothesized that (i) the effect of mineral vs. organic fertilizer sources on soil properties can be detected even in large commercial plantations, (ii) the response of soil properties to fertilizer sources depends on the soil type and land form characteristics.

This paper describes a landscape-scale approach that was developed to assess the effect on soil fertility of long-term application of organic and mineral fertilizers in uniform or mixed fertilizer sequences. This approach relied on (i) a one-off soil survey to describe soil types and soil fertility (0-15 cm depth) status within defined land units (called blocks), (ii) an expert index to assign a value to the historical fertilizer sequence in each block and (iii) statistical analysis to compare the soil response to fertilizer sources, within soil classes. Then, the results were interpreted and synthesized in the form of a conceptual model that considers soil biogeochemical processes. The landscape-scale approach was tested in a 4000 ha industrial oil palm plantation in Indonesia, with the goal of providing recommendations for targeted application of organic fertilizers within the plantation to sustain and improve the soil fertility status.

2.3. Materials and methods

2.3.1 Site description

2.3.1.1 Study area

The study area was located in the Petapahan area in the Kampar District, Riau Province, in the Sumatran Central Basin (Figure 2.1). Until 1970, tall *Dipterocarp* forests dominated 95 % of the Petapahan area (Suyanto et al., 2004). Land use in Riau Province has changed rapidly over the past two decades as logged-over forests were cleared for timber and oil palm cultivation (Potter and Badcock, 2001). Since 1991, the oil palm plantation area has doubled in the Petapahan area (Suyanto et al., 2004). Soils are Ferralsols (FAO/ISRIC/ISSS, 1998) that were developed on recent alluvium, with peat deposits in small depressions (Blasco et al., 1986). The relief is flat to slightly undulating. The site has a tropical humid climate with an average annual rainfall of 2400 mm (230 mm month^{-1} in the wet season, 140 mm month^{-1} in the dry season), and the average monthly temperature ranges from 26 to 32°C.

This study was undertaken on a 4000-hectare, 15-year-old industrial oil palm plantation. During the immature stage (1-5 yr old), the blocks had leguminous cover crops (*Mucuna Bracteata*) which died with canopy overlap when palms were 5 yr old. The plantation is divided into 154 blocks for management. The average block size is 26 ha. Oil palm density averages 141 palms ha^{-1} across the plantation.

2.3.1.2. Preliminary soil classification

There was no accurate soil map available to delineate pedological units within the study area, nonetheless local discrimination between main soils of the study site is possible on the basis of the soil texture classes. Field observations suggested that soil spatial distribution was linked to land form. An interpolation method was used to analyze the spatial distribution of soil textures. A digital elevation model was used as an independent layer in a final cross-analysis of the soil texture and topographic derivatives maps that allowed us to propose a pedogeomorphological categorization of the landscape.

Input data came from 73 composite soil samples taken along a regular 1-km grid in the plantation surroundings with georeferenced positions and from 118 composite soil samples taken within the plantation blocks. At each sampling point, 3 sub-samples were collected (0-15 cm depth) and mixed to produce a composite soil sample of the point. Mean semivariograms were established and fitted using exponential models (Figure 2.2).

Geostatistics (Krige, 1951; Matheron, 1965; Gooverts, 1999; Webster and Oliver, 2000) were applied to identify the spatial pattern in soil texture (based on the sand and clay content). The semi-variogram function ($\gamma(|h|)$ (Eq. (1)) was used to quantify the spatial variation of a regionalised variable z, in $N(h)$ number of paired locations x_i, where the variable value is known $z(x_i)$ and separated by a lag distance h.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad (1)$$

Interpolation at the landscape scale was performed with ordinary kriging (Eq. (2)):

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \qquad (2)$$

where $\hat{z}(x_0)$ is the value of the variable z at location x_0, as estimated (1) from the n location of x_i where the value is known and denoted $z(x_i)$ and (2) from the weight of each location λ_i, depending on the variogram model parameters. Then, interpolation was performed via ordinary kriging using Vesper software (Minasny et al., 2005) to determine the spatial distribution of soils with similar texture.

Landform analysis was performed with the Spatial Analyst® extensions of ArcGis 9.3® software. Slope (%) and curvature (m^{-1}) were computed with a SRTM digital elevation model at 90-m resolution. As expected, geomorphological attributes were strongly related to the spatial distribution of soil textures leading to partition the landscape into three pedomorphological categories: (i) sandy soil (100 g kg^{-1} of clay, 750 g kg^{-1} of sand) in the upper part of the colluvial / hillslope domain, ii) loamy-sand soil (160 g kg^{-1} of clay, 500 g kg^{-1} of sand) in the middle part of the colluvial / hillslope domain, and iii) clay soil (510 g kg^{-1} of clay, 110 g kg^{-1} of sand) in alluvial/fluvial domain of the large Tapung Kiri river (Figure 2.3).

Field observations were made to describe drainage conditions related to these geomorphological positions. Sandy upland soils have good drainage throughout the year and cover 42 % of the plantation area. Loamy-sand lowland soils have a shallower water table; they cover 50 % of the plantation area. The remaining 8 % of the plantation were composed of poorly drained clay soil.

2.3.1.3. Fertilizer management

The industrial oil palm plantation applies mineral and organic fertilizers to blocks (Table 2.1). Additionally, palm fronds and understory vegetation cut around the palm tree and along paths through the plantation are deposited in frond piles to decompose and recycle nutrients. Mineral fertilizers include urea, rock phosphate (RP), triple super phosphate (TSP), diammonium phosphate (DAP), muriate of potash (KCl), kieserite, dolomite and high-grade fertilizer borate (HGFB). Mineral fertilizers are applied by hand on the soil surface around the tree (the area covered corresponds to the palm circle) or sprayed over the palms from an airplane. Application of urea, TSP and MOP generally occurs twice a year, from February to March and from October to November, while other mineral fertilizers tend to be applied once per year.

Organic fertilizers were POME and EFB. The POME is a brownish colloidal suspension discharged from the mill into open wastewater treatment ponds for anaerobic digestion followed by aerobic digestion (Singh et al., 2010). Then, it is applied through irrigation pipe once (750 m^3 ha^{-1}) or twice (2 x 375 m^3 ha^{-1}) a year in the alleys between oil palm trees. In terms of fertilizer use, one tonne of POME is equivalent to approximately 2.2 kg of urea, 1.5 kg of TSP, 5.8 kg of MOP and 0.6 kg of kieserite (Caliman, pers. com) assuming a density of 1000 kg m^{-3}. Total carbon content represents 31.5 % of the POME dry matter (Wong et al., 2008). EFB is a wet (about 70 % water content) cellulose-rich residue with 65.5 % holocellulose, 21.2 % lignin, 3.5 % ash, 5.6 % hot water-soluble substances and 4.1% alcohol-benzene soluble substances on a dry matter basis. Total carbon content represents 44.1 % of the EFB dry matter (Thambirajah et al., 1995; Wong et al., 2008). Within a few days of processing at the mill, fresh EFB are surface-applied in the alleys between oil palm trees. Direct application of one tonne of EFB to the block is equivalent to approximately 6.1 kg of urea, 1.7 kg of TSP, 16.3 kg of MOP and 3.0 kg of kieserite (Caliman et al., 2001).

2.3.2. Landscape-scale approach: description and assumptions

A landscape-scale approach was developed to assess soil responses to long-term organic and mineral fertilizer applications, across diverse soil classes and variable fertilizer sequences. This approach permits analysis of soil responses when there is no historical record of soil analysis, but historical fertilizer applications to blocks are known. We assumed that the initial soil fertility level was the same for a given soil class across the plantation.

2.3.2.1 Attributing a soil class to each block

The block was the basic land unit for agronomic management, so the first step was to assign a soil class to each block in the plantation (Figure 2.4a).

2.3.2.2 Calculation of the fertilizer application sequence value for each block

We obtained the historical record of fertilizer application for each block from the plantation manager, which included data from a 7-yr period, from 2004 to 2010 inclusive. Some blocks had a uniform fertilizer sequence (mineral fertilizer only, organic fertilizer only) during the study period, but most blocks had mixed fertilizer sequences (i.e., yearly alternation of organic and mineral fertilizer applications). Additionally, the mixed fertilizer sequences have different levels of heterogeneity. For example, a mixed fertilizer sequence of 7 years including 2 years of organic fertilizer applications + 2 years of mineral fertilizer applications + 2 years of organic fertilizer applications + 1 year of mineral fertilizer applications has greater heterogeneity than a mixed fertilizer sequence including 5 years of mineral fertilizer applications followed by 2 years of organic fertilizer applications. Given the variability among mixed fertilizer sequences in this plantation, blocks that received similar mixed fertilizer sequences were grouped before comparative statistical tests was done. An expert index was conceptualized to calculate and attribute a fertilizer sequence value (FSV) to each block. The FSV expresses (i) the dominance of organic or mineral fertilizer in the fertilizer sequence, and (ii) the level of heterogeneity in the fertilizer sequence.

The expert index calculates the FSV for each block using two coefficients: a time coefficient (Y, in years) and a fertilizer application coefficient (F) (Eq.(3)). The expert index assumed that fertilizer application in the first year of the sequence (Y_1) had the least effect, whereas fertilizer application in the last year of the sequence (Y_n) had the greatest effect on soil fertility status at sampling time Y_n. Thus, the coefficient Y was an integer from 1 to n, with a value of 1 assigned to the first year of the fertilizer application sequence and n assigned to the last year (Y_n) (i.e. the year that soil response was measured). A slightly higher weight was allocated to organic fertilizer application (+2) relative to mineral application (-1) because organic matter addition has long-lasting effect *per se* (mineralization) (Diacono and Montemurro, 2010; Szott and Kass, 1993), and because nutrient input from organic fertilizers exceeded that from mineral fertilizers of an equal surface area (Table 2.1). Opposite signs allowed us to distinguish between organic (+) and mineral (-) fertilizer dominance through a fertilizer sequence.

$$FSV = k\sum_{i=Y1}^{Yn} Y_i.F_i \qquad (3)$$

k: normalization coefficient.

Yi: time (year) coefficient with $\{Y_{1;}\ Y_{i;}\ Y_n\} = \{1; i; n\}$

Fi: fertilizer application coefficient (mineral fertilizer: *Fi* = -1; organic fertilizer: *Fi* = +2).

By construction, the FSV produces discrete values. The FSV values are negative for mineral dominant sequences and positive for organic dominant sequences. They range between -50 for uniform mineral sequence to 100 for uniform organic sequence. This index is used to classify the blocks according to their fertilizer sequences (Figure 2.4b&c) and leads to compare the soil properties of blocks between each group.

There were 19 different fertilizer application sequences on the 96 blocks considered in this study, and their FSV are presented in Table 2.2. The lowest FSV was -50 in blocks that received mineral fertilizer only and the greatest FSV was 100 in blocks with organic fertilizer only during the period under consideration (2004-2010, inclusive). A negative FSV indicates the dominance of mineral fertilizer application, while positive FSV indicates the dominance of organic fertilizer application in a mixed fertilizer sequence. A FSV close to zero indicates a mixed fertilizer sequence with a high level of heterogeneity.

2.3.2.3. Construction of nested sets within each soil class

To better assess the effect of organic vs. mineral historical fertilizer sequences on soil properties, we first aimed to compare the effect of organic vs. mineral fertilizer applications on blocks that received uniform fertilizer sequences. Then, we checked whether the effect observed for blocks with uniform fertilizer sequences would still be discernible when adding blocks with increasing heterogeneity in their fertilizer sequences. To achieve this, within each soil class identified in the plantation, we built nested sets of blocks based on their FSV. Each nested set included two groups of blocks: (1) blocks that received a predominantly organic fertilizer sequence and (2) blocks that had a comparably dominant mineral fertilizer sequence. The first set (S_1) included two block groups:

(1) blocks that received a uniform organic fertilizer sequence (S_1o) and (2) blocks that received a uniform mineral fertilizer sequence (S_1m). The second set (S_2) included blocks with mixed fertilizer sequences having a low level of heterogeneity, in addition to the blocks already included in S_1. The procedure was repeated by progressively adding blocks with increasing heterogeneity until the last set (S_n), which included all blocks. The spatial variability of fertilizer management across the plantation is illustrated in Figure 2.5.

In this study, blocks were allocated to 4 nested sets (S_1, S_2, S_3 and S_4) based on their FSV and soil class. The FSV ranges chosen to construct the 4 nested sets were: S_1 = [-50] U [100]; S_2 = [-50, -30 [U] 60, 100]; S_3 = [-50, -10[U] 20, 100]; and S_4 = [-50, 0[U] 0, 100] (Figure 2.4d, Table 2.2). The number of soil samples within each set and soil classes are given in Figure 2.5. The clayey soil class received mineral fertilizers only (null sample size from S_1o to S_4o) and was not considered further in the comparative analysis. Statistical analysis was performed with data from the dominant soil classes, loamy-sand uplands (n=126) and loamy lowlands (n=138) (Figure 2.4e).

2.3.2.4 Soil fertility survey and soil analysis

The next step was to perform a one-off soil survey at the landscape scale to assess the current soil fertility status across the plantation. An one-off soil survey was done in the 4,000 ha plantation in 2010. We selected 96 of the 154 blocks within the plantation, and within those blocks collected soil samples at a density of one sampling location per two hectares for assessment of soil fertility status. Due to the heterogeneous structure of the oil palm plantation, a stratified soil sampling method was employed to account for intra-block variability (Maena et al., 1979; Law et al., 2009). This involved taking three sub-samples of soil (0-15 cm depth) from three zones in the vicinity of a palm tree: the palm circle, the harvest path and the frond piles. All sub-samples from a particular zone (e.g., palm circle) were mixed to obtain a representative sample from that block, and then composited with samples from the same zone, taken from other locations in the block. In total, 288 composite soil samples (96 blocks x 3 zones) were collected.

Soil fertility properties considered in this study were: the pH, determined in water using a pH meter (soil: water ratio of 1:1); organic carbon (OC) content, measured using the Walkley-Black method (Nelson and Sommers, 1982); Kjeldahl nitrogen (TN) content according to Bremmer and Mulvaney (1982); the cation exchange capacity (CEC) was determined using the ammonium replacement method (CH_3COOH, pH = 7.0) (Thomas, 1982); the sum of bases was calculated by summing exchangeable K, Mg, Ca and Na concentrations measured with the ammonium acetate method (van Reeuwijk, 1993); and the base saturation (BS) was calculated as the ratio of the sum of bases to the CEC. Analytical results represent the nutrient levels and other soil physico-chemical parameters in mineral soil, which did not include undecomposed residues (EFB, fragments of vegetation and other organic residues) since those residues were not included at the time of sampling and visible fragments were removed prior to analysis.

2.3.2.5 Statistical analysis

Finally, comparative statistical analysis was performed on soil fertility parameters within each soil class, between the groups S_io and S_im, from each set S_1 to S_n. Tests were performed on the measured soil fertility parameters (pH, OC, TN, CEC, sum of bases and BS) of the two groups (organic-fertilized blocks (S_im) vs. mineral-fertilized blocks (S_io) when the population size of each group was at least n=10. Data were not normally distributed before and after log transformation, so comparisons (e.g., S_1m vs. S_1o, S_2m vs. S_2o and so on, for each soil class) were based on the non-parametric Wilcoxon test. Statistical analyses were performed using R (R Development Core Team, 2011).

2.4. Results

2.4.1. Overall soil fertility status

All soils in the study area were acidic, with pH values between 3.43 and 5.30. Other soil fertility properties varied according to the soil class: OC was between 8.6 and 499 g kg^{-1}, TN ranged from 4 to 121 g kg^{-1}, CEC was between 2.1 and

63.1 cmol kg^{-1}, the sum of bases was 0.1 to 15.1 cmol kg^{-1}, and the BS was 1 to 93 %. Figure 2.6 synthesizes the measured soil properties over the plantation by showing average values (from the three sampling positions) per block.

The average values of pH, OC, TN, CEC and sum of bases were significantly greater on the loamy lowlands than on the loamy-sand uplands (Table 3). Considerably pH, OC, TN and CEC values for tropical acidic soils under oil palm (Gow and Chew, 1997), the pH and TN levels were high on the loamy lowlands, but moderate on the loamy-sand uplands. The OC level was very high on both soil classes, while the CEC level was moderate on the loamy lowlands and low on the loamy-sand uplands.

2.4.2. Effect of organic versus mineral fertilizer on soil fertility in uniform fertilizer application sequences

There was significantly ($p<0.05$) greater pH, OC, TN, CEC, sum of bases and BS in blocks that received uniform organic fertilizer sequences (S_1o) than uniform mineral fertilizer sequence (S_1m) on the loamy-sand uplands (Figure 2.7). There was no S_1m sequence on the loamy lowlands, so it was no possible to compare the effect of uniform fertilizer sequences with organic vs. mineral fertilizer in this soil class.

2.4.3. Effect of organic versus mineral fertilizer on soil fertility in mixed fertilizer sequences

Mixed fertilizer sequences increased in heterogeneity from S_1 (uniform fertilizer application sequence) to S_4. Figure 2.7 shows the fertility parameters value as a function of the level of heterogeneity of the mixed fertilizer sequences. Fields on the loamy-sand uplands receiving predominantly organic fertilizer had significantly ($p<0.05$) greater pH, TN, sum of bases and BS than those with dominant mineral fertilizer application, even as heterogeneity increased in the fertilizer sequence (Figure 2.7). In the loamy-sand uplands, significant differences ($p<0.05$) in OC and CEC between organic-fertilized and mineral-fertilized blocks at S_1 became non-significant by S_2. Fields on the loamy lowlands had significantly ($p<0.05$) greater OC, TN, CEC and sum of bases when they received predominantly organic fertilizer, regardless of the homogeneity level, but the difference in pH between blocks fertilized with predominantly organic or mineral fertilizers decreased with increasing heterogeneity and was not significant by S_4. The BS was higher in organic-fertilized than mineral-fertilized blocks in the loamy lowlands at S_3 but not in other nested sets (Figure 2.7).

2.5. Discussion

The key finding from this study is the significant soil response to long-term organic fertilizer application in both loamy-sand uplands and loamy lowlands. This was expected, based on previous studies that document a rapid response to organic fertilizer application on low-fertility tropical soils (i.e., highly weathered, having high iron and aluminum oxide concentration), similar to the Ferralsols considered in this study (Turmel et al., 2011). However, the expected response is based on plot-scale studies where organic fertilizers were applied recently or there were several years of repeated organic fertilizer applications. The novelty of the landscape-scale approach developed for this study is that it allows us to describe soil responses to multi-year fertilizer applications with mixed fertilizer sequences, alternating between mineral and organic fertilizer sources and having an unequal number of applications of each source, across a large spatial area (4000 ha). Results of this study for blocks receiving mixed fertilizer sequences reveal differences in soil responses between loamy-sand uplands and loamy lowlands soil classes. Blocks receiving continuous organic fertilizer sequence had higher levels of OC content and CEC than others. Increasing heterogeneity in the mixed fertilizer sequence led to a decline in pH in the loamy lowlands, and the BS in this soil class was little affected by fertilizer application. These soil responses to fertilizer application are interpreted based on a conceptual model of soil biogeochemical processes in acidic tropical soils (Figure 2.8).

2.5.1. Effect of organic fertilizer application on soil fertility parameters in loamy-sand uplands and loamy lowlands

2.5.1.1. Soil pH

In the loamy-sand uplands, continuously organic-fertilized blocks had pH values 0.55 units higher than mineral-fertilized blocks, and the difference was maintained even when organic fertilizer application was infrequent. The blocks from loamy lowlands were a little less acidic, around pH 4.1 in blocks with predominantly mineral fertilizer application. Although pH differed significantly between mineral and organic groups in the S2 and S3 sets, it did not differ significantly in the S4 set, because the values converged with increasing heterogeneity of fertilizer sequence. Overall, a greater improvement in soil pH was achieved by applying organic fertilizer to loamy-sand uplands than loamy lowlands.

Organic fertilizers often have a liming effect on acidic soils, and our results are consistent with the significant increase in pH observed following application of POME and EFB (Abu Bakar et al., 2011; Caliman et al., 2001; Okwute and Isu, 2007). There are several processes by which soil pH can be raised when organic matter is added, including denitrification, mineralization and decomplexation of organically-bound metals, mineralization of organic N, sulphate reduction, microbial uptake of mineral N, S or P (van Breemen et al., 1983). Some authors suggested that the increase in soil pH is due to ash alkalinity (organic anion content) in the organic fertilizer (Mokolobate and Haynes, 2002; Noble et al., 1996) or from microbial activity (Yan et al., 1996) because the microbial breakdown of organic anions is a decarboxylation reaction that causes proton consumption (Barekzai and Mengel, 1993). Release of basic cations like K^+ from fresh organic matter can displace the acidic cations Al^{3+} and H^+ from soil surfaces and permit the consumption of H^+ ions, thereby increasing the soil pH (Li et al., 2008; Pocknee and Sumner, 1997; Tang and Yu, 1999). Abu Bakar et al. (2011) attributed the pH increase following EFB to its high K content. Budianta et al. (2010) noted that anaerobic soil conditions following EFB application could cause a pH increase because this would reduce cations from high valence states to lower states, thus releasing the hydroxide ion and creating a microenvironment with alkaline conditions. However, the effect of EFB on soil reducing conditions would likely be temporary and so is unlikely to explain the long-term effect of organic fertilizers on soil pH, particularly in mixed fertilizer sequences where organic fertilizers were applied infrequently (e.g., S_3 and S_4). Future work on mechanisms underlying the apparent liming effect of POME and EFB should investigate how the non-acidic cations in these materials may contribute to displacement of H^+ ions, followed by proton consumption with organic anions or associated with microbial activity.

Soils from the loamy-sand uplands class were more acidic than those from loamy lowlands soil class, which was expected. Intensively cultivated sandy soils are sensitive to acidification because they are more vulnerable to leaching, have lower buffering capacity and tend to receive more fertilizer N inputs than loamy or clayey soils (Nawaz et al., 2011). Mineral N fertilizers are implicated in soil acidification because two protons are produced when NH_4^+-N is nitrified to NO_3^--N (Anuar et al., 2008; Thomas and Hargrove, 1984). The application of urea and ammonium-based fertilizers reduces soil pH on oil palm plantations (Caliman et al., 1987; Kee et al., 1995; Nelson et al., 2010), particularly when long-term application of N fertilizers causes a decline in exchangeable K^+ due to the displacement of K^+ by NH_4^+-N that results in K^+ leaching through the soil profile (Anuar et al., 2008). Examining the mixed fertilizer sequences that received predominantly mineral fertilizer showed no difference in soil pH from S_1 to S_4 in the loamy-sand uplands, but a trend of increasing pH from S_2 to S_4 in the loamy lowlands, which may suggest that acidification from mineral N fertilizer was occurring in the loamy lowlands. The liming effect of dolomite applications may limit pH acidification caused by urea applications. Blocks that received urea plus dolomite had pH values of 4.06 on the SLL (n=12) and 3.88 on the SU (n=12), which was not statistically different from blocks that received urea only (pH=4.18 on SLL (n=9) and pH 3.99 on SU (n=27), $p>0.05$, Wilcoxon test). This suggests that dolomite applications did not increase the soil pH in the study region. This suggested that, in this study, dolomite applications did not seem to have a significant effect on the soil pH. The loamy lowlands appeared to have a higher inherent buffering capacity against acidification than the loamy-sand uplands soil class. At the low pH of these soils it is likely to be due mostly to the dissolution of clay minerals and other minerals (Bloom, 2000).This buffering capacity may be ascribed to hydrolysis of pedogenic Al compounds (Wiseman and Püttmann, 2006), which are present in greater concentration in the loamy lowlands than the loamy-sand uplands (data not shown). Aluminum hydroxides (e.g., $Al(OH)_3$) react with protons to release Al^{3+} and three protons are consumed in the reaction, thus the pH changes at a slower rate than predicted from acidification reactions (Harter, 2007; Thomas and Hargrove, 1984).

2.5.1.2. Organic C and total N

Organic fertilizers are a source of fresh organic matter, which is gradually mineralized to CO_2 or transformed into stable soil organic matter (Schvartz et al., 2005). Of the two organic fertilizers available in this study, EFB might be expected to decompose more slowly due to its high lignin content (25-30 % on a dry weight basis), yet total decomposition of EFB in oil palm plantations occurs in less than 12 months (Haron et al., 1998; Teh Boon Sung et al., 2010). Continuous application of organic fertilizers resulted in 1.6 times more OC in the loamy-sand uplands, but these levels declined rapidly when organic fertilizer application occurred less frequently. Fields in the loamy lowlands soil class had up to 1.8-fold more OC in the mixed fertilizer application sequences with predominantly organic fertilizer application, compared to mineral fertilizer application. Since OC declined significantly between S_1 and the mixed fertilizer sequences in the loamy-sand uplands, but not the loamy lowlands, this suggests that organic fertilizers were more susceptible to mineralization in the loamy-sand uplands. Conditions in the loamy-sand uplands favored mineralization because those soils were typically well drained and aerated, which would favor microbially-mediated mineralization. In contrast, the loamy lowlands had a higher water table, which probably led to the accumulation of organic matter (Sahrawat, 2003). Another difference in the soil classes was the greater clay content in the loamy lowlands than the loamy-sand uplands, which implies organo-mineral associations with clay minerals and/or iron oxides that may sequester OC and protect it from decomposition (Eusterhues et al., 2003; Krull et al., 2001; Wiseman and Püttman, 2006).

The TN concentration was up to 2 times greater in the loamy-sand uplands blocks and about 1.6 times greater in the loamy lowlands blocks with uniform and mixed fertilizer application sequences dominated by organic fertilizers, compared to mineral fertilizers, which was significant regardless of the level of heterogeneity in the mixed fertilizer sequence. These results seem to suggest that TN is not mineralized and lost from soil at the same rate as OC content in oil palm plantations, but the mechanisms responsible for conserving TN in these soils require further study. Overall, the improvement in OC content from regular application of organic fertilizer was greater in the loamy-sand uplands than loamy lowlands soil class.

2.5.1.3. Cation exchange capacity and base saturation

The CEC is an indicator of potential nutrient adsorption on organo-mineral complexes, particularly the retention of basic cations (e.g., K, Na, Ca and Mg) by electrostatic forces (Zech et al., 1997). Higher CEC is associated with an increase in soil organic matter and pH (Diacono and Montemuro, 2010; Helling et al., 1964). In the loamy-sand uplands, blocks receiving continuous organic fertilizer application had the highest CEC value, due to the concomitantly high OC and pH values. There was a decline in the CEC between S_1 and the mixed fertilizer sequences, which mirrored the decline in OC in the loamy-sand uplands. The lowlands had greater CEC when receiving mixed fertilizer application sequences dominated by organic fertilizers, compared to mineral fertilizers, and the pattern of CEC was consistent with the OC concentration in loamy lowlands. This leads us to conclude that CEC was controlled more by the OC concentration than soil pH in both loamy-sand uplands and loamy lowlands in the oil palm plantation. This is consistent with van Wambeke (1979), who noted that most of the CEC in soils dominated by kaolinite and amorphous oxides, such as Ferralsols, is associated with soil organic matter rather than with the mineral components. Labile organic matter is often considered to be the most important source of CEC in tropical soils (Duxbury et al., 1989; Zech et al., 1997). To maintain high CEC values, we recommend regular application of organic fertilizer to loamy-sand uplands.

We observed that CEC declined with increasing heterogeneity in the organic dominant fertilizer sequences (dotted line) while BS remained constant. On one hand, increasing heterogeneity in organic dominant fertilizer sequence implies a decrease of organic fertilizer inputs. This induced a decrease of the CEC since the CEC was strongly correlated to organic matter ($R^2 = 0.83$). On the other hand, the sum of bases remained constant with increasing heterogeneity in organic dominant fertilizer sequences, likely due to increasing mineral fertilizer inputs. Since BS is the ratio between the sum of bases and the CEC, when CEC decreases while the sum of bases remained constant, the BS should have increased. However, it remained constant for both soil types. Consequently, the decreasing CEC and constant BS suggest that nutrients may be lost more easily with increasing heterogeneity when mineral fertilizer applications replaced organic fertilizer applications.

The CEC was approximately twice as high in the loamy-sand lowlands than the loamy-sand uplands, which is related to the higher clay and organic matter contents in the loamy lowlands. While the sum of bases increased under mineral fertilizer sequences in both soil types as a result of increasing organic fertilizer application (continuous line), the BS was significantly greater under organic fertilizer sequence vs. mineral sequence in the loamy-sand uplands only. Organic fertilizers are a source of non-acidic cations, but they must be retained in CEC sites to be included in the sum of bases and BS measurements. These results suggest that a greater proportion of non-acidic cations were adsorbed to the solid phase in the loamy-sand uplands than in the loamy lowlands (the remainder of the non-acidic cations in the loamy lowlands were in soil solution, rather than adsorbed to the solid phase). To shift the equilibrium between the solid phase and soil solution will require greater inputs of non-acidic cations in the loamy-sand uplands. We conclude that larger inputs of organic fertilizer or mineral fertilizers containing non acidic cations (particularly K, Ca and Mg) could be helpful to maintain an adequate soil solution concentration of these essential plant nutrients in the loamy-sand uplands, for optimal fertilizer management of oil palm.

2.6. Conclusion

A landscape-scale approach was used to assess the soil response to long-term mineral and organic fertilizer applications across a 4000-hectare industrial oil palm plantation. This approach required information on the spatial distribution of soil classes and historical fertilizer sequences across the landscape, as well as the biogeochemical processes that explain soil responses to long-term application with uniform and mixed fertilizer sources. We demonstrated a general improvement in soil fertility status with organic fertilizer applications compared to mineral applications in an oil palm plantation, which was expected, and a decline in some soil fertility parameters when organic fertilizers were applied infrequently over a 7-yr period. For instance, the pH, OC and CEC levels in loamy-sand uplands were highest when organic fertilizer was applied continuously and declined significantly ($p<0.05$) when organic fertilizer was applied infrequently. We recommend regular application of organic fertilizer to maintain OC and CEC in this soil class.

Information on initial soil conditions in fields when the plantation was established and follow-up soil sampling at regular intervals during the life-cycle of oil palm would be helpful in describing the evolution of soil responses and validating predictions from the landscape-scale approach. We recommend that soil sampling campaigns be undertaken within the plantation every 3-5 yrs to track the evolution of soil fertility within blocks and adjust the fertilizer application program accordingly. Since the category of organic fertilizers included two types (POME and EFB), future investigations to compare mineral fertilizer to each type of organic fertilizer could provide further insight into the strategic use of these limited resources in oil palm plantations. Still, the landscape-scale approach may be the only feasible way to evaluate the long-term soil response to organic vs. mineral fertilizer applications in large commercial plantations. The approach could be extrapolated to describe soil response in other oil palm plantations under similar pedoclimatic conditions, or adapted to assess the soil response to fertilizer sequences in other large perennial crop systems.

Table 2.1. Description of mineral fertilizer-equivalent nutrient inputs from organic fertilizers, empty fruit bunches (EFB) and palm oil mill effluents (POME), along with average application rates for each fertilizer (kg ha^{-1}) in an oil palm plantation.

Fertilizer	Application rate (kg ha^{-1} yr^{-1})	Nutrient application rate (kg ha^{-1} $year^{-1}$)*				
		N	P	K	Mg	Ca
Organic fertilizers						
POME	750,000	750	225	2175	975	-
EFB	40,000-60,000	108-162	déc-18	324-486	20-30	20-30
Mineral fertilizers						
Urea	35-560	7.4-258	0	0	0	0
TSP	35-350	0	9.1-91	0	0	4.2-50
MOP	35-700	0	3.9-105	17.4-349	0	0
Kieserite	35-280	0	0	0	5.7-45.6	0
RP	105-490	0	15.4-72	0	0	0
DAP	35-560	7.4-119	8.2-132	0	0	0
Dolomite	70-210	0	0	0	7.6-22.8	14-51

* After Caliman et al., 2001; APOC 2003, 2004

EFB : empty fruit bunch ; POME : palm oil mill effluent ; TSP : triple super phosphate ; MOP : muriate of potash (KCl); RP : rock phosphate ; DAP : diammonium phosphate

Table 2.2. Calculation of the fertilization sequence value (FSV) based on the expert index, and membership of data analysis sets for each fertilizer sequence.

Fertilization sequence							FSV	Set membership
2004	2005	2006	2007	2008	2009	2010		
M	M	M	M	M	M	M	-50	S_1m, S_2m, S_3m, S_4m
O	M	M	M	M	M	M	-45	S_2m, S_3m, S_4m
O	O	M	M	M	M	M	-34	S_2m, S_3m, S_4m
O	O	O	M	M	M	M	-18	S_3m, S_4m
M	M	M	M	M	O	M	-18	S_3m, S_4m
O	O	M	O	M	M	M	-13	S_3m, S_4m
M	O	M	M	M	O	M	-7	S_4m
O	O	M	M	M	O	M	-2	S_4m
O	O	O	O	M	M	M	4	S_4o
M	O	O	M	M	O	M	9	S_4o
O	O	O	M	M	O	M	14	S_4o
O	O	M	O	M	O	M	20	S_3o, S_4o
O	M	O	M	O	O	M	30	S_3o, S_4o
O	O	O	O	M	M	O	41	S_3o, S_4o
O	O	O	M	O	O	M	41	S_3o, S_4o
O	O	O	O	O	O	M	63	S_2o, S_3o, S_4o
O	O	O	O	M	O	O	73	S_2o, S_3o, S_4o
O	O	O	M	O	O	O	79	S_2o, S_3o, S_4o
O	O	O	O	O	O	O	100	S_1o, S_2o, S_3o, S_4o

M : Application of mineral fertilizers

O : Application of organic fertilizers

Table 2.3. Mean ± standard error values for soil fertility parameters in loamy-sand uplands and loamy lowlands in the industrial oil palm plantation

	pH	OC ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	CEC ($cmol\ kg^{-1}$)	Sum ($cmol\ kg^{-1}$)	BS (%)
Loamy-sand uplands (n=126)	4.18 ± 0.38	32.1 ± 19.2	1.5 ± 0.7	8.2 ± 4.3	0.88 ± 0.78	12.2 ± 12.3
	Moderate	Very high	Moderate	Low		
Loamy lowlands (n=138)	4.25 ± 0.34	62.4 ± 36.0	2.6 ± 1.5	15.7 ± 7.7	1.81 ± 1.85	11.9 ± 10.3
	High	Very high	Very high	High		
p-value (Wilcoxon test)	*	*	*	*	*	NS

The classification of pH, organic C (OC), total N (TN) and cation exchange capacity (CEC) was done after Gow and Chew (1997).

Sum: sum of base; BS: base saturation

*: $p<0.05$; NS: non significant

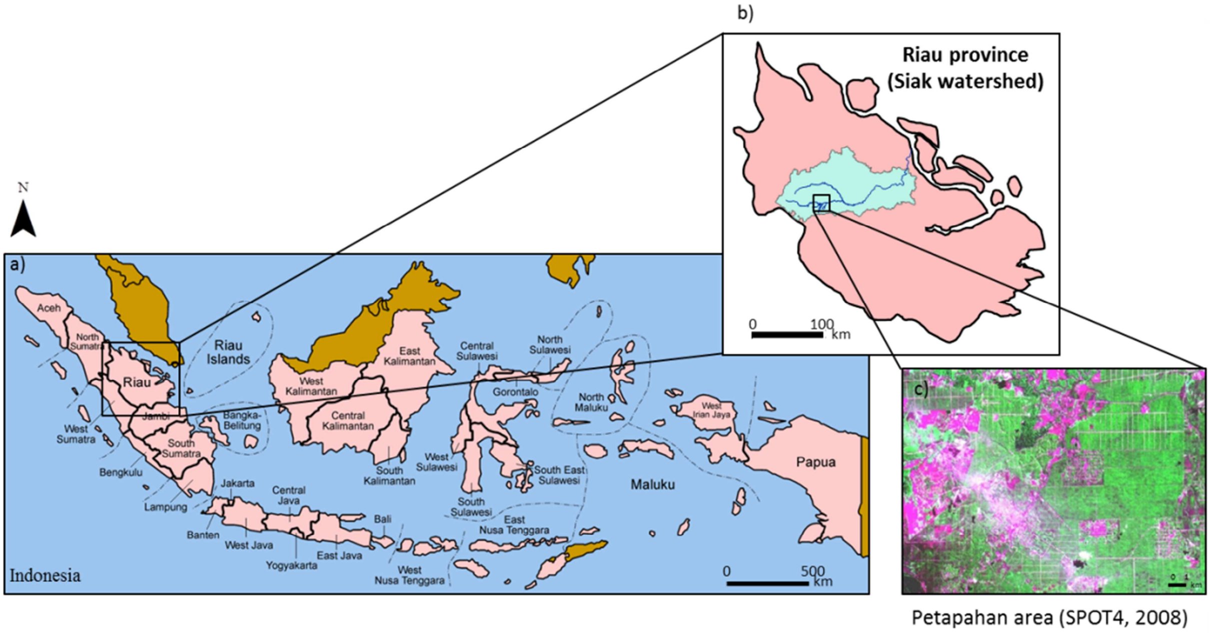


Figure 2.1. Location of the study area in Riau province, Indonesia.

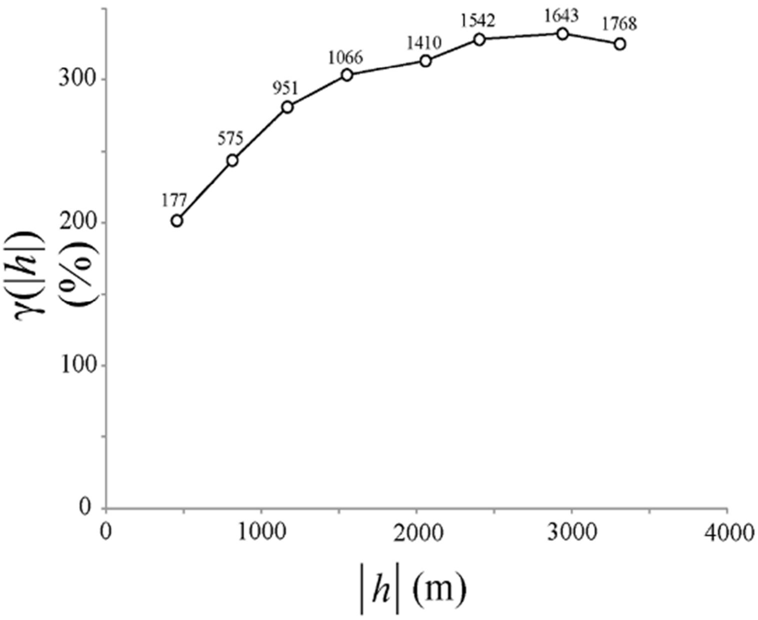


Figure 2.2. Semi-variogram of sand variable.

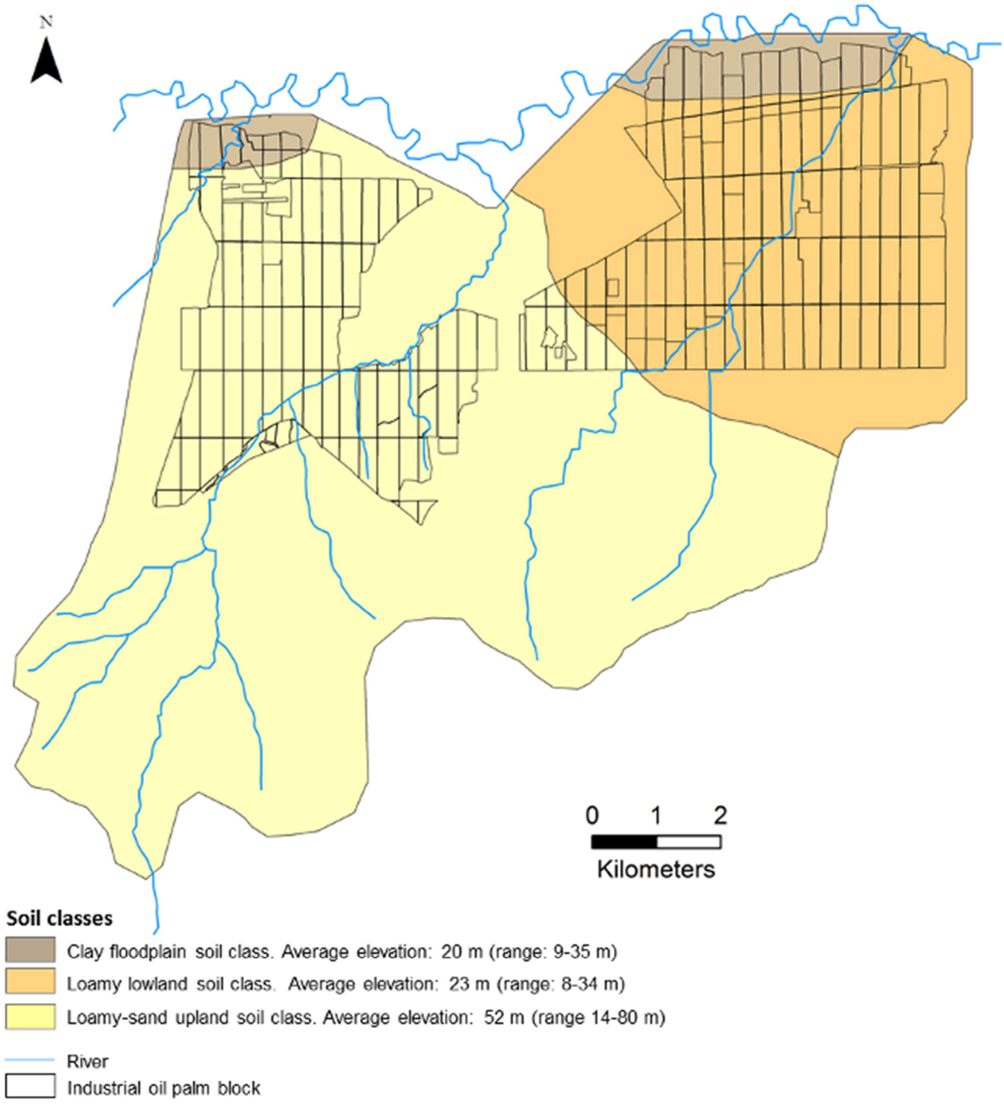


Figure 2.3. Categorization of soil classes in the study area.

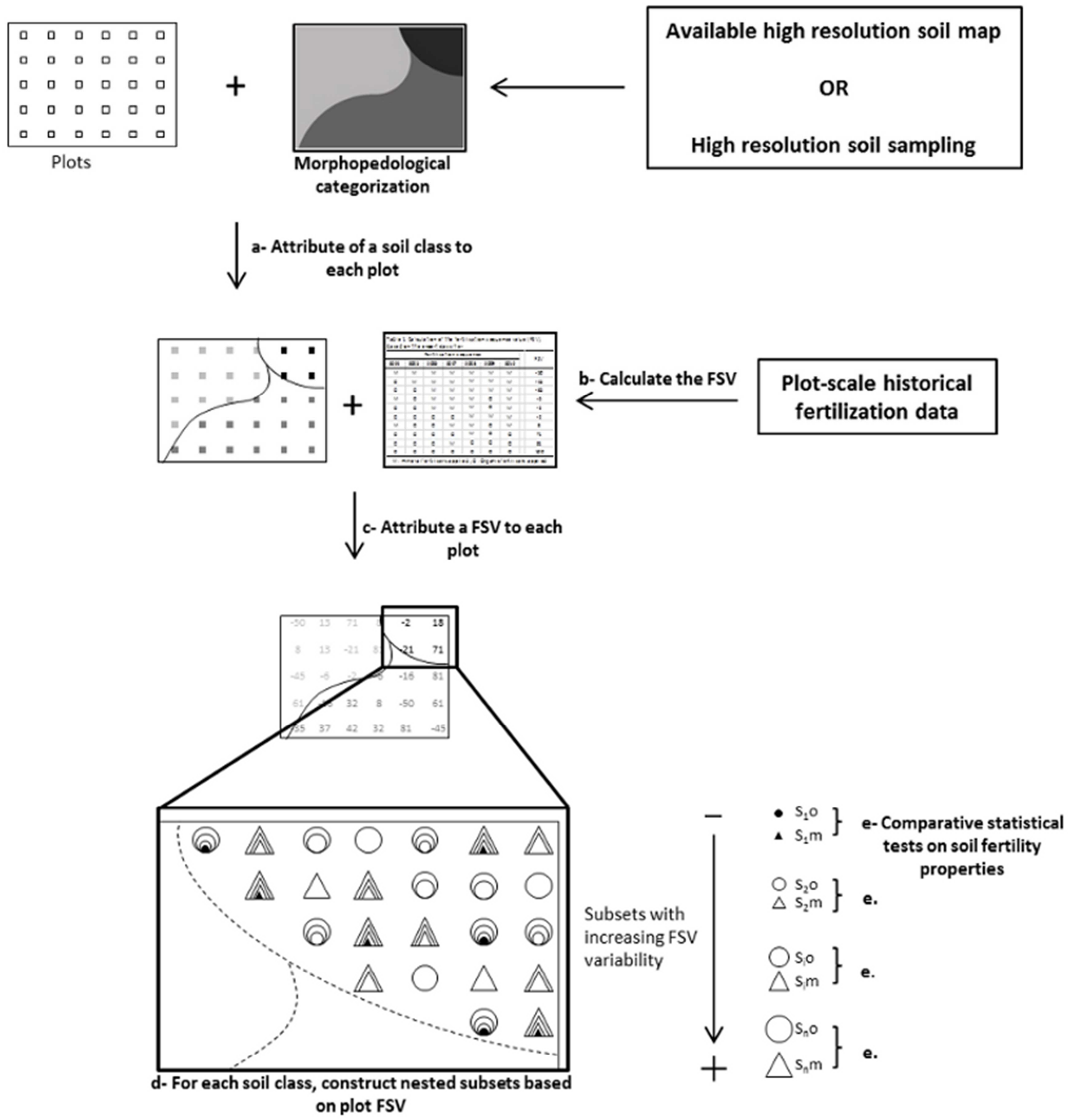


Figure 2.4. Methodological steps in the aggregation of blocks according to their soil class and their fertilizer application sequence value (FSV) prior to performing comparative statistical tests (organic- vs mineral-fertilized blocks). The scheme included (a) assigning a soil class to each block; (b) calculating the fertilizer application sequence value (FSV); (c) assigning a FSV to each block constructing nested subsets of fields within each soil class; (e) conducting comparative statistical tests between S_1o and S_1m, then between S_io and S_im, and so on until S_no and S_nm.

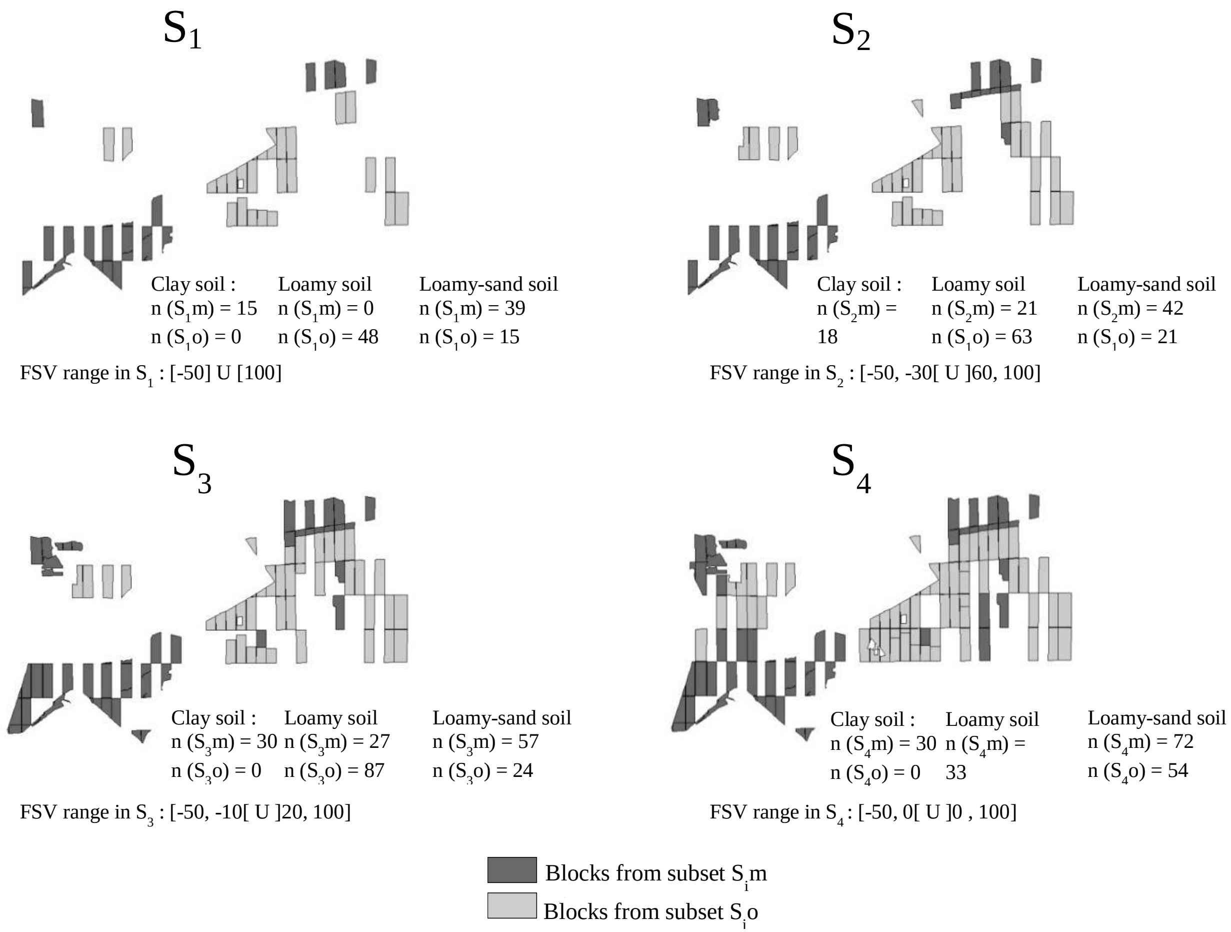


Figure 2.5. Spatial distribution (based on fertilizer sequence value) of organic- and mineral-fertilized fields across the plantation. n (S_im): number of soil samples from mineral-fertilized fields for each soil class and within each subset (S_i). n (S_io): number of soil samples from organic-fertilized fields for each soil class and within each subset (S_i). Values of *i* were 1 to 4.

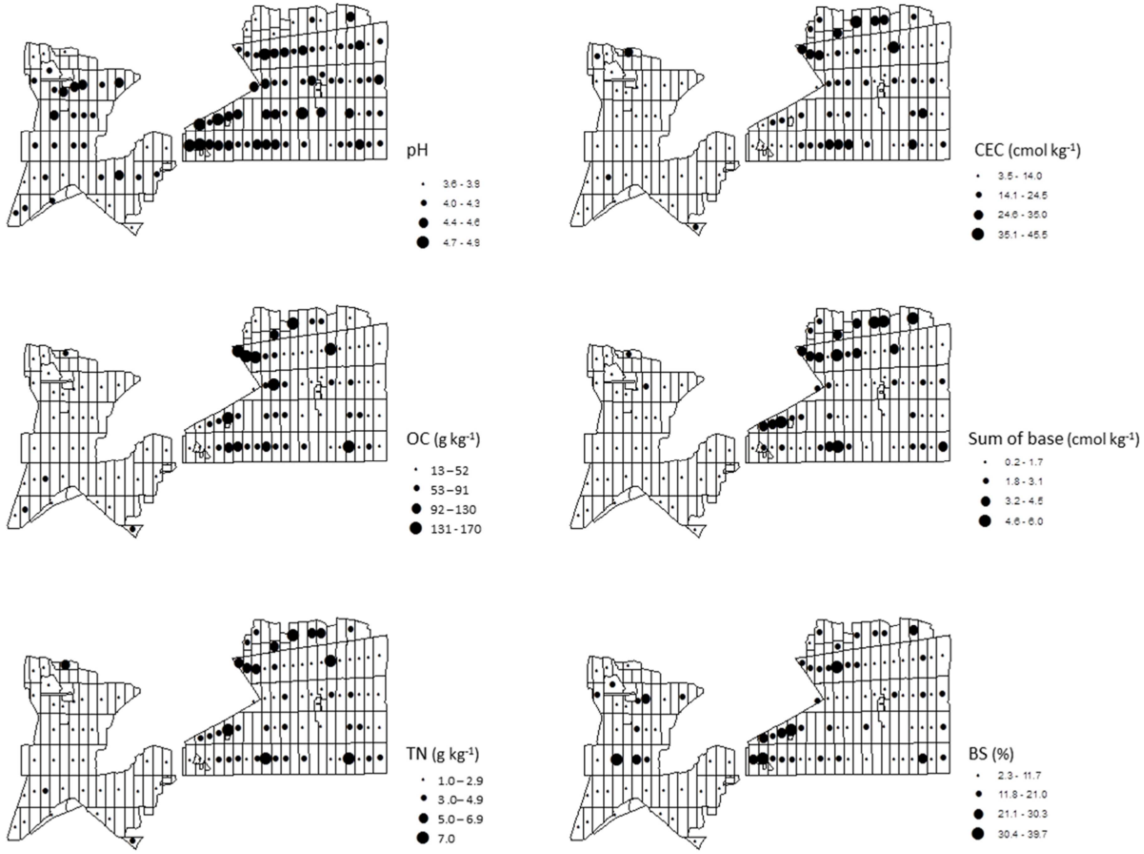
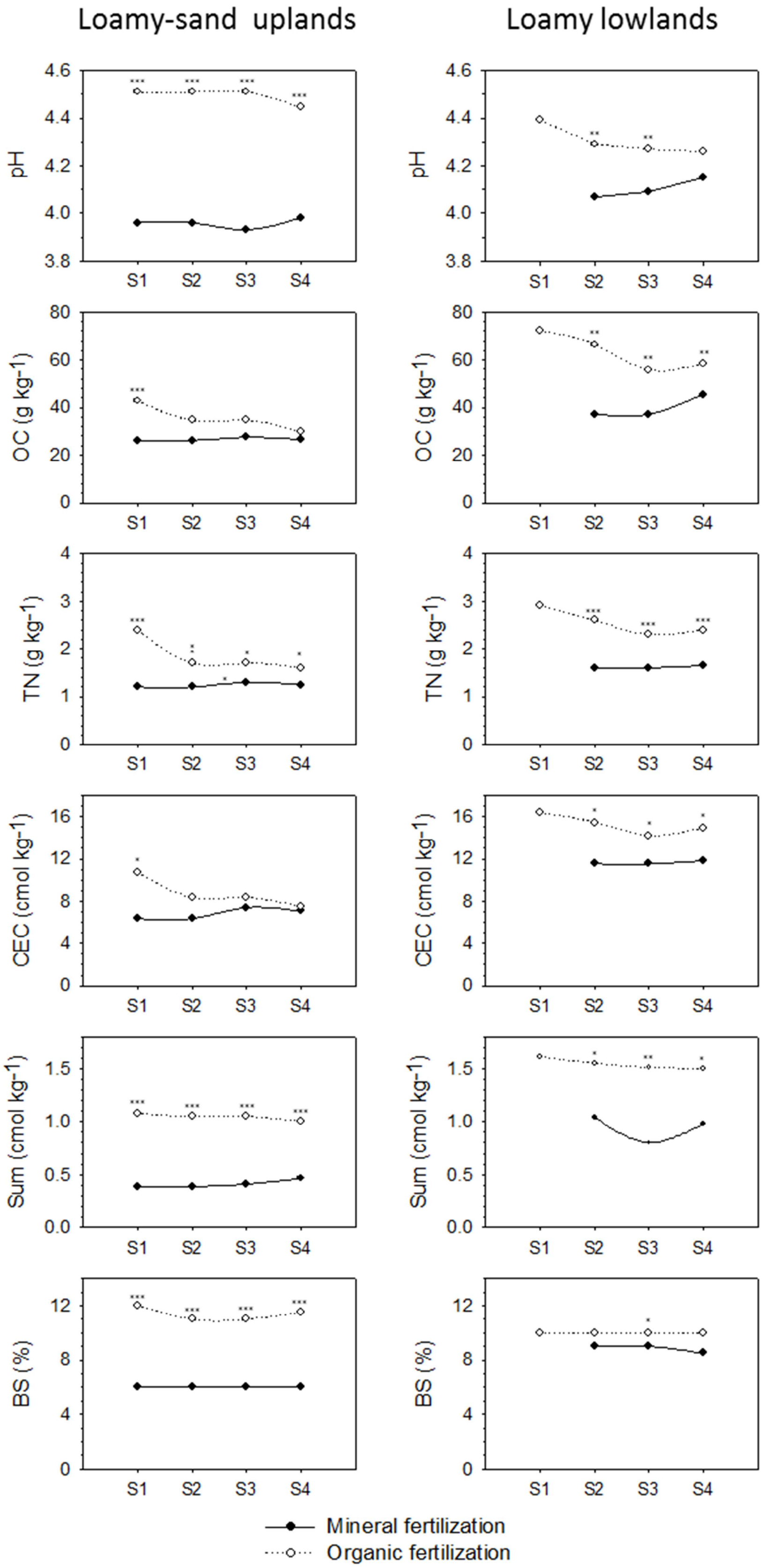
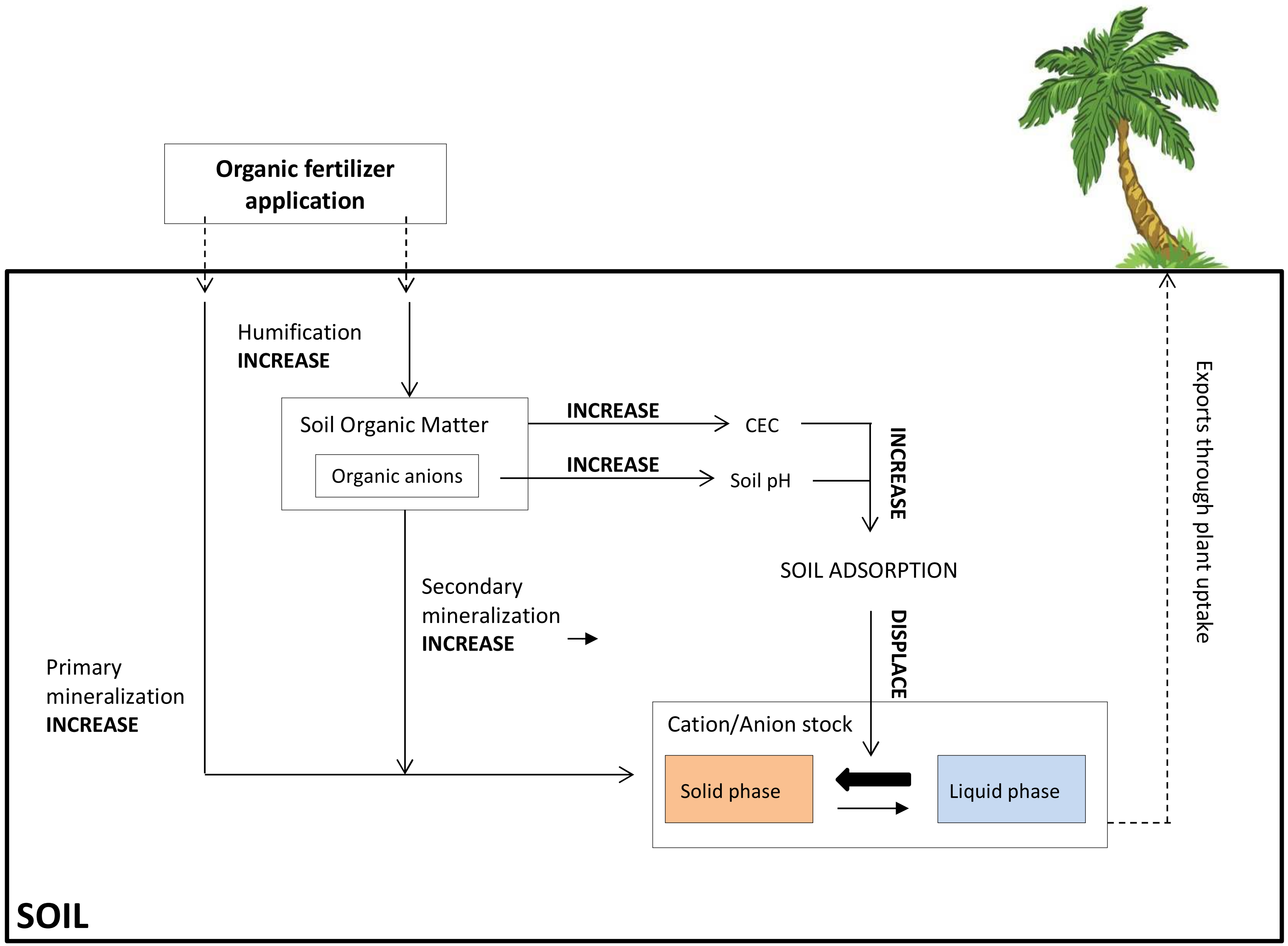


Figure 2.6. Spatial distribution of the average values of pH, organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), sum of bases (Sum) and base saturation (BS) in the blocks as measured on the soil surface (0-15 cm). The *Equal interval* method was used to classify the values. For reasons of clarity, the map presents the averaged values from the three positions per block.



Loamy-sand uplands
Loamy lowlands
pH
OC (g kg-1)
TN (g kg-1)
CEC (cmol kg-1)
Sum (cmol kg-1)
BS (%)
S1
S2
S3
S4
Mineral fertilization
Organic fertilization

Figure 2.7. Evolution of the median values (Sm_i and So_i) of pH, organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), sum of bases (Sum) and base saturation (BS) as a function of the level of heterogeneity of the fertilizer application sequence for the loamy-sand upland soil class and the loamy lowland soil class. The dotted lines represent the organic-fertilized blocks, and the continuous lines represent the mineral-fertilized blocks. Graphs show the Wilcoxon test results between organic- and mineral-fertilized blocks (S_im vs. S_io): * when $p < 0.05$; ** when $p < 0.01$; *** when $p < 0.001$.
Values of *i* were 1 to 4.



Organic fertilizer application
Humification
INCREASE
Soil Organic Matter
Organic anions
INCREASE
CEC
INCREASE
Soil pH
INCREASE
SOIL ADSORPTION
DISPLACE
Secondary mineralization
INCREASE
Primary mineralization
INCREASE
Cation/Anion stock
Solid phase
Liquid phase
Exports through plant uptake
SOIL

Figure 2.8. Conceptual model illustrating how soil biogeochemical processes control the soil response following the addition of organic fertilizers compared to mineral fertilizer applications in an acidic soil under tropical humid climatic conditions. The arrows ⟶ represent biogeochemical processes with causal relationships; the arrows - - -> represent nutrient inputs/outputs; and the arrows represent nutrient transfers between soil solid and liquid phases. The thickness of the arrow ⟶ represents the relative amount of nutrients. The notations INCREASE/DECREASE/DISPLACE describe a biochemical reaction that changed soil properties following the application of organic fertilizers.

Connecting Paragraph to Chapter 3

In Chapter 2, I characterized the relationship between fertilizer management and soil fertility status. The landscape-scale approach developed to evaluate this relationship showed that long term fertilization sequences could alter the soil fertility status, influenced by soil characteristics (i.e., sandy soils showed marked increases in pH and base saturation when fertilized with organic amendments, compared to loamy-sand soils).

Since soil type and fertilization sequences affect the concentration of plant-available nutrients in oil palm plantations, these factors will also influence the pool of nutrients that are susceptible to loss from soil and potentially transferred to streams. As soil texture also controls hydrological processes that govern water movement through subsurface flow or surface runoff, it may determine nutrient behavior and nutrient fluxes exported from the oil palm agroecosystems to streams.

The literature review (Chapter 1) highlighted the lack of watershed-scale hydrological studies in oil palm agroecosystems. Chapter 3 aims to assess the stream water quality over a 100 km^2 landscape including 16 watersheds dominated by oil palm cultivation. The influence of soil characteristics and fertilizer management will be investigated in groundwater and at the watershed-scale by assessing nutrient fluxes to streams, as recommended by my literature review.

CHAPTER 3. Multi-site assessment of water quality in oil palm agroecosystem and influence of soil types and fertilizer management on nutrient fluxes to streams

3.1 Abstract

High fertilizer input is necessary to sustain high yields in oil palm agroecosystems, but may endanger neighboring aquatic ecosystems when excess nutrients are transported to waterways. Few studies have examined the consequences of fertilizer application on water quality and nutrient fluxes to streams surrounding large-scale oil palm plantations. Multi-site monitoring was carried out in a 100 km^2 landscape dominated by mature oil palm agroecosystems, including 16 watersheds and 7 piezometers with variable dominant soil types and fertilizer management. As coarse-textured soils induced high soil infiltrability, subsurface flow was expected to be the dominant pathway for nutrient export from mature oil palm plantation to stream flow. This study aimed to characterize the baseflow magnitude, assess stream water quality and the influence of soil types and fertilizer management on groundwater chemistry and on nutrient fluxes to streams. High amount of rainfall quickly flows through the soil and leads to annual renewal of the groundwater. Seasonal variations in water quality suggested that nutrients in groundwater at the end of the dry season were likely flushed out at the beginning of the wet season increasing nutrient concentrations in streams. The low nutrient concentrations recorded in the streams throughout the landscape (Indonesian water quality standards) indicated that the studied mature oil palm plantations did not contribute to the eutrophication of the aquatic ecosystems. This was ascribed to high nutrient uptake by oil palm, a rational fertilizer program, and dilution of nutrient concentrations due to heavy rainfall in the study area. The soil type played a crucial role on DIN and TP fluxes, loamy-sand uplands being more sensitive to losses than loamy lowlands. Organic fertilization helped to reduce nutrient fluxes compared to mineral fertilizers. However, the short groundwater residence time induces a low resilience of the hydrosystem regarding the nutrient balance.

Keywords: water quality, nutrient fluxes, oil palm, baseflow, watershed-scale.

3.2. Introduction

Oil palm (*Elaeis guineensis*) is one of the most rapidly expanding crops in the tropics, especially in Indonesia, which is now the top producer in the world with about 5.37 million ha dedicated to this production (FAOSTAT, 2010). Smallholder oil palm plantations represent 39 % of Indonesian oil palm plantations and 52 % are large private plantations operated by private industry (IMA, 2010). The Indonesian government established a strategy called the Nucleus Estate Scheme, whereby industrial plantations (nucleus) helped smallholder farmers to grow oil palm in the surrounding area called plasma (Bangun, 2006; IEG, 1993; Zen et al., 2005). Plasma smallholders received technical and management assistance. Industrial plantations benefited from this arrangement by receiving fees for their services and returns from milling smallholder fruit into crude palm oil (Zen et al., 2005).

Oil palm growers usually apply fertilizers to sustain high yields. Organic fertilizers derived from mill wastes are generally applied in the industrial oil palm plantation on plots close to the mill due to transportation costs; other areas of industrial plantations receive mineral fertilizers and smallholders rely on mineral fertilizers only. Fertilizers applied to oil palm plantations could pose a risk to the sustainability of nearby aquatic ecosystems, which is a concern when nutrient inputs exceed the requirements to maintain palm trees and ground cover growth and the nutrient removal by harvested products (Sheil et al., 2009).

The Round Table for Sustainable Oil Palm encourages growers to evaluate the environmental impact of oil palm cultivation, notably on water quality (Lord and Clay, 2006). However, few studies have examined how fertilizers applied to oil palm agroecosystems may affect nutrient loading and water quality in waterways (Ah Tung et al., 2009). Most of hydrological studies carried out in oil palm landscapes focused on the plot-scale (i.e. a few hectares), whereas Indonesian oil palm plantations managed by industry and neighboring smallholders can cover

3000 to 20 000 hectares and extend across several watersheds. Knowledge of the watershed-scale hydrology in oil palm agroecosystems is limited to a study by Yusop and Katimon (2007), which quantified runoff processes on a small watershed of 8.2 ha, and a study by DID (1989) that assessed nutrient loads at the watershed-scale (97 ha) after forest clearing and during the first year of oil palm cultivation. It is difficult to extrapolate from these studies to assess streamflow and nutrient fluxes from mature oil palm plantations at larger spatial scales. Indeed, it is well established in many cropping systems that topography affects the movement of water and nutrients. (Franzen et al. 1999; Balasudram, 2006) and that watershed geomorphology influences baseflow through infiltration process and recharge of subsurface water (Brutsaert, 2005; Price, 2010). Spatial variability in soil characteristics and use of organic vs. mineral fertilizers throughout the landscape are also expected to strongly influence nutrient loads and the resulting water quality of streams.

Previous studies indicate that surface runoff is an important transport pathway for nutrient transport from oil palm agroecosystems to waterways, at least during land clearing and in the first few years of cultivating oil palm (DID, 1989). By the time they are 15 years old, oil palms are 10 m tall and have substantial understory vegetation; as well, fronds cut from the oil palm are left on the soil surface to decompose, which limits surface runoff. This promotes water infiltration, which is further enhanced when oil palm is grown on coarse-textured loamy soils and drainage systems are installed. Therefore, subsurface flow is expected to be the dominant pathway for nutrient export from mature oil palm plantations as shallow groundwater was reported to be the major contributor to stream flow in coarse-textured soils of the humid tropics (Malmer, 1996) due to high soil infiltrability (Banabas et al., 2008, Maena et al., 1979).

The objectives of the study were to (i) characterize the magnitude of sub-surface flow that contributes to streamflow (ii) assess stream water quality (pH, electrical conductivity, nutrient concentrations (($N\text{-}NO_3$, $N\text{-}NO_2$, $N\text{-}NH_4$, total P, K, Mg and Ca), biological and chemical oxygen demand, dissolved oxygen) and nutrient fluxes in streams in mature oil palm agroecosystems, and (iii) assess the influence of soil types and fertilizer management at the local-scale on groundwater chemistry, and at watershed-scale on nutrient fluxes. The hydrochemical dynamics of streams and groundwater were evaluated with bi-weekly measurements for one year on 16 watersheds (6 nested watersheds and 10 headwatesheds), and related to the spatial distribution of soil and fertilization practices across a landscape of 100 km², dominated by oil palm cultivation (nucleus, plasma and independent smallholders oil palm plantations), in Central Sumatra, Indonesia.

3.3. Material and Methods

3.3.1. Description of the study area and watershed delineation

The study area was located in the Petapahan area of Kampar District, Riau Province, within the Siak watershed (~ 11,500 km²) in the Sumatran Central Basin (cf. Figure 1 in Chapter 2). This area has a tropical humid climate, with average annual rainfall of 2400 mm yr^{-1} (2000-2010). The wet season runs from September to April and the dry season runs from May to August. The average monthly temperature is 26 to 32°C. Soils are Ferralsols (FAO/ISRIC/ISSS, 1998) that were developed on recent alluvium with peat deposits in small depressions (Blasco et al., 1986). Within the study area, three main soil types were identified: loamy-sand uplands, loamy lowlands, and more marginally clayey floodplain with patches of peat (no more than 10 cm thick) and a black river flows close to the study area (Figure 1a). The physico-chemical properties of these major soil types are given in Table 1. Field observations recorded abundant understory vegetation beneath oil palm trees throughout the study area.

The relief is slightly undulating in the loamy-sand uplands to flat in the loamy lowlands and clayey floodplain, but locally uneven due to micro-relief. Land use in the study area included a nucleus mature (15 yr old) oil palm plantation (35.1 km²) that will be referred to as "industrial" in the rest of the paper, plasma mature (15 yr old) oil palm plantation (19.6 km²), independent smallholdings (mosaic of mainly smallholder oil palm plantations, but also rubber (*Hevea Brasiliensis*) plantations, housing and garden, 55.2 km²) that will be referred to as “smallholder” in the rest of the paper, and remaining *Dipterocarp* forest (20.2 km²) (Figure 1b).

The hydrographic network was digitalized in a geographic information system (ArcGIS 9.3® software) from satellite imagery (SPOT4, 2008) and field surveys. Sampling points for stream monitoring were headwatershed outlets or selected locations apportioned along the two main streams to capture nutrient fluxes at transition points between contrasting land uses. Watershed area covered by each sampling point was delineated from a digital elevation model (SRTM, 90m resolution) using ArcHydroTools ® extension of ArcGIS 9.3 ®. In total, 16 sampling points throughout the study area were selected, 6 points located along the two mainstreams (Petapahan river and Ramalah river) as nested watersheds to represent replicated outlets of diverse land uses, and 10 points located at the headwatershed outlets of land under a unique cultural system (5 for the industrial, 3 for the plasma and 2 for the smallholder oil palm plantations). In addition, a sampling point was located immediately downstream from the mill (RA2) for water quality monitoring only. Description of the watershed characteristics for sampling points, including dominant land use, soil type and fertilization practices are provided in Table 2. Groundwater survey was done with 7 piezometers (10 cm dia.) installed to a depth of 3 m, distributed considering land uses, soil classes and fertilizer management practiced in the study area (Figure 1c). During the study period, rainfall and evapotranspiration (ET) data were recorded using two automatic weather stations (DAVIS Instruments Corp., Hayward, California, USA) located in the industrial plantation and were spatially interpolated based on Thiessen polygon routines (Table 3). Under the tropical humid climatic conditions occurring in the study area, actual ET was assumed to be equal to reference ET, because of the low likeliness of hydric stress (DID, 1989; Henson, 1999).

3.3.2. Fertilizer management and nutrient inputs

The industrial oil palm plantation applied mineral and organic fertilizers. Mineral fertilizers included urea, rock either phosphate (RP) triple super phosphate (TSP), or diammonium phosphate (DAP) as phosphate fertilizers, muriate of potash

(MOP), either kieserite or dolomite as magnesium fertilizers, and high-grade fertilizer borate (HGFB). A site specific rational fertilizer program was followed in the industrial oil palm plantation, which aimed to match nutrient inputs with oil palm nutrient demand based on annual leaf analysis at the plot-scale (Caliman et al., 1994). A split application (2 times per year) of mineral fertilizers was generally followed to improve nutrient use efficiency. Given the large area of the industrial plantation, plot by plot applications of mineral fertilizers are scheduled throughout the year.

Organic fertilizers, consisting of empty fruit bunches (EFB) and palm oil mill effluent (POME), are usually applied once a year to dedicated plots in the industrial plantation that are close to the mill, due to transportation cost. The mill location is usually chosen close to a river (for water availability) on site with suitable soil physical characteristics to support buildings and other infrastructure. The soil fertility or susceptibility to nutrient losses is generally not taken in account in this choice (Caliman, pers. com).

Plasma plantations receive mineral fertilizers only, based on recommendations provided by the industrial oil palm plantation. Typical fertilizer application rates and nutrient inputs from each fertilizer source were given in Chapter 2, Table 1. Additionally, frond pruning occurred year-round in both industrial and plasma oil palm plantations, resulting in frond piles around each palm stem, but this was considered to recycle nutrients rather than serve as a nutrient input. Unfortunately, no information on fertilization practices was collected for the independent smallholdings, due to the large number of owners, the high variability of land use and fertilization practices, and inexistent land register.

Fertilizer applications between September 2009 and August 2010 were recorded for each plot in the industrial and plasma plantations (plot size is 30-40 ha with tree density of about 140 palms ha^{-1}). I calculated the annual input of N, P, K, Mg and Ca input per plot, based on nutrient contents in fertilizers (cf. Table 1 in Chapter 2), and the watershed-level nutrient input was the sum of nutrients applied to all plots within a given watershed. When a plot straddled two adjacent watersheds, the nutrient input was partitioned according to the plot area located within each watershed. Throughfall and stemflow nutrient depositions were assumed to be uniform in the studied landscape and negligible relative to fertilizer inputs.

3.3.3. Groundwater and watershed monitoring

Three piezometers were implemented in loamy-sand uplands, one in an unfertilized rubber-tree plantation in smallholder area (SP-P0), one in the industrial oil palm plantation with mineral fertilization (SP-P2), and one in the remaining forest (SP-P4). Three piezometers were installed in loamy lowlands in the industrial oil palm plantation, one in a mineral fertilized plot (SP-G), one in an EFB fertilized plot (SP-F), and one in a POME fertilized plot (SP-E). The last one was placed in peat soil, in mineral fertilized plot in the plasma oil palm plantation (SP-RB1). Groundwater sampling (September 1st 2010 to June 7th 2011) consisted of discrete water sampling every 2 weeks for water quality analysis, plus water table measurements in the piezometers every 2 weeks. A bottle tied on a stick was used to sample water in the piezometer before filling the high-density polyethylene bottles. All material (stick and bottles) were washed with distilled water before each sampling. The water table measurements were carried out using a float tied to a graduated stick.

Hydrological studies designed to calculate nutrient loads generally rely on continuous discharge data from a water level probe and rating curve, with discrete water sampling to assess nutrient concentrations and other water quality parameters. Given the large number of sampling points in this landscape-scale study and financial constraints, no watershed could be gauged with an automatic station, so monitoring was carried out manually. For discharge monitoring, a rating curve was constructed from manual discharge measurements taken every 2 weeks from 1 September 2009 to 31 August 2010 using a current meter (Flo Mate 2000, COMETEC, Mandres-les-Roses, France) and hydraulic radius (Rh) calculation. Rh was calculated from manual water level measurements done along the river section. The bi-monthly discharge Q was calculated from the rating curve and manual water level measurements at each sampling point, except for site RA2, which was monitored for water quality only. Discrete water sampling at each sampling point was also done every 2 weeks to ensure sufficient replication, while taking account of laboratory capacities and logistical constraints. Many hydrological studies are carried out with monthly sampling frequency (Martins and Probst, 1990; Brunet and Astin, 1999; Raymond, 2011), so bi-monthly sampling is considered to be a reasonable frequency given logistical constraints. Bi-monthly sampling was also used by Hélie et al. (2002) when measuring annual carbon fluxes through the St-Lawrence River. The sampling scheme was as follows: one sample for river sections less than 1 m wide, two samples for river sections less than 4 m wide, and three samples for river sections greater than 4 m wide. Each sample consisted of duplicate high-density polyethylene bottles, immersed to half-depth in the stream. Sampling bottles were placed in icebox for transport to the lab, and stored at 4°C until analysis.

3.3.4. Water sample analysis

Water pH and electrical conductivity (EC) were measured. The chemical oxygen demand (COD) was determined with the closed reflux, colorimetric method (SNI 06-6989.2-2004; APHA (5220D), 1998). The total organic carbon (TOC) was analyzed using high-temperature combustion method (SNI 06-6989-28-2005, APHA (5310B), 1998). As the apparatus was not available at the beginning of the work, the TOC concentrations for the year 2009-2010 were calculated from linear regressions between concentrations of COD and TOC (Dubber and Gray, 2010) measured from August 2010 (TOC = 1.53 * COD – 27.54, $R^2 = 0.92$, n = 281). The biological oxygen demand BOD5 (SNI 06-2875-1992; SNI 06-6989.14-2004), and dissolved oxygen were determined (SNI 06-6989.2-2004; APHA, 1998).Total phosphorus (TP) was determined using flow injection analysis for orthophosphate (SNI M-52-1998-03; APHA (4500PG), 1998). The concentrations of the cations K^+, Mg^{2+}, Ca^{2+}, Fe^{2+} and Mn^{2+} were determined using Atomic Absorption Spectrometry (AAS) (SNI, 1994). NO_3-N and NO_2-N were determined using colorimetry and AAS (RRIM, 1980). NH_4-N was determined using Nessler reagent and analyzed with AAS (SNI 06-2479-1991). The dissolved inorganic nitrogen (DIN) was the sum of NO_3-N, NO_2-N, and NH_4-N. Total dissolved solids (TDS) were determined at 105°C after filtration (45µm). In addition to water quality parameters, the SiO_2 concentration was analyzed (APHA (3120B modified), 2005), as an indicator of groundwater residence time.

3.3.5. Estimation of water flow, nutrient concentrations and fluxes.

3.3.5.1. Annual water yields from water budget.

The study area is in the humid tropics, which are characterized by high rainfall (> 2000 mm yr^{-1}) and evapotranspiration exceeding 1000 mm yr^{-1} (Table 3), which led to high flow according to the water budget equation 1:

$$AWY_1 = R - ET + \Delta S \qquad (1)$$

AWY_1 = Annual water yield $[L].[T]^{-1}$
R = Annual rainfall $[L].[T]^{-1}$
ET = Annual evapotranspiration $[L].[T]^{-1}$
ΔS = variation of the stock at the end of the hydrological year $[L].[T]^{-1}$, assumed to be negligible when compared to others terms of the water budget

3.3.5.2. Water flow estimation

Soils were coarse-textured and exhibited high infiltrabilities. The plantations under study have relatively flat topography, with abundant ground cover, including frond piles, and are surrounded by drainage ditches, which limit water ponding at the soil surface and reduce overland flow. These field conditions lead me to conclude that infiltration was the primary route for water flow from these oil palm plantations. Moreover, considering the high water table level (0-2 m below the soil surface throughout the monitoring period), I assumed that stream flow was dominated by baseflow from shallow groundwater. Consequently, I chose a one-compartment reservoir model with a daily time step to estimate daily discharge. This robust and parsimonious method was used by many authors (e.g. Perrin et al., 2003). In lumped reservoir models the watershed is considered as a whole system in performing the rain-flow transformation. This modeling approach has the advantage of taking account of the storage effect of the watershed, so it is adapted to infiltrant system. The watershed is schematically represented in the form of a reservoir, where groundwater drainage is linear function of water storage at each time step. Water storage is calculated as a function of rainfall, evapotranspiration and discharge calculated at the previous time step. Reservoir modeling has also the advantage to be based on simple mathematical formulation (2):

$$DWY_2(t) = S(t).\ \alpha \qquad (2)$$

The storage S(t) is determined as follows: $S(t) = S(t-1) + R(t) – ET(t) – WY_2(t-1)$

$DWY_2(t)$ = Daily water yield $[L].[T]^{-1}$
α = Draining coefficient $[T]^{-1}$
S(t) = Water storage [L]
R (t) = Daily rainfall $[L].[T]^{-1}$
ET (t) = Daily evapotranspiration $[L].[T]^{-1}$

This model provides water yield expressed as water depths (mm) at each daily time step, which has to be weighting by the watershed contributive area to be expressed as water fluxes Q (m^3 s^{-1}). The contributive zone represents the proportion of the watershed area that effectively contributes to the discharge at the outlet. It depends on the topography and on the presence of artificial draining pathways (e.g. ditches).

$$Q(t) = DWY_2(t).Cz.A \qquad (3)$$

Q(t) = Discharge $[L]^3.[T]^{-1}$

Cz = Contributive proportion of the watershed area [dimensionless], the value of Cz is equal to 1 when the draining watershed area equals the topographic watershed area.

A= Watershed topographic area $[L]^2$

Input data were daily rainfall and evapotranspiration. Initial condition was initial water storage S(t=0) and the calibration parameters were the contributive proportion Cz and the coefficient of groundwater drainage by the hydrographic network α (called drainage coefficient in the rest of the Chapter). Cz was derived from field observations and α from manual calibration based on (i) the fitting of daily simulation with punctual observations (outside storm events), and (ii) the coherence of the α values between watersheds: similar watersheds (soil, topography and land uses) were given similar α values. Then daily water yields were summed to get annual water yield AWY_2 (Appendix 3, Table 4.1).

For JA1, JB1 and PA1, there was insufficient data to calibrate the model, so a regionalization approach was used to select relevant model parameters from another watershed (i.e. having similar size and pedoclimatic conditions) (Parajka et al., 2005). In addition, I verified that the reference watershed was appropriately chosen by examining the correlation between instantaneous discharge measurements from both watersheds on the same date. JA1 and JB1 model calibration used parameters from the JC1 watershed (r=0.85 and 0.88, respectively), while the model calibration of PA1 was based on parameters from the PC1 watershed (r = 0.88).

3.3.5.3. Annual nutrient fluxes in streams

The nutrient flux during a time interval [t1; t2] results from the integration of the instantaneous nutrient concentrations weighted by the instantaneous discharges during the same time interval:

$$F_{t1}^{t2} = \int_{t1}^{t2} C(t).Q(t).dt \qquad (4)$$

F = Flux during the time interval [t1; t2] $[M].[T]^{-1}$
C = instantaneous Concentration $[M].[L]^{-3}$
Q = instantaneous Discharge $[L]^3.[T]^{-1}$

In this study, I considered daily time intervals (Δt = 1 d) to be sufficiently small that the instantaneous measured nutrient concentration was considered constant during Δt and designated as Cj (Raymond, 2011). Since water sampling was done every 2 weeks, daily estimated concentration for TP, NO_3-N, NO_2-N, NH_4-N, K, and Mg was the average between two sampling dates. The hydrological model allowed directly calculation of daily discharge Qj and the daily flux Fj was calculated as follows:

$$Fj = Cj.\ Qj.\ \Delta t \qquad (5)$$

Then, the annual export for a given watershed was calculated by summing daily fluxes for the study period (one year). Annual nutrient export fluxes were calculated for all watersheds (excluding RA2) and the total fluxes (t yr^{-1}) for sections P1-P4, R1-R2 and R1-R3 were calculated by deducting total flux(es) at the inlet(s) from the total flux at the outlet. Then, to be able to compare fluxes between watersheds, specific fluxes were calculated dividing total flux by the watershed area (kg ha^{-1} yr^{-1}).

3.3.6. Data analysis

The magnitude of annual total streamflow was deducted from the annual water budget WY_1 and from the ratio WY_1/R. The hydrological model used in this study provided baseflow water yields WY_2. I verified my assumption of stream flow dominated by baseflow by comparing WY_1 and WY_2. The seasonal periods were deducted from the analysis of temporal rainfall variations at the annual-scale. Analysis of the water table temporal variations provided information on the effect of seasonal variations on groundwater. Finally, the temporal variations of groundwater SiO_2 concentrations provided information on groundwater residence time.

Mean annual pH, EC values and other water quality parameter concentrations were calculated for each sampling point. Then stream water quality was assessed by comparing mean annual values from the study area to Indonesian water quality standards (class II) (GR 82/2001). Class II standard refers to water quality required for recreational purposes (swimming, fishing), irrigation and cattle raising, that are common water uses in the study area. Comparisons between the watersheds were performed on the basis of annual fluxes and annual specific fluxes calculated for each outlet, and finally comparisons with bibliographic references were discussed.

The influence of soil and fertilizer management on water quality was assessed (i) locally by plotting groundwater annual mean of physico-chemical parameters: pH vs. EC; DIN vs. TP; K vs Mg, and (ii) at the watershed-scale by plotting the annual nutrient inputs vs. annual nutrient fluxes for each watershed. Soil variability and fertilizer applications variability (mineral vs. organic) occurred in the industrial oil palm plantation only. These comparisons were made for watersheds in the industrial plantation only.

Comparisons between piezometers were completed by statistical tests for each parameter. I used non parametric Kruskall-Wallis test due to non-normal data and non-homogeneity of the variances. Statistical tests were performed using R freeware (R Development Core Team, 2011).

3.4. Results

3.4.1 Hydrological behavior

The study was conducted under tropical humid climatic conditions, characterized by alternating wet and dry seasons. About 40 % of the annual precipitation occurs in the dry season and the remainder falls in the wet season. The wet season generally occurs from September to February and the dry season from February to August. Within the dry season, there is generally a one-month period with higher rainfall in April-May (Table 3).

Annual water yields WY_1 were between 1473 and 1539 mm yr^{-1}. Water yields deduced from the hydrological model WY_2 were 1482 and 1563 mm yr^{-1}, within 3 % of the water yields WY_1 (Table 4). The WY_2 / R ratios were between 57 and 60 % indicating that annual outflows were dominated by streamflow rather than evapotranspiration. Strong seasonal dynamics were observed, with up to 80 % of the annual water yield discharged during the wet periods.

Groundwater table was 50 to 210 cm below the soil surface, but tended to be shallower in loamy lowlands and peat (50 to 80 cm) than in sandy loamy-sand uplands (140 to 210 cm). Water table fluctuations were between 88 and 187 cm throughout the study area during the hydrological year. The SiO_2 concentration measured in the piezometers ranged from 0 (below the detection limit) by the end of the wet period to 10 mg L^{-1} in the dry period. This suggests short water residence time in shallow groundwater. Temporal variations in pH and EC in groundwater from piezometers located on loamy-sand uplands and loamy lowlands was opposite to rainfall pattern: pH and EC increased during dry periods and decreased during wet periods, EC being strongly correlated to the sum of K, Mg and Ca (r = 0.89) (Figure 2). The same pattern was also observed for EC but not for pH, in groundwater taken from the piezometer located in peatsoil.

3.4.2. Stream water quality and nutrient fluxes in the landscape

3.4.2.1 Water quality

In the landscape (excluding RA2 and R3 which are located downstream the mill), stream water was generally acidic, with pH ranging between 4.42 and 5.41. Low EC and TA were measured: 12.8 to 22.7 µS cm^{-1} and 4.28 to 7.53 mg L^{-1}, respectively. Low nutrient concentrations were recorded, as the mean annual concentrations of DIN, TP, K, Mg and Ca throughout the landscape ranging between 0.13 and 1.01 mg L^{-1}, 0.01 and 0.07 mg L^{-1}, 0.35 and 2.46 mg L^{-1}, 0.16 and 0.28 mg L^{-1} , and 0.56 and 1.09 mg L^{-1}, respectively. However, the rivers showed high organic matter content, between 13.9 and 18.6 mg TOC L^{-1} (Table 5).

Water quality parameters recorded immediately downstream from the mill (RA2) gave the highest values recorded accross the landscape: + 404 % EC, + 1052 % K, + 528 % Mg, + 611 % Ca, + 35 % DIN, + 13 % TDS, + 464 % TA, compared to the landscape average (excluding RA2 and R3). Further downstream at point R3, the EC, K, Mg and Ca values were intermediate between RA2 and the landscape average, while others parameters values were close to the landscape average. Regarding K concentrations, watersheds receiving high organic fertilizer applications showed higher concentrations compared to the others, and the ones established on loamy lowlands showed higher concentrations of Ca+Mg. Higher DIN concentrations were recorded in watersheds dominated by industrial oil plantations compared to those dominated by smallholder and plasma plantations. In general higher TOC concentrations were measured in watersheds receiving organic fertilizers than mineral fertilizer (Figure 3). Seasonal dynamics of water quality parameters revealed increasing concentrations of major cations (+ 19-25 % of K, Mg and Ca), increasing DIN concentrations (+ 35 %), increasing EC (+ 23 %), but decreasing pH values (-1.3 unit) during the wet season throughout the landscape.

3.4.2.2. Nutrient fluxes to streams

The DIN fluxes were between 1.88 and 9.17 kg ha^{-1} yr^{-1}, fluxes of NO_3-N between 1.53 and 8.24 kg ha^{-1} yr^{-1} and TP fluxes between 0.05-1.16 kg ha^{-1} yr^{-1}. Major cations K, Mg and Ca gave fluxes of 5.4-37.9, 2.0-5.4, and 4.5-29.9 kg ha^{-1} yr^{-1} respectively. Potassium contributed up to 50 % of major cations fluxes (K + Ca + Mg) in watersheds receiving organic fertilizers and 35 % on average in those receiving mineral fertilizers. Due to higher water yields and higher nutrient concentrations during wet periods, higher nutrient fluxes were recorded in wet season than dry season for all sampling points ($p<0.05$).

Annual specific fluxes from watersheds under industrial oil palm cultivation (JA1, JB1, JC1, PA1 and PD1) did not exceed fluxes from smallholder watersheds (P0, P1, PB1 and PC1). Lower fluxes of TP, K, Ca and NH_4-N were even recorded in the industrial headwatersheds compared to smallholder watersheds.

Generally, lower fluxes were recorded in headwatersheds under plasma oil palm cultivation (R1, RA1 and RB1) on loamy-sand uplands than watersheds under industrial oil palm on loamy-sand uplands receiving mineral fertilizers (except for Ca and NO_2-N fluxes). Higher fluxes of TOC, K, Mg, Ca and DIN were recorded in R1 headwatershed, which had a larger area with housing (278 ha) compared to the two other plasma watersheds (RA1, RB1).

3.4.3. Influence of the soil and fertilizer management on water chemistry and nutrient transfers

3.4.3.1 Nutrient inputs

Nutrient inputs were generally greater in the industrial plantation than the plasma plantation, especially in plots that received organic fertilizer because EFB and POME tend to supply more N (135 kg N ha^{-1} yr^{-1}), P (67 kg ha^{-1} yr^{-1}), K (480 kg K ha^{-1} yr^{-1}) and Mg (173 kg Mg ha^{-1} yr^{-1}) than average mineral fertilizer applications. The industrial watersheds JA1, JB1, JC1 on loamy-sand uplands and the industrial nested watersheds R1-R2 and R1-R3 on loamy lowlands received from 65 to 93 % of the nutrient input from organic fertilizer (Table 7).

3.4.3.2. Influence at the local-scale: groundwater hydrochemistry

The annual mean pH varied from 4.15 in the piezometer located in peatsoil to pH > 5.75 in the loamy-sand uplands under native forest (pH = 5.79) and under unfertilized rubber plantation (pH = 5.96). In the loamy-sand uplands under mineral fertilized oil palm, pH was 5.39, significantly different ($p<0.05$) from other piezometers in loamy-sand uplands. Intermediate pH values (between peatsoil and loamy-sand uplands) were recorded in piezometers located in loamy lowlands: pH was 4.54 under mineral fertilizer applications, 5.08 under EFB applications, and 5.33 under POME applications. The pH values were significantly ($p<0.05$) different between each piezometer located in loamy lowlands. We observed that pH was negatively correlated to EC when pH <5 (r=-0.79, n=20) and positively correlated to EC when pH >5 (r=0.82, n=41). The tendency was clearer during the wet season (Figure 4a).

Regarding TP concentrations, no statistical difference were observed among all piezometers, although lower concentrations were recorded in the piezometers located in the loamy lowlands and under organic fertilization. Higher DIN concentrations ($p<0.05$) were recorded in the piezometer under forest (annual mean: 3.19 mg DIN L^{-1}) than in all others piezometers under oil palm cultivation (0.71 to 1.02 mg DIN L^{-1}). Among oil palm plantations, the lowest DIN concentrations were recorded under organic fertilizer applications in loamy lowlands (0.71 to 0.77 mg DIN L^{-1}). Similar DIN concentrations were observed under mineral fertilized oil palm on loamy lowlands and loamy-sand uplands (1.02 and 1.00 mg DIN L^{-1} respectively). The DIN concentration was lower ($p<0.05$) in in loamy lowlands receiving EFB (SP-F) than in loamy lowlands receiving mineral fertilizers (SP-G) (Figure 4b).

The piezometer under POME-amended had higher K concentrations (9.24 mg K L^{-1}) ($p<0.05$), relative to others piezometers (1.55 to 3.49 mg K L^{-1}). On loamy-sand uplands, lower K and Mg concentrations ($p<0.05$) were recorded under mineral fertilized oil palm (1.86 and 0.73 mg L^{-1}, respectively) than forest (3.02 and 1.43 mg L^{-1}, respectively) and unfertilized rubber plantation (2.27 and 0.67 mg L^{-1}, respectively). Higher Mg concentrations ($p<0.05$) were recorded under natural forest (1.43 mg Mg L^{-1}) than most other piezometers, except the piezometer under POME application (0.88 mg L^{-1}). Lowest Mg concentrations ($p<0.05$) were recorded in the piezometer under EFB applications (0.43 mg L^{-1}) and in the piezometer located on peat, compared to other piezometers (Figure 4c).

3.4.3.3. Influence at the watershed-scale: nutrient inputs and nutrient fluxes

Inputs and fluxes were plotted for N, P, K and Mg to assess the effect of soil types, fertilizers type (i.e. mineral vs. organic) and amount on nutrient fluxes (Figure 5). Three groups clearly appeared: the organic fertilized watersheds on loamy lowlands (R2,R3 and R1-R3), the organic fertilized watersheds on loamy-sand uplands (JA1, JB1, JC1) and the mineral fertilized watersheds on loamy-sand uplands (PA1, PD1 and section P1-P4).

Higher nutrient inputs did not trigger higher nutrient fluxes of DIN and TP. Although inputs of N and P were much higher in organic fertilized watersheds on loamy lowlands (up to 200 kg N ha^{-1} $yr^{-1}$and up to 100 kg P ha^{-1} yr^{-1}), recorded fluxes of 3 to 5 kg N ha^{-1} $yr^{-1}$and 0.05 to 0.15 kg P ha^{-1} yr^{-1} did not exceed fluxes from the others watersheds (3 to 8 kg N ha^{-1} yr^{-1} and 0.09 to 0.57 kg P ha^{-1} yr^{-1}) that received lower inputs (< 120 kg N ha^{-1} yr^{-1}). Nonetheless, Fertilizer management appeared to be important on loamy-sand uplands where organic fertilized watersheds had lower DIN and TP fluxes despite higher inputs than mineral fertilized watersheds (Figure 5a,b).

The effect of fertilizer management seemed more important for K (compared to N and P) since K fluxes to streams increased with fertilizer K inputs. Indeed, organic fertilized watersheds on loamy lowlands received the highest inputs (up to 400 kg K ha^{-1} yr^{-1}) and exported up to 19 kg K ha^{-1} yr^{-1}, more than compared to all others watersheds. On the loamy-sand uplands, watersheds receiving organic fertilizers also received higher K inputs (up to 300 kg K ha^{-1} yr^{-1}) and exported higher K fluxes than those receiving mineral fertilizer (Figure 5c).

Regarding Mg, both the fertilizer management (type and amount) and the soil type had an effect on the exported Mg fluxes. Organic fertilized watersheds on loamy lowlands received highest inputs and exported higher Mg fluxes than organic fertilized watersheds on loamy-sand uplands. Also, within the loamy-sand uplands soil type, organic fertilized watersheds exported lower Mg fluxes than mineral fertilized watersheds despite higher Mg inputs. It is notable that mineral fertilized watersheds exported more Mg per unit of Mg input than the organic fertilized watersheds (Figure 5d).

3.5. Discussion

3.5.1. Streams mainly fed by shallow groundwater

The climatic conditions in the study area were characterized by high rainfall ($R = 2600$ mm yr^{-1} during the year 2009-2010) which led to high flow (i.e. high WY_1/R) according to the water budget equation (1). Based on field considerations, soil infiltrability measurements and hydrogram analysis of storm events (Appendix 1 and 2), I assumed that stream flow was dominated by baseflow and used a reservoir model that simulated baseflow only. Results showed that simulated baseflow (AWY_2) was close to the total streamflow (AWY_1) deducted from the water budget (i.e. the difference between AWY_2 and AWY_1 was less than 3 %). This confirmed that the assumption was reasonable and the model used in this work was thought to provide decent approximation for the hydrological behavior occurring in the study area.

The concentrations of SiO_2 in the piezometers returned to zero by the end of the rainy season, suggesting annual renewal of the groundwater. In addition, SiO_2 concentrations remained low throughout the year (< 10 mg L^{-1}) despite acidic soil conditions conductive to silicon dissolution. Those observations suggested a short residence time of water in the soil. The high amount of rainfall on infiltrant soils induced quick subsurface flows and diluted nutrient concentrations in streams.

Seasonal variations in hydrochemical dynamics of groundwater showed increasing groundwater nutrient concentrations during drier periods due to less water movement through the soil profile and then a decrease as a consequence of dilution due to higher flow during wetter periods. This was consistent with Legout et al. (2007) who reported low concentrations during rising water table followed by a progressive increase in concentrations during water table recession. Seasonal variation in stream water quality was observed, with higher water yields in wet season accompanied with higher nutrient concentrations. This suggested that more concentrated groundwater at the end of the dry season was likely flushed out at the beginning of the wet season, increasing nutrient concentrations in streams. This led to up to 80 % of nutrient fluxes exported during the wet period of the studied hydrological year (2009-2010).

3.5.2. Low concentrations and low fluxes exported in the landscape

3.5.2.1. Overall stream water quality in the landscape

The water quality observed throughout the studied landscape was characterized by an acidic pH, low EC and low nutrient concentrations. Values in this study were within the range for water quality parameters reported in studies carried out in forested tropical watersheds (DID, 1989; Gasim et al., 2006; Yusop et al., 2006; Duncan et al., 2010). At the annual-scale, nutrient concentrations recorded in streams did not exceed water quality standards established by Indonesian water quality standards (class II) (GR 82/2001). However, the values of the parameters related to organic parameters (COD, BOD) were higher than recommended quality standards. Although organic fertilization may have played a role, which should be further investigated, natural sources of organic matter are likely important in the study area since even higher organic carbon concentrations were reported in black rivers in Central Sumatra. Alkhatib et al., (2007) recorded 60 mg DOC L^{-1} in Dumai river, while Baum et al., (2007) reported 23 to 43 mg DOC L^{-1} in peat draining Mandau river (tributary of the Siak river). Peat soil patches within the study area, and the presence of a black river flowing close to the studied watersheds, point to natural sources of organic matter as contributors to the load of organic substances in streams.

Highest pH, EC, nutrient and dissolved organic matter concentrations were recorded at the site RA2, immediately downstream the mill. However, the mill impact on stream water quality was no different at the plantation outlet (R3) compared to the overall study area, which suggests considerable in-stream dilution of nutrients and other substances important for water quality.

3.5.2.2. Overall nutrient fluxes to streams in the landscape

Dilution of subsurface drainage water was not the only factor explaining the low nutrient concentrations observed in the streams. The Ferralsols present in the study area had low inherent fertility and low export fluxes, in contrast to higher export fluxes that were reported on richer soils such as volcanic or limestone soil, even under rainforest (Bruinjzeel, 1991; Crowther, 1987a,b). However, despite high fertilizers inputs, nutrient fluxes were within the range of those reported from forested watersheds on low fertile soils (Ultisols, Oxisols) (Abdul Rahim and Yusof, 1987; Malmer, 1996; Brinkmann, 1985) (Table 8). I conclude that oil palm likely played a role as a nutrient sink and limited nutrient fluxes to streams.

Fluxes recorded at the industrial oil palm plantation outlet in P4 did not exceed inflows in P1. That suggested low impact of the industrial oil palm plantation on fluxes in streams. However, in this case the plantation area was small compared to the watershed area (27 %), so the impact may have been obscured. But when comparing loamy-sand uplands headwatersheds under mineral fertilizer applications (PD1, PA1) to smallholder headwatersheds (PB1 and PC1) also on loamy-sand uplands, lower exports were recorded from industrial oil palm plantation, compared to those recorded from smallholder area. Unfortunately, we did not get fertilizer applications data in smallholder area, but it is also possible that housing in the smallholder area could increase nutrient fluxes through domestic wastes. Indeed, higher fluxes of TOC, K, Mg, Ca and DIN were recorded in plasma watershed R1 (including the larger housing area) despite lower agricultural inputs compared to RA1 and RB1. However, lower fluxes were recorded in the plasma watersheds compared to the smallholder watersheds. This suggested that rational and site specific fertilizer management practiced in the studied industrial and plasma plantations may have helped to reduce nutrient fluxes to streams. Nutrient fluxes recorded in plasma watersheds (on loamy-sand uplands) were also lower than fluxes recorded in mineral fertilized industrial headwatersheds on the same soil type, which was ascribed to higher nutrient inputs applied in the industrial watersheds than in the plasma area.

3.5.3. Soil characteristics and fertilizer management influenced groundwater chemistry and nutrient fluxes

Soil characteristics mainly influenced groundwater chemistry, based on the difference in pH and EC values of groundwater related to the soil types where the piezometers were installed. First, a gradation of pH values were observed as follows: piezometer located in peatsoil < piezometers located in loamy lowlands < piezometers located in loamy-sand uplands. Then, EC was negatively correlated to pH at pH < 5.5, and positively correlated to pH at pH > 5.5. The EC increase when pH < 5.5 was ascribed to the dissolution of aluminum since acidic tropical soils such as Ferralsols with high aluminum oxides content may release aluminum through dissolution at pH < 5.5 (Larssen et al., 1999; Guo et al., 2007). At pH > 5.5, higher EC was generally recorded in piezometers located in loamy-sand uplands than in loamy lowlands, suggesting a better retention capacity of loamy lowlands relative to loamy-sand uplands. This observation at the local-scale was also highlighted at the watershed-scale leading to counter-intuitive results: the more nutrient inputs in the watershed, the less nutrient fluxes exported at the outlet. With the exception of K, that will be discussed later.

The more threatening elements to aquatic ecosystems are N and P that trigger eutrophication when excessively flushed into streams (Smith et al., 1999). Lower DIN and TP fluxes were generally recorded from watersheds on loamy lowlands compared to watersheds on loamy-sand uplands despite higher N and P inputs, and mill wastes in stream. This is consistent with groundwater observations and confirmed that the soil type played a major role in the DIN and TP losses to streams, loamy-sand uplands soil being more sensitive to losses than loamy lowlands soil; this is also consistent with the higher nutrient retention in loamy lowlands, which have higher clay content and organic matter content than loamy-sand uplands (Chapter 2). Another reason for lower DIN fluxes exported from loamy lowlands could be denitrification processes occurring in the soil. Denitrification was not assessed in this study, however it has been demonstrated that the accumulation of soil moisture and soil organic matter down the slope increases soil denitrification rates (Florinsky et al., 2004). Denitrification may also occur in water bodies which may explain the low DIN fluxes recorded throughout the study area (Mulholland et al., 2009). It is well-known that clay and aluminum oxide content in the soil are responsible for P adsorption (Muljadi et al., 1966; Udo and Uzo, 1972; Brennan et al., 1994), so the high aluminum oxide content in the Ferralsols within the study area could adsorb and limit P leaching into groundwater, particularly in loamy lowlands that have a greater clay content than loamy-sand uplands. Since this study examined soluble TP in streams, future work should also assess particulate P bound to sediments and entering streams.

The fertilizer management (mineral vs. organic) also influenced DIN and TP losses, although to a lesser degree than soil characteristics. In loamy-sand uplands, lower DIN and TP fluxes were exported from organic fertilized watersheds than mineral fertilized watersheds, despite higher inputs in the former. This suggests that organic fertilizer applications may help to reduce DIN and TP losses to streams compared to mineral fertilization. Unlike mineral fertilizer applications, organic fertilizers constitute progressive nutrient inputs through mineralization process, which favors plant uptake while avoiding nutrient losses via leaching (Kasim and Abd Majid, 2011). This was consistent with groundwater observations. Unfortunately, the effect of mineral vs organic fertilizer applications in piezometers located in loamy-sand uplands could not be analyzed because there was no piezometer installed in an organic fertilized plot on loamy-sand uplands. However, lower DIN concentrations were measured in the piezometers under organic fertilizer applications compared to mineral fertilization in the loamy lowlands in the following order: EFB fertilized plot (SP-F) < POME fertilized plot (SP-E) < Mineral fertilized plot (SP-G). The same order was observed for TP concentrations, but the differences were not statistically different, likely due to very low TP concentrations detected throughout the year as a result of P adsorption/fixation reactions within the soil profile.

An exception to this trend concerns K fluxes: the more K input, the more K fluxes exported at the watershed outlets, whatever the soil type (mineral fertilizers on sandy upland < EFB fertilizers on loamy-sand uplands < POME fertilizers on loamy lowlands). POME and EFB applications represent extremely high K inputs, much more than N, P and Mg, POME representing even more K inputs (2175 kg K ha^{-1}) than EFB applications (324-486 kg K ha^{-1}). POME was applied on loamy watersheds while organic fertilized watersheds on loamy-sand uplands received EFB applications only. Thus, higher K fluxes recorded on loamy watersheds compared to all others suggest that once the input level exceeds the oil palm uptake threshold, higher K fluxes will be exported regardless of soil type. The same was true for EFB fertilized watersheds on loamy-sand uplands, although to a lesser extent than POME fertilized watersheds. This was consistent with groundwater observations that showed significantly higher K concentrations in

POME fertilized plots compared to others (except in piezometers located under other land uses).

Although EFB fertilizer applications represent higher Mg input (+135 %) than mineral fertilizer applications, lower Mg fluxes were recorded from the EFB fertilized watersheds, suggesting that EFB applications helped to reduce Mg losses. EFB fertilizer applications represent lower Mg inputs than K inputs, reducing the risk of excess Mg inputs relative to oil palm Mg requirements. Moreover, 100 % of K content in EFB is released within 90 days after application, while 80 % of Mg content in EFB is released during the first year (Caliman et al., 2001). Higher Mg fluxes recorded from POME fertilized watersheds on loamy lowlands compared to EFB fertilized watersheds on loamy-sand uplands suggest that POME applications likely exceeded oil palm Mg requirements. However, Mg fluxes from POME fertilized watersheds did not exceed Mg fluxes recorded from mineral fertilized watersheds on loamy-sand uplands.

Moreover, groundwater observations in the piezometers also showed that higher EC, DIN, and Mg concentrations were recorded in the piezometers under forest and unfertilized rubber plantation compared to piezometers under oil palm. This is likely due the high nutrient demand of oil palm (Ng, 2002) and highlighted the efficiency of the rational fertilizer program that avoided excess nutrient losses to streams (except K losses under organic fertilizer applications).

Groundwater and watershed-scale observations were consistent with each other. They highlighted the role played by the high nutrient uptake of oil palm and rational fertilizer program in limiting nutrient losses to streams. The soil characteristics played a major role in controlling nutrient losses to streams (because stream flow mainly fed by infiltrating water), the loamy-sand uplands being more sensitive to nutrient losses than loamy lowlands. The role of the soil is tempered by the fertilizer management since organic fertilizer applications helped to reduce DIN, P and Mg fluxes to streams compared to mineral fertilizer applications.

3.5.4. Agronomic and environmental implications

The expected impact of oil palm cultivation on water quality due to high fertilizer inputs was not observed. This study reported low nutrient concentrations in water streams, partly because of the high volume of water drained through soil under humid tropical climatic conditions diluted the nutrient transfers. Consequently, the low impact of oil palm cultivation on water quality should be further confirmed in areas under drier climatic conditions (especially in the context of global climate change), where lower dilution may increase the concentrations, potentially triggering eutrophication in the aquatic ecosystem.

However, the dilution conditions occurring throughout the study area did not fully explain the low concentrations observed at the watershed-scale, nor did the low inherent fertility of the Ferralsols. High nutrient uptake by oil palm seemed to play a crucial role as nutrient sink which may explain why low nutrient exports were observed despite high fertilizer inputs. This highlights that the site specific and rational fertilizer management practiced in the industrial and plasma plantations seemed to efficiently reduce the risk of nutrient losses. In particular, the application of organic fertilizers seemed to be effective in reducing the exported fluxes of DIN, TP and Mg despite higher nutrient inputs compared to mineral applications. In this study, the sandy upland soil appeared to be more sensitive to nutrient leaching to the water bodies compared to loamy lowlands. This is likely due to the more acidic pH, lower CEC and coarser texture in loamy-sand uplands soil class that favored leaching conditions compared to loamy lowlands (Chapter 2). Thus, organic fertilizer should be preferentially applied on more sensitive soils to maintain soil fertility at the plantation-scale and prevent nonpoint source pollution of waterways. Therefore, the development of a spatial strategy of fertilizer application to take into account the soil variability within the plantation would be agronomically and environmentally beneficial. Fertilization management (even rational fertilization) is generally performed at the plot-scale and the organic fertilizers usually applied in the plots surrounding the mill due to transportation cost without taking account of the soil fertility characteristics. Consequently, the choice of the mill location plays a crucial role in the spatial strategy of organic applications, so industrial producers should also take account of the spatial distribution of the more sensitive soil within the plantation when establishing a new plantation. Consequently, the plot-scale fertilizer management should be complemented with a landscape-scale strategy of fertilizer applications for higher efficiency in the long-term.

This study reported a short residence time of water with renewal of shallow groundwater after wet periods. This highlighted a high sensitivity of the system to inputs because nutrients can be quickly flushed to streams and could potentially increase nutrient concentrations in streams when fertilizer inputs exceed oil palm requirements. On the other hand, potential soil degradation (acidification and nutrient depletion due to high nutrient uptake by oil palm) in case of under-fertilization should be investigated.

Finally, this study showed high concentrations of organic matter related parameters in streams, likely due to natural conditions (presence of peatsoil patches within the study area, and a black river close to the study area). High organic matter losses associated with the high system sensitivity to inputs could trigger a risk to aquatic ecosystems because many pesticides bind to organic matter (Vereecken, 2005), which becomes dissolved and exported to streams, making the dissolved organic matter load a good indicator of exported pesticide fluxes (Page and Lord, 2006; Pessagno et al., 2008).

3.6. Conclusion

As well as providing us information about the state of water quality in an oil palm dominated landscape, this study characterized the hydrological behavior and assessed nutrient fluxes exported from several watersheds taking account of variability in soil properties and fertilizer practices. Low nutrient concentrations recorded in the streams throughout the landscape indicated that the mature oil palm plantations in this study did not contribute to eutrophication of the aquatic ecosystems. This was ascribed to high nutrient uptake by oil palm, a site specific and rational fertilizer program that aimed to closely match fertilizer applications to oil palm nutrient requirements, and nutrient dilution due to heavy rainfall in the study area. Subsequent investigations should provide a nutrient budget including measurement of nutrient uptake by the palm trees and ground cover.

The spatial design of the study (with pseudoreplicated watersheds) permitted analysis of the influence of soil type and fertilization management on nutrient fluxes and results were consistent with our expectations deducted from groundwater chemistry analysis at the local-scale. The soil type played a crucial role on DIN and TP fluxes, loamy-sand uplands being more sensitive to losses than loamy lowlands. Organic fertilization helped to reduce nutrient fluxes compared to mineral fertilizers, especially N and P loads. However, when K inputs exceeded the oil palm requirement threshold, high K fluxes can be expected, especially when groundwater has a short residence time and is the dominant source of subsurface water contributing to baseflow.

Table 3.1. Soil physico-chemical properties (0-15 cm depth) from oil palm plantations studied in the Petapahan area, Sumatra, Indonesia.

	Loamy lowlands (n=176)	Loamy-sand uplands (n=188)	Clayey floodplain (n=30)	Peatsoil (n=21)
	$mm\ h^{-1}$			
Infilrability*	80-130	90-770	6-10	245-565
	$g\ kg^{-1}$			
Sand	500	730	110	-
Loam	340	160	370	-
Clay	160	110	520	-
pH	4.22	4.24	3.74	3.99
OC	0.61	0.35	0.62	1.45
Total N	0.03	0.02	0.04	0.05
	$mg\ kg^{-1}$			
Total P	194	122	346	296
Total K	67	36	212	75
Bray-P	51	42	36	57
	$cmol\ kg^{-1}$			
CEC	15.50	8.53	24.80	35.45
Ca^{2+}	0.88	0.45	2.02	1.99
Mg^{2+}	0.59	0.24	0.81	1.63
Na^{+}	0.05	0.05	0.08	0.07
BS	11.70	11.20	13.40	14.35
Exch H	0.69	0.55	2.37	1.32
Exch Al	2.74	1.68	10.63	5.48

OC : Organic Carbon; CEC: Cation exchange capacity; BS: Base saturation; Exch : Exchangeable; WC: Water content

* n=2 for Loamy lowlands; n=2 for Loamy-sand uplands; n=2 for Clayey floodplain; n=3 for peatsoil

Table 3.2. Watershed delineation and sampling points for water quality and discharge monitoring across a landscape dominated by oil palm plantations in the Petapahan area, Sumatra, Indonesia. Geographical attributes (watershed drainage area, slope and elevation) as well as the dominant land use, fertilizer source and soil type are provided.

Watershed	Outlet location X / Y**	Area (ha)	Min-Max elevation (m AMSL)	Dominant land use	Dominant fertilizer source	Dominant soil
Watershed Jernih						
JA1	727759 / 61925	232	83-164	Industrial	Organic	LSU
JB1	728889 / 61545	179	69-182	Industrial	Organic	LSU
JC1	725808/61571	152	73-160	Industrial	Organic	LSU
Watershed Petaphan						
P0	726058 / 54335		114-198	Mixed	Mineral	LSU
P1	726169 / 56992	3016	104-198	Mixed	Mineral	LSU
P2	727740 / 58405	4136	95-198	Mixed	Mineral	LSU
P4	729731 / 59573	4795	89-198	Mixed	Mineral	LSU
PA1	729360/ 58491	176	97-173	Industrial	Mineral	LSU
PB1	727236 / 57812	1119	97-180	Smallholder	Mineral	LSU
PC1	726061 / 54342	456	117-181	Smallholder	Mineral	LSU
PD1	729000 / 58710	185	91-173	Industrial	Mineral	LSU
Section P1-P4	729731 / 59573	1315	89-166	Industrial	Mineral	LSU

Table 3.2. (Continued)

Watershed	Outlet location X / Y**	Area (ha)	Min-Max elevation (m AMSL)	Dominant land use	Dominant fertilizer source	Dominant soil
Watershed Ramalah						
R1	732990 / 58602	726	92-174	Plasma	Mineral	LSU
R2	735304 / 61690	2505	82-174	Industrial	Organic	LL
R3	736659 / 63491	3801	41-174	Industrial	Organic	LL
Section R1-R2	735304 / 61690	928	82-142	Industrial	Organic	LL
Section R1-R3	736659 / 63491	1861	36-142	Plası	Organic	LL
RA1	731326 / 58589	310	104-174	Plasma	Mineral	LSU
RA2*	731355 / 59592	563	91-174	Industrial	Mineral	LSU
RB1	734212 / 58613	851	89-171	Plasma	Mineral	LSU

LSU: Loamy-sand uplands

LL: Loamy lowlands

AMSL: Above mean sea level

* Site immediately downstream the mill. Water quality monitoring only.

**Spatial reference: UTM zone 47N, WGS-1984.

Table 3.3. Rainfall and evapotranspiration (mm) measured using two automatic stations (DAVIS) in the Petapahan area, Sumatra, Indonesia

	Station 1*	Station 2**	Average (mm)
Year 2009-10			
Rainfall			
Annual	2615	2607	2611
dry season (170 days)	711	777	744
wet season (195 days)	1904	1830	1867
Evapotranspiration			
Annual	1076	1134	1105
dry season	485	528	507
wet season	591	606	599
Year 2010-11			
Rainfall			
Annual	2280	2076	2178
dry season (212 days)	1122	947	1035
wet season (153 days)	1158	1129	1144
Evapotranspiration			
Annual	1134	1174	1154
dry season	668	697	683
wet season	466	477	472

* Coordinates (X/Y) station 1 : 727150 / 60580 (UTM 47N)

** Coordinates (X/Y) station 2 : 735490 / 61135 (UTM 47N)

Table 3.4. Parametrization of the hydrological reservoir model used in the study, and water yields for the hydrological year 2009-2010 in the Petapahan area, Sumatra, Indonesia.

Watershed	Model			Water yields			Difference between AWY_1 and AWY_2
	Initial conditions	Calibration parameters		AWY_2	AWY_2 / R	Wet AWY_2 / AWY_2	
	S(t=0)* (mm)	α (day^{-1})	Cz	mm yr^{-1}	%	%	%
Jernih							
JA1	53	0.060	0.50	1563	60	82	-1.6
JB1	53	0.060	0.50	1563	60	82	-1.6
JC1	53	0.060	0.50	1563	60	83	-1.6
Petapahan							
P0	69	0.055	1.00	1530	59	82	0.6
P1	71	0.055	1.00	1532	60	82	0.5
P2	77	0.050	0.90	1544	60	82	-0.3
P4	73	0.055	1.00	1546	60	82	-0.4
PA1	56	0.080	1.50	1549	58	82	-0.6
PB1	79	0.040	1.00	1533	60	82	0.4
PC1	56	0.080	1.50	1549	60	83	-0.7
PD1	15	0.060	0.80	1492	58	85	3.0

Table 3.4. (Continued)

Watershed	Model			Water yields			Difference between AWY_1 and AWY_2
	Initial conditions	Calibration parameters		AWY_2	AWY_2 / R	Wet AWY_2 / AWY_2	
	S(t=0)* (mm)	α (day^{-1})	Cz	mm yr^{-1}	%	%	%
Ramalah							
R1	53	0.080	1.00	1501	58	80	-1.9
R2	46	0.100	0.90	1509	58	80	-2.5
R3	72	0.050	0.80	1488	57	80	-1.0
RA1	53	0.080	0.80	1501	58	80	-1.9
RB1	53	0.080	0.70	1502	58	80	-1.9

* t=0 is Sept 1st 2009

AWY_1: annual water yields deduced from water budget

AWY_2 : simulated annual water yields

R: Annual rainfall (mm yr^{-1})

Wet AWY_2: simulated water yields during the wet season using reservoir model (mm yr^{-1})

S: water storage

α: drainage coefficient

Cz: contributive zone

Table 3.5. Mean annual values of water quality parameters throughout the landscape (12 stream sites) in the Petapahan area, Sumatra, Indonesia, and Indonesian water quality standards, class II (GR 82/2001).

Water quality parameters	Throughout the landscape*			Downstream from mill		Standards**
	Overall range	Overall average	sd (n=16)	RA2	R3	
pH	4.42-5.41	4.91	0.26	5.79	5.45	6-9
			$\mu S\ cm^{-1}$			
EC	12.8-22.7	18.10	2.96	91.23	32.08	-
			$mg\ L^{-1}$			
TOC	13.94-18.63	16.10	1.52	21.36	18.10	-
TP	0.01-0.07	0.03	0.02	0.16	0.02	< 0.2 (PO_4)
K	0.35-2.46	0.80	0.54	9.22	2.85	-
Mg	0.16-0.28	0.22	0.04	1.37	0.52	-
Ca	0.56-1.09	0.77	0.16	5.48	1.57	-
DIN	0.13-1.01	0.34	0.23	0.46	0.34	
NO_3-N	0.11-0.96	0.30	0.23	0.09	0.22	< 10
NO_2-N	0.01-0.02	0.010	0.003	0.01	0.02	< 0.06
NH_4-N	0.01-0.10	0.03	0.02	0.36	0.10	-
TDS	35.0-54.5	42.02	5.23	47.50	35.85	< 1000
TA	4.28-7.53	6.03	0.78	34.05	9.95	-
			$mg\ O_2\ L^{-1}$			
BOD	4.60-6.44	5.5	0.53	6.42	6.01	< 3
COD	27.1-30.5	28.68	1.00	31.19	30.01	< 25
DO	6.50-7.39	6.96	0.24	7.27	7.27	< 4

EC: Electrical conductivity; TOC: Total organic Carbon; TP: Total Phosphorus; DIN: Dissolved inorganic Nitrogen; TDS: Total dissolved solids; TA: Total alkalinity; BOD: Biological oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen

* The Annual mean values were calculated for the stream sites: JA1, JB1, JC1, P0, P1, P2, P4, PA1, PB1, PC1, PD1, R1, R2, R3, RA1, RA2, RB1.

Then the average at the landscape-scale was calculated from annual means on all sites, excepted RA2 and R3.

** Indonesian water quality standard class 2.

Table 3.6. Range and average of annual nutrient fluxes throughout the landscape (16 watersheds) in the Petapahan area, Sumatra, Indonesia

	TP	K	Mg	Ca	DIN	NO_3-N	NO_2-N	NH_4-N
	kg ha^{-1} yr^{-1}							
Min-Max	0.05-1.16	5.36-37.86	2.03-5.40	4.48-29.95	1.88-9.17	1.53-8.24	0.04-1.14	0.14-1.28
Average	0.37	14.10	3.55	12.65	4.99	4.27	0.23	0.51

* The average values were calculated from annual fluxes recorded for each stream sites: JA1, JB1, JC1, P0, P1, P2, P4, PA1, PB1, PC1, PD1, R1, R2, R3, RA1 and RB1

Table 3.7. Nutrient inputs in industrial and plasma oil palm plantations in the Petapahan area, Sumatra, Indonesia

	Mineral fertilizers (kg ha^{-1} yr^{-1})					Organic fertilizers (kg ha^{-1} yr^{-1})					Total fertilizers (kg ha^{-1} yr^{-1})				
Watersheds	N	P	K	Mg	Ca	N	P	K	Mg	Ca**	N	P	K	Mg	Ca
Industrial plantation															
Dominant mineral applications															
section P1-P4*	49	19	13	19	13	4.9	1.4	18	1.5	0.6	54	20	31	20	14
PA1	83	28	24	25	15	0	0	0	0	0	83	28	24	25	15
PD1	69	25	25	21	22	0	0	0	0	0	69	25	25	21	22
Dominant organic applications															
JA1	30	38	7.0	12	28	86	25	310	26	9.7	116	63	317	37	38
JB1	7.2	21	1.2	6.1	17	92	34	331	62	8.3	99	55	333	68	26
JC1	10	48	4.1	15	47	83	24	301	25	9.4	93	72	305	40	57
R2	56	21	23	13	21	96	54	339	154	3	151	75	362	167	24
R3	52	23	22	15	25	149	87	527	251	4	201	110	549	266	29
section R1-R2*	100	39	39	26	41	212	116	751	321	7.8	312	154	790	348	49
section R1-R3*	79	35	33	22	36	227	131	800	376	6.3	305	166	834	398	43

Table 3.7. (Continued)

Watersheds	Mineral fertilizers (kg ha^{-1} yr^{-1})					Organic fertilizers (kg ha^{-1} yr^{-1})					Total fertilizers (kg ha^{-1} yr^{-1})				
	N	P	K	Mg	Ca	N	P	K	Mg	Ca**	N	P	K	Mg	Ca
Plasma smallholder plantation															
R1	48	17	24	7.9	15	0.0	0.0	0.0	0.0	0.0	48	17	24	8	15
RA1	40	18	21	12	19	0.0	0.0	0.0	0.0	0.0	40	18	21	12	19
RB1	76	27	40	13	25	0.0	0.0	0.0	0.0	0.0	76	27	40	13	25

* sections concerns the part of the watershed that is only under industrial oil palm plantation

** from empty fruit bunched applications only. No data on Ca content in palm oil mill effluent.

Table 3.8. Nutrient fluxes exported to waterways reported in other studies carried out in the Tropics (natural forest and oil palm plantation).

Location	TP	K	Mg	Ca	TN	NO_3-N	NO_2-N	NH_4-N	Source
	kg ha^{-1} yr^{-1}								
In the study area (Petapahan area)	***0.05-1.16***	***5.4-37.9***	***2.0-5.4***	***4.5-30.0***	***-***	***1.53-8.24***	***0.04-1.14***	***0.14-1.28***	
Tropical Rainforest									
Rainforest, volcanic soils				24.8-29					Turvey, 1974; Bruijnzel, 1983
Rainforest, limestone soil				764-795					Crowther, 1987a,b
Close tropical rainforest, Guyana, plot-scale		5	1	2	4	3		1	Brouwer and Riezebos, 1998
Rainforest Amazon, Latosols	0.3		0.5	0.9	29	3.25	0.11	3.7	Brinkmann, 1985
Intact forest, Coast Rica, fertile clayey ultisol, plot-scale		3.6	8.2	5.5	17.3				Parker, 1985

Table 3.8. (Continued)

Location	TP	K	Mg	Ca	TN	NO_3-N	NO_2-N	NH_4-N	Source
	kg ha^{-1} yr^{-1}								
In the study area (Petapahan area)	***0.05-1.16***	***5.4-37.9***	***2.0-5.4***	***4.5-30.0***	***-***	***1.5-8.2***	***0.04-1.14***	***0.14-1.28***	
Hill dipterocoarp forest, gleyic podsol and haplic acrisol	0.65	30.5	5.8	10.1	6.2				Malmer, 1996
tropical cloud forest, Costa Rica						4-6			Brookshire, 2012
Oil palm plantation, plot-scale studies									
Unfertilized adult oil palm (22 years) , volcanic soil, Nigeria		29	32	123	65				Omoti et al., 1983
Unfertilized young oil palm (4 years), volcanic soil, Nigeria		3	32	165	32				Omoti et al., 1983

TP: Total Phosphorus; TN : Total Nitrogen

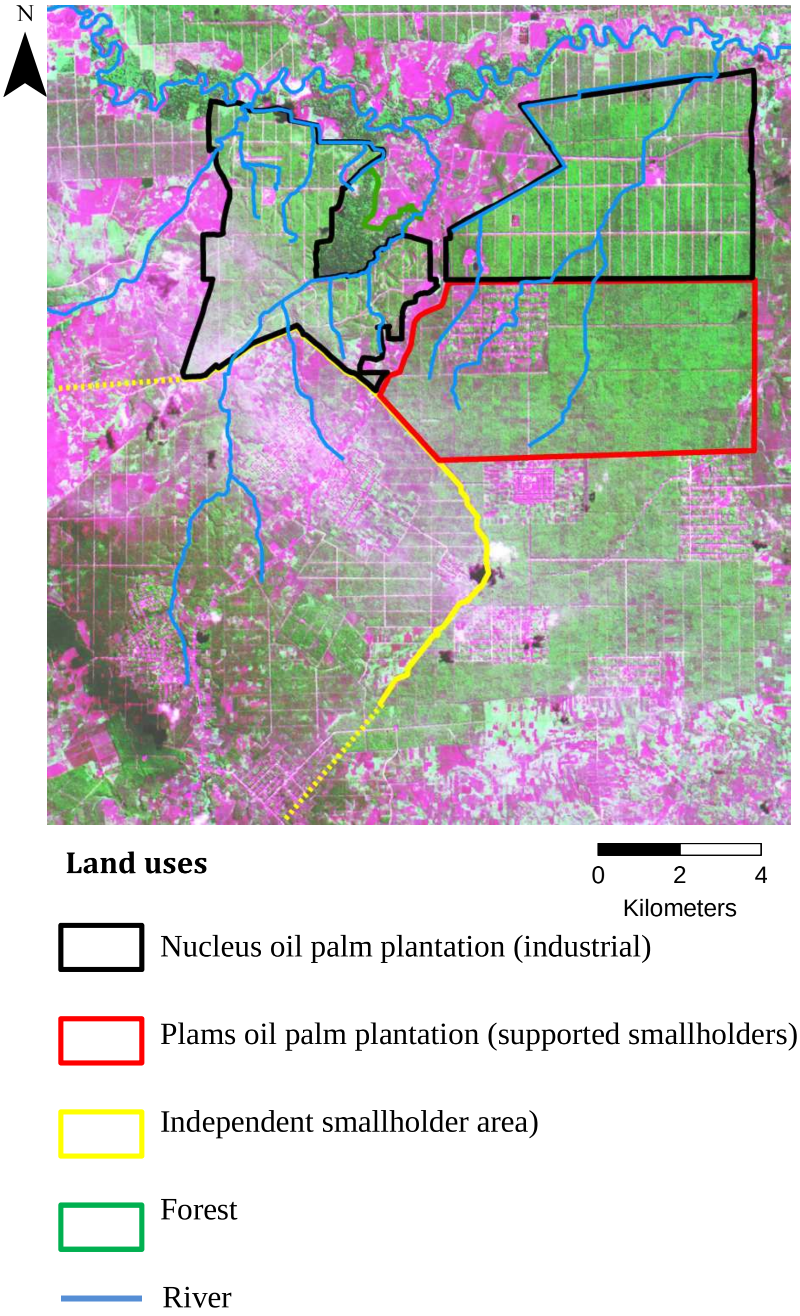


Figure 3.1. Characterization of the study area, in the Petapahan area, Sumatra, Indonesia. a/ Identification of land uses from satellite imagery (SPOT4/2008).

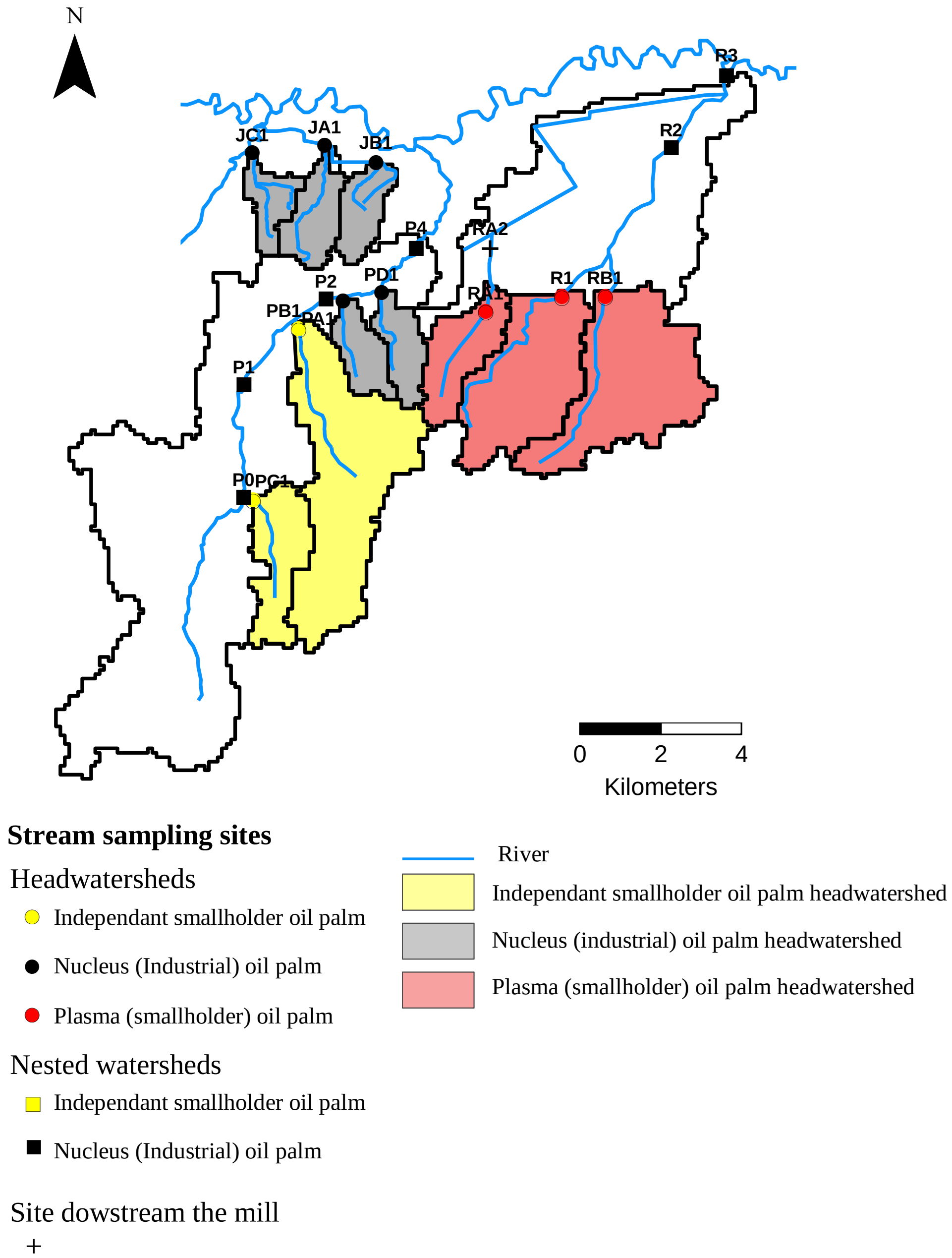


Figure 3.1. (Continued) b/ Watershed delineation and stream monitoring design.

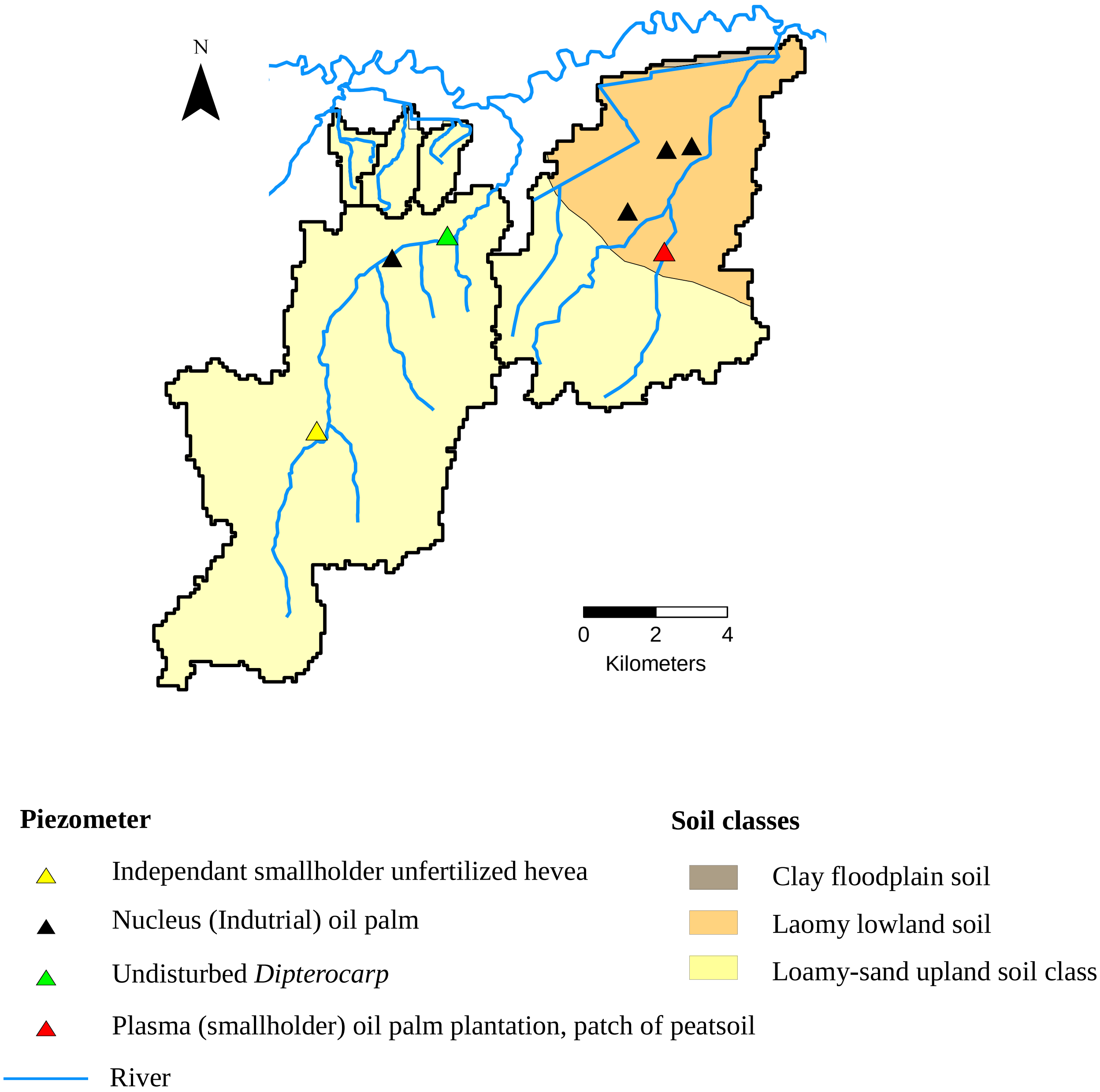


Figure 3.1. (Continued) c/ Categorization of the soil classes and groundwater monitoring design.

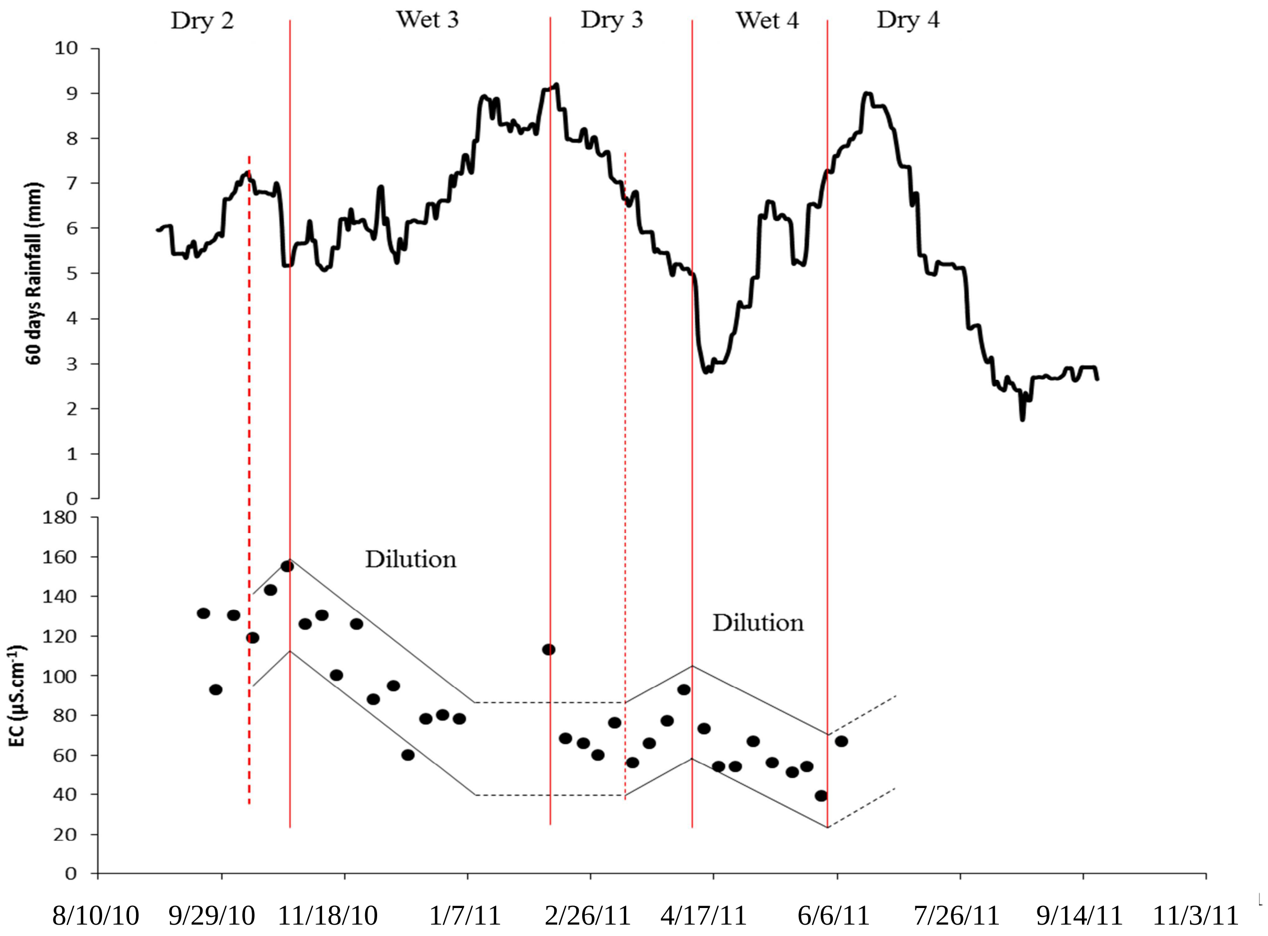


Figure 3.2. Electrical conductivity (EC) values in groundwater and 60 days-averaged rainfall pattern from September 1st, 2010 to June 6th, 2011 (EC values measured in the piezometer SP-P0 are shown as illustration).

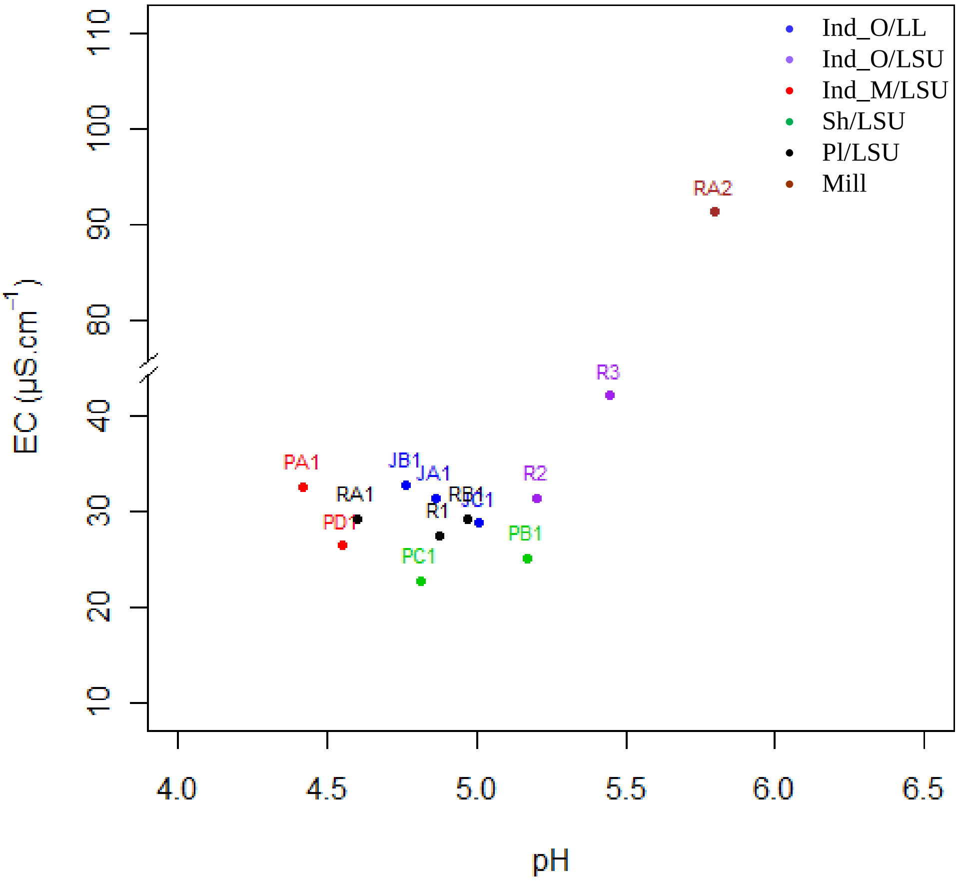


Figure 3.3. Annual mean values water quality parameters measured in stream water in the Petapahan area, Sumatra, Indonesia. a/ pH vs. electrical conductivity (EC). Ind: Industrial ; Sh: Smallholder ; Pl: Plasma ; O: Organic fertilization ; M : Mineral fertilization ; LSU: Loamy-sand uplands ; LL: Loamy lowlands.

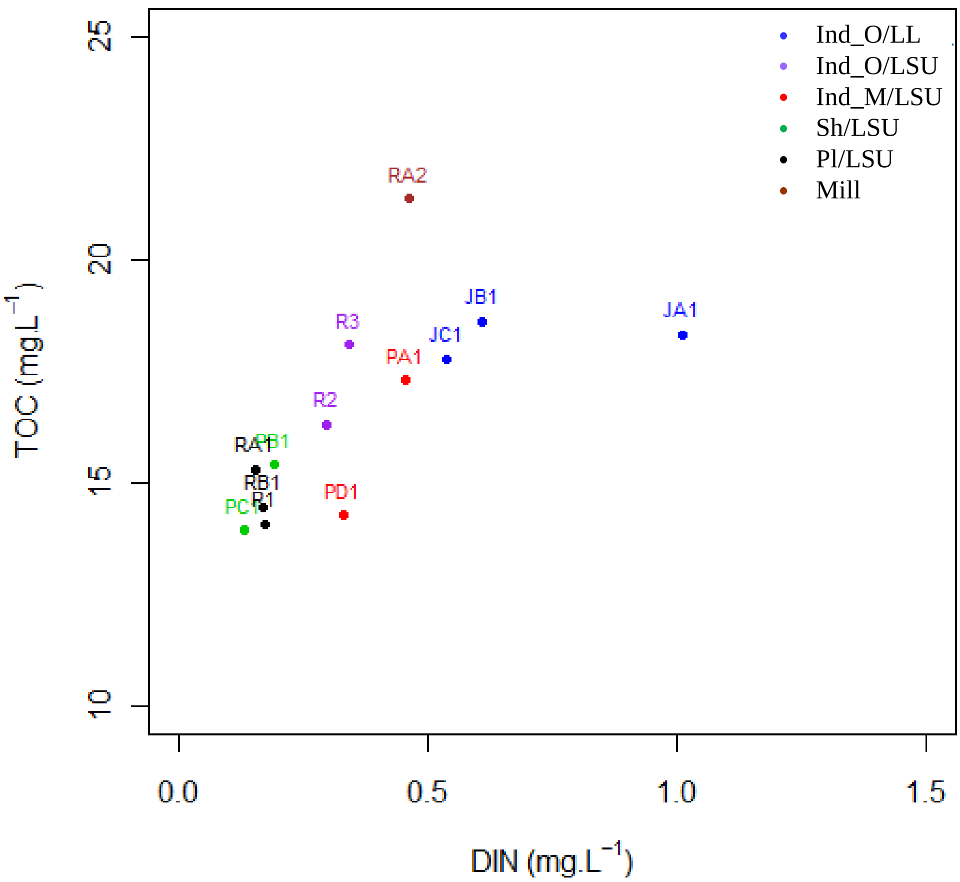


Figure 3.3. (Continued) b/ dissolved inorganic Nitrogen (DIN) vs. total organic carbon (TOC). Ind: Industrial ; Sh: Smallholder ; Pl: Plasma ; O: Organic fertilization ; M : Mineral fertilization ; LSU: Loamy-sand uplands ; LL: Loamy lowlands.

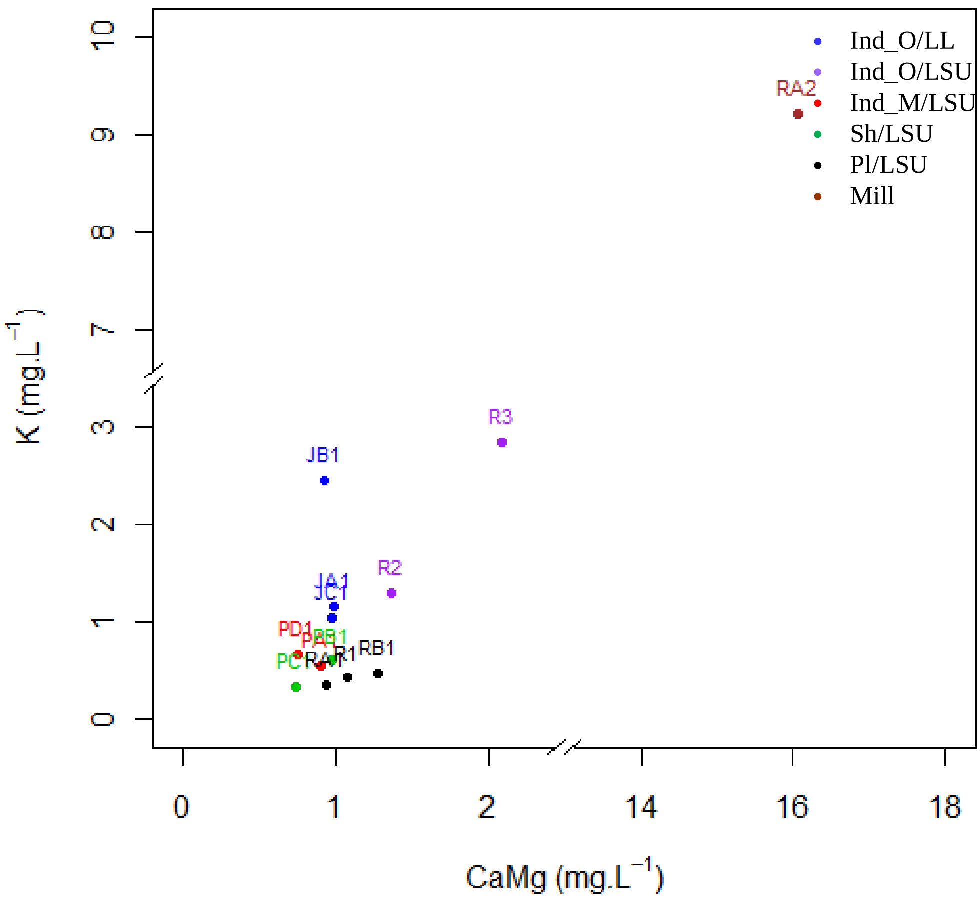


Figure 3.3. (Continued). c/ sum of Ca and Mg (CaMg) vs. K.

Ind: Industrial ; Sh: Smallholder ; Pl: Plasma ; O: Organic fertilization ; M : Mineral fertilization ; LSU: Loamy-sand uplands ; LL: Loamy lowlands.

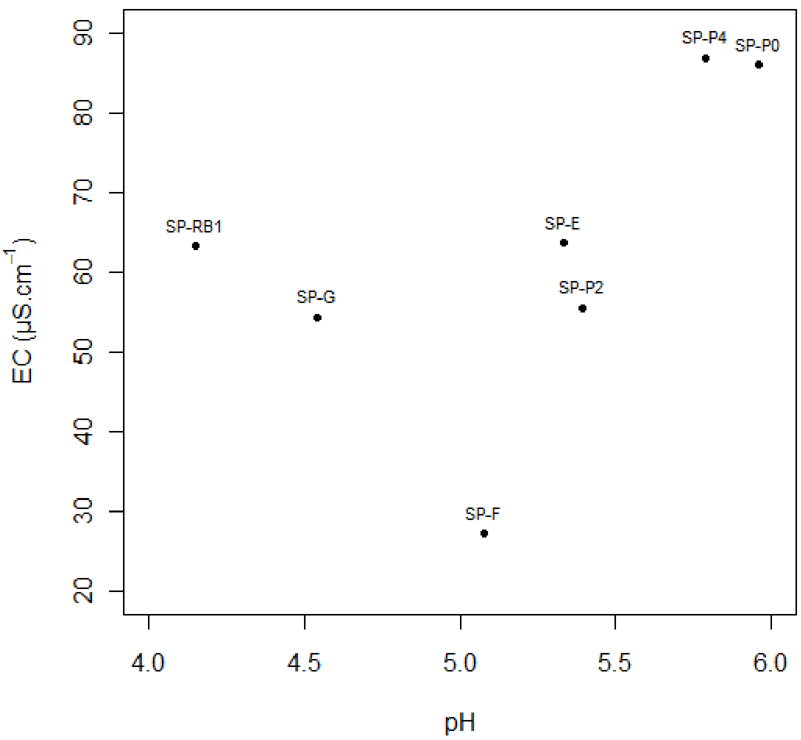


Figure 3.4. Annual mean values water quality parameters measured in groundwater in the Petapahan area, Sumatra, Indonesia. a/ pH vs. electrical conductivity (EC). SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under natural forest; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation. Letter a, b, c… represent the results of Kruskall-Wallis test performed between the piezometers (when $p<0.05$).

	SP-P0	SP-P2	SP-P4	SP-E	SP-F	SP-G	SP-RB1
pH	a	c	b	c	d	e	f
EC	a	de	ab	bc	f	e	cd

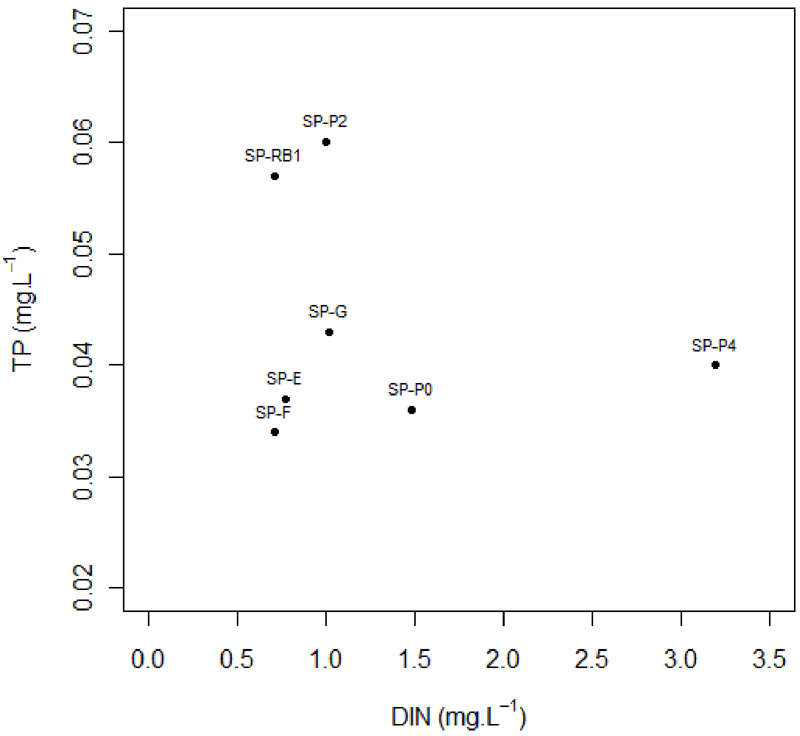


Figure 3.4. (Continued). b/ dissolved inorganic Nitrogen (DIN) vs. total phosphorous (TP). SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under natural forest; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation. Letter a, b, c… represent the results of Kruskall-Wallis test performed between the piezometers (when $p<0.05$).

	SP-P0	SP-P2	SP-P4	SP-E	SP-F	SP-G	SP-RB1
DIN	a	bc	a	bc	c	b	c
TP	-	-	-	-	-	-	-

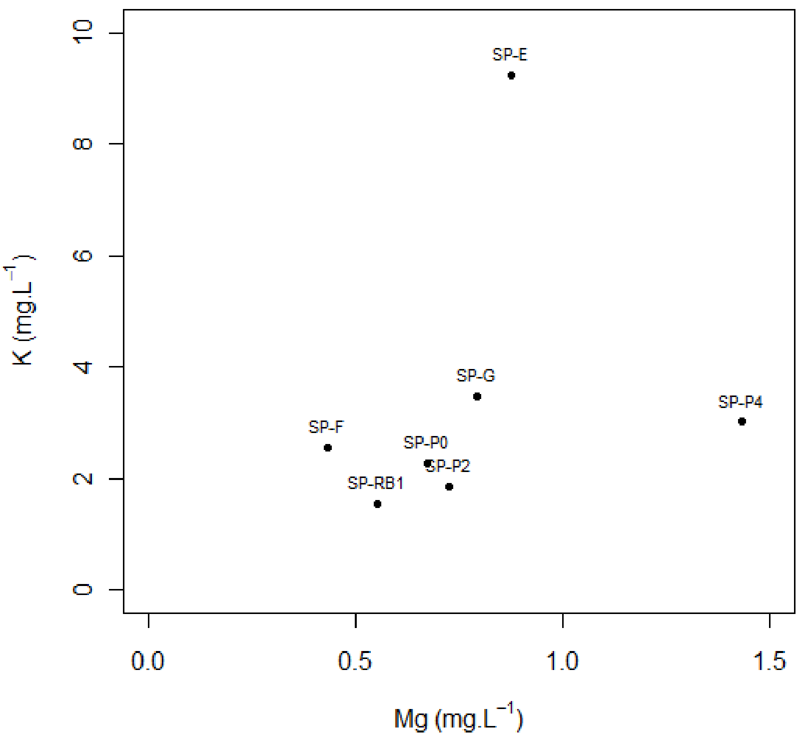


Figure 3.4. (Continued). c/ Mg vs. K.

SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under natural forest; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation. Letter a, b, c… represent the results of Kruskall-Wallis test performed between the piezometers (when $p<0.05$).

	SP-P0	SP-P2	SP-P4	SP-E	SP-F	SP-G	SP-RB1
Mg	b	b	a	a	d	b	c
K	c	d	bc	a	bc	bc	d

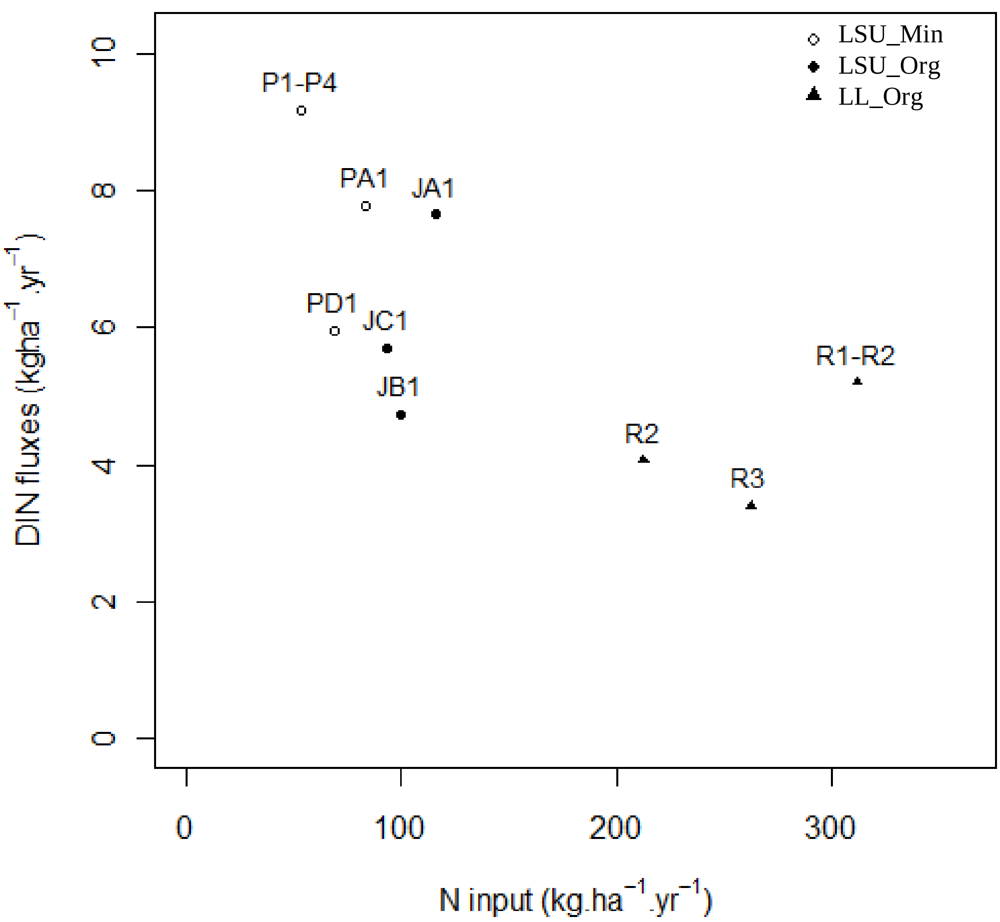


Figure 3.5. Nutrient inputs as fertilizers and nutrient fluxes exported to streams in industrial oil palm plantation watersheds. a/ N inputs vs. dissolved inorganic N (DIN) fluxes exported. LSU_Min: Mineral fertilized watersheds located on loamy-sand uplands; LSU_Org: Organic fertilized (empty fruit bunch only) watersheds located on loamy-sand uplands; LL_Org: Organic fertilized watersheds (mainly palm oil mill effluent) located on loamy lowlands. The R3 outlet is located downstream from the mill.

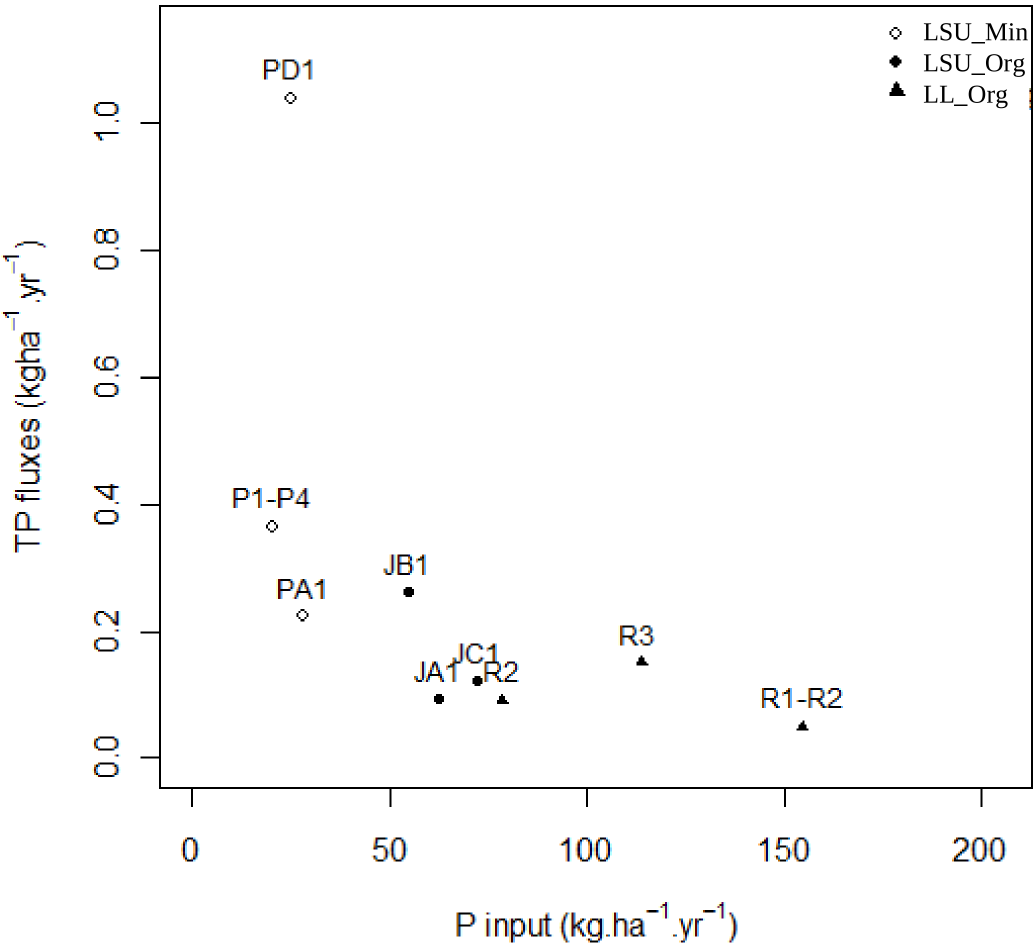


Figure 3.5. (Continued). b/ P inputs vs. total P (TP) fluxes exported.

LSU_Min: Mineral fertilized watersheds located on loamy-sand uplands; LSU_Org: Organic fertilized (empty fruit bunch only) watersheds located on loamy-sand uplands; LL_Org: Organic fertilized watersheds (mainly palm oil mill effluent) located on loamy lowlands. The R3 outlet is located downstream from the mill.

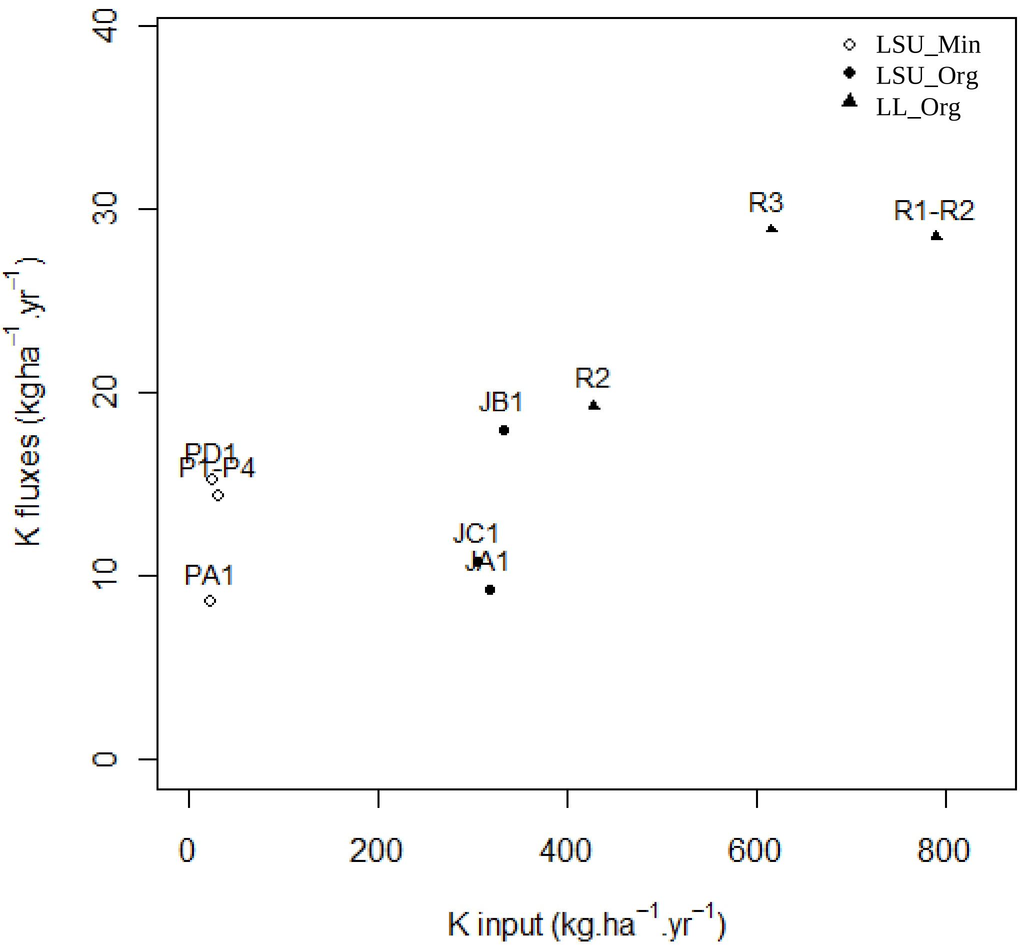


Figure 3.5. (Continued).c/ K inputs vs. K fluxes exported.

LSU_Min: Mineral fertilized watersheds located on loamy-sand uplands; LSU_Org: Organic fertilized (empty fruit bunch only) watersheds located on loamy-sand uplands; LL_Org: Organic fertilized watersheds (mainly palm oil mill effluent) located on loamy lowlands. The R3 outlet is located downstream from the mill.

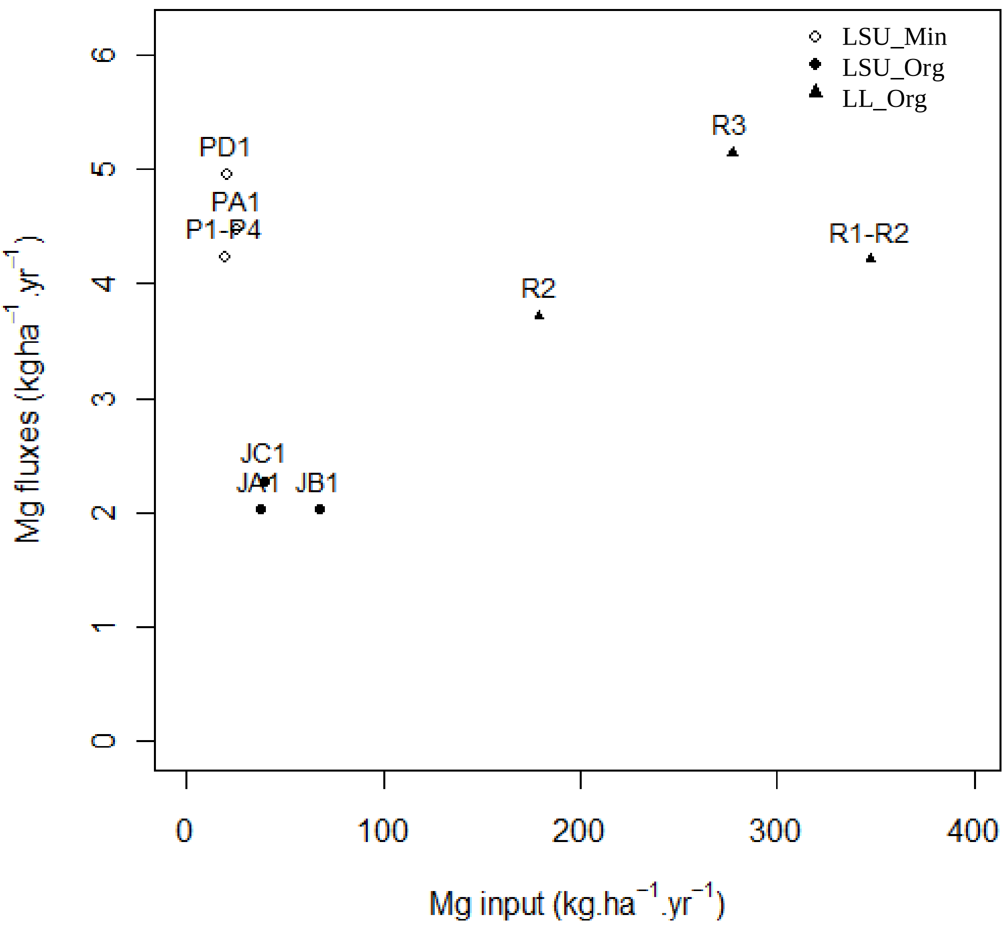


Figure 3.5. (Continued). d/ Mg inputs vs. Mg fluxes exported.

LSU_Min: Mineral fertilized watersheds located on loamy-sand uplands; LSU_Org: Organic fertilized (empty fruit bunch only) watersheds located on loamy-sand uplands; LL_Org: Organic fertilized watersheds (mainly palm oil mill effluent) located on loamy lowlands. The R3 outlet is located downstream from the mill.

General conclusion

The rapid expansion of oil palm cultivation in Southeast Asia raised environmental concern, necessitating a critical evaluation of the impacts of this production system on ecological health. Oil palm growers are faced with the challenge of sustaining high yields to keep pace with the growing global demand for oil and fats, while reducing the environmental impacts of oil palm cultivation. Environmental impacts associated with the deforestation at the initial phase of an oil palm plantation establishment are well documented, however the environmental impacts of mature oil palm plantation remain poorly investigated, especially regarding the risk of nutrient export to waterways. Soil characteristics and fertilizer management in oil palm plantations were expected to alter the soil fertility status and nutrient loads to waterways. This hypothesis led me to ask several questions in my research: do mature oil palm plantations endanger aquatic ecosystems through nutrient loads to waterways? Do planters need to improve their fertilizer management to ensure suitable soil fertility status across various soil types while reducing nutrient losses to waterways? What are the dominant hydrological processes involved in the nutrient transfers from mature oil palm agrosystems to waterways?

The literature review confirmed that most hydrological studies in oil palm plantations were carried out at the plot-scale, without taking account of the variability in soil characteristics and fertilization practices across the plantation. However, sustaining high yields on such large-scale plantations, while improving land and water management, requires the development of landscape-scale approaches to assess the soil response to fertilizer applications and the risk of nutrient export to waterways. Developing landscape-scale approaches is challenging, especially in poor tropical countries. First, it requires accurate soil and hydrographic network maps, aerial photography to identify the land uses, which are rarely available in under-investigated study areas in tropical countries. Thus, to be able to set up a spatially explicit sampling protocol, a preliminary characterization of the study area was required even before this study could begin. It included a digital elevation model and satellite imagery acquisition (no available aerial photography) and analysis, a field survey (with GPS tracking) to map the hydrographic network, and landscape-level soil sampling and spatial analysis to map the different soil classes within the study area.

Studying commercial fields distributed across the landscape to assess the soil response to long term fertilizer applications required that I develop a framework that permitted me to assess the soil-fertilizer relationship despite the paucity of historical soil test data and high heterogeneity in long term fertilizer sequences applied to each field. The landscape-scale approach that I developed consisted of simple statistical analysis of soil data coming from an one-time soil survey and relied on an index to characterize the long term fertilization sequences as mineral dominant or organic dominant, also considering the temporal heterogeneity in fertilizer use (i.e., organic fertilizers only, mineral fertilizers only or both during a 7-year period). In the same way, assessing the nutrient export to streams while accounting for spatial variability in soil properties and fertilizer management required me to consider several watersheds across the landscape as pseudoreplicates. To face the constraints raised by an one-year monitoring on a multi-site design, the study proposed a framework based on bi-monthly hydrochemical measurements and the reconstitution of daily discharge time series through baseflow modeling, allowing me to calculate annual nutrient fluxes to streams. The approaches I developed for my thesis research were easily applicable and robust, so that they could be adopted by researchers working on other perennial cropping systems and/or under similar pedoclimatic conditions.

My results show that low-fertility Ferralsols responded significantly to continuous organic fertilization and a decline in some soil fertility parameters when organic fertilizers were applied infrequently over a 7-yr period. I also demonstrated that coarser textured soils benefit more from repeated applications of organic fertilizers. This was consistent with the conceptual model of soil biogeochemical processes described in Chapter 2. Another important outcome of this study was my report of low nutrient concentrations in streams adjacent to mature oil palm plantations under rational fertilizer program, which I attributed to either low nutrient transfer to groundwater and streams or to a dilution effect (e.g., high water flow infiltrating in soil induced the dilution of nutrient concentrations in groundwater and streams that are mainly fed by baseflow). I concluded that the dilution effect in my study area, which was humid and had fast-draining pedoclimatic conditions, definitely played a role in the resulting low nutrient concentrations recorded in the streams. Moreover, low nutrient exports were recorded in streams despite high nutrient inputs to the agroecosystem. This was ascribed to the high nutrient requirements of oil palm, combined with the rational fertilizer management program in the studied nucleus-plasma plantation where nutrient export did not exceed the export recorded in the smallholding area. Higher nutrient exports were observed in streams in watersheds where soils were predominately loamy-sand uplands, despite lower fertilizer inputs in the loamy-sand uplands than loamy lowlands. This is consistent with my expectation that soil characteristics control nutrient export across the watershed. Organic fertilizers seemed result in lower nutrient export than mineral fertilizers when similar nutrient inputs were applied from each source.

The study opened the way to the idea that a higher level of spatial consideration should be considered by industrial planters, as well a higher integration of organic and mineral fertilizers, to improve the quality of nutrition management, and minimizing any risk on the environment. In particular, organic fertilizers should be preferentially applied on coarser textured soils, where repeated applications are expected to improve soil fertility status. Although coarse textured soils are more susceptible to export nutrients to waterways, this should not endanger the aquatic ecosystem given the high annual rainfall that dilutes the nutrient load in streams within the study area, and provided that growers follow a rational fertilizer management program. The location of oil palm processing mills is an important factor that affects long term strategy for applying organic fertilizer in the plantation due to transportation costs of organic fertilizers. The choice of the mill location is usually based on water availability (close to a river) and having soils with good physical structure to support the facility. Soil fertility in the nearby blocks is generally not taken in account in this choice. Thus, I recommend that managers also consider whether local soils are more sensitive to nutrient losses and benefit more from repeated organic fertilizers applications to improve soil fertility when they choose a location for the mill, during the establishment phase of the plantation.

My thesis considered large-scale spatial variability in soil types and fertilizer management within an industrial plantation, which functions as a landscape, to provide information to aid decision-making at the landscape-scale. A subsequent level of complexity can be added by including the different production systems (independent smallholders, plasma smallholders, industrial plantation), considering the large scale of industrial plantations vs. the small scale of smallholder holdings (< 50 ha). However, smallholder production systems are numerous, heterogeneous and difficult to characterize. Vegetation is more diverse and smallholders (either plasma or independent) currently rely on mineral fertilizers only. Thus, smallholders do not currently cope with the development of a spatial strategy of organic vs. mineral fertilizer applications in their holdings. Incidentally, when smallholders sell their harvested fruit bunches to the palm oil mill, they also give organic materials that are retained by the industrial producer and applied as organic fertilizer in the industrial plantation. This represents a net depletion of organic matter from smallholders and a net gain by industrial planters. Although it is beyond the scope of this thesis to consider how smallholders should be compensated for such organic materials, it could be considered in the context of carbon trading credits by policy makers in Indonesia.

Future research directions

The research presented in this thesis was a first step in the landscape-scale assessment of oil palm fertilizer management effect on soil response and nutrient exports to waterways. Here I suggest directions for further research that were identified during the course of this work.

- This study focused on nutrient fluxes although it has reported high organic matter content in streams. Further research is required to investigate carbon cycle in oil palm plantations. This would allow determining the carbon balance in oil palm agroecosystem and analyzing potential transfers of pesticides (to control weed in palm circle) to streams when bonded on dissolved organic matter.
- Integrating yields and processes involved in the transfer of nutrient and other agrochemicals (e.g. pesticides) to waterways with modeling software would allow scientists and plantation managers to perform simulations of various management scenarios. This would lead to agro-environmental optimization of the fertilizers and agrochemicals applied throughout the oil palm cultivation cycle (clearing to replantation), considering pedoclimatic conditions and describing spatio-temporal dynamics, notably in a context of global climatic change.
- Future work should investigate the effect of mature oil palm plantation on nutrient transfers in different contexts:
    - In areas under drier climatic conditions which limits the dilution effect on nutrient concentrations in streams.
    - Under unbalanced fertilizer program. Under fertilizing may contribute to nutrient depletion in the soil (due to high oil palm uptake) when no fertilizers are applied to replenish the soil nutrients removed by this perennial crop. Given the short residence time of groundwater, over fertilizing may trigger high nutrient fluxes to streams. In particular, fertilization practices in independent smallholder oil palm plantations remain under-investigated due to challenging data collection.

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Appendix 1: Soil infiltrability measurements

1. Definitions

Infiltration is the process by which water on the soil surface penetrates the soil. Infiltration can be quantified by the soil infiltrability or infiltration rate. Infiltration rate is the volume of water moving downward into the soil surface per unit of area per unit of time and has the dimensions of velocity. It is usually measured by the depth (in mm) of the water layer that can enter the soil in one hour. In dry soil, water infiltrates rapidly. This is called the initial infiltration rate (Brouwer et al., no date). Generally, during an infiltration event, the comparatively very high initial soil infiltrability decreases rapidly with time. As more water replaces the air in the pores, the rate of decrease slows down exponentially and the infiltration rate gradually reaches a steady state, i.e., the steady or final infiltration rate. The final soil infiltration rate is equal to, or very close to, the saturated hydraulic conductivity (Lili et al., 2008)

2. Double ring method description

A number of methods have been developed for soil infiltrability measurement. The double ring infiltrometer is a widely used method of infiltrability (Parr and Bertrand, 1960). The double-ring infiltrometer method consists of driving two open cylinders, one inside the other, into the ground (to a depth of 10-20 cm). Water is added within the two rings simultaneously and constant level is then maintained throughout the measurement. The volume of water added to the inner ring, to maintain the water level constant is the measure of the volume of liquid that infiltrates the soil. The outer cylinder is used only as a tool to ensure that water from the inner cylinder will flow downwards thus greatly reducing the horizontal leakage. The water volume supplied to the inner ring, in order to maintain a constant level of water, was recorded as a function of time and then used for infiltrability computation. A Mariotte tube was used for maintaining the water level and for measuring the quantity of water. The average soil infiltration rate for a given time period is estimated from the volume of the water supplied to the inner ring divided by the area of the inner ring. Infiltration rate is usually expressed in centimeter per hour and plotted versus elapsed time (Johnson, 1963; Lili et al., 2008).

2. Field survey

Infiltration measurements were done using the double ring method at locations across the study area with contrasting soil characteristics. Aluminum rings were used, the inner ring being 20 cm diameter and the outer ring being 40 cm diameter. A Mariotte tube was used for maintaining the water level and for measuring the quantity of water. In total, measurements were carried out on two locations on sandy uplands (SU), two on sandy-loam lowlands (SLL), one on clayey floodplain (CF), and three on peatsoils in the three pedomorphological classes (SLL_peat, SU_peat and CF-peat). Water volumes were recorded every 5 to 15 min until infiltration rates reached steady states after 60 to 110 min.

In general, high infiltration rates were recorded over the study area: 9 to 77 $cm.h^{-1}$ on SU, 8 to 13 $cm.h^{-1}$ on SLL, 24 to 57 $cm.h^{-1}$ on peat soils. Low infiltration rate (0.6 $cm.h^{-1}$) was recorded on CF.

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Appendix 2: Flood hydrograph analysis

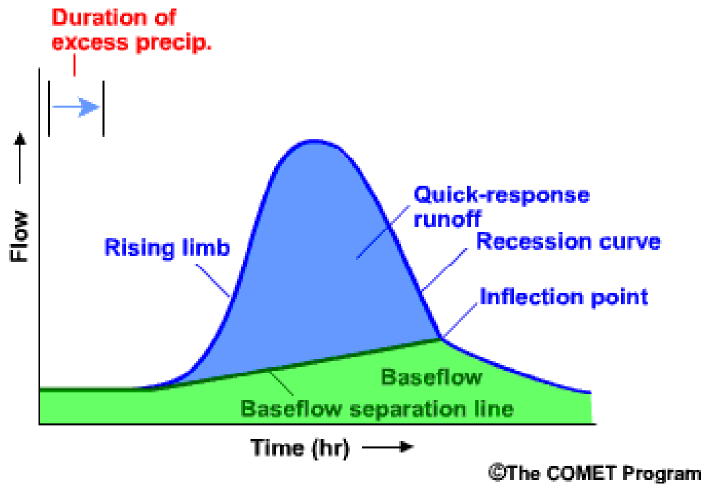
1. Definitions and method description

Water reaching the soil surface may either infiltrates into the soil and reach the stream through long-term flow (baseflow) or flow directly to the stream through surface runoff (quick-response runoff). The runoff coefficient (K) is the fraction of precipitation that runs off into streams.

$$K\ (\%) = \frac{Quick\ response\ runoff\ (mm)}{Precipited\ rainfall\ (mm)}$$

Depending on the soil type and rainfall intensity the runoff coefficient from pervious areas could be as low as no runoff at all (e.g. in the case of low rainfall intensity and sandy soil) or up to 80% (e.g. in the case of high rainfall intensity and heavy clay soil). The analysis of flood hydrograph aims to separate the baseflow (from infiltrated water) and quick-response runoff (from surface runoff) components of the hydrograph and to provide surface runoff coefficient for the watershed during the recorded storm event.

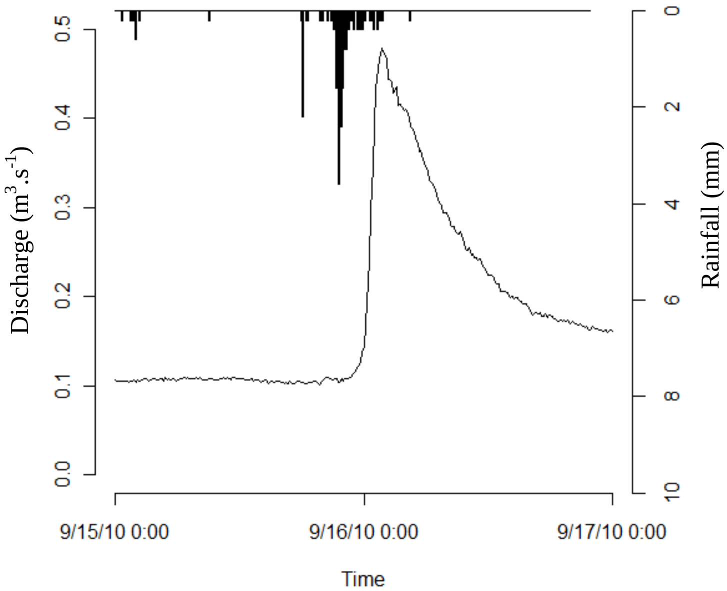
The straight line method is a simple, commonly used, graphical approximation for separating baseflow from quick-response runoff. It results in the baseflow separation line, which separates the part of the total hydrograph that is the result of long–term flow (baseflow) from the part that is short–term, quick–response runoff. The inflection point is the point on the recession curve of the hydrograph where the slope of the graph becomes less steep. This point indicates where the baseflow becomes more important to the total flow than the quick–response runoff.



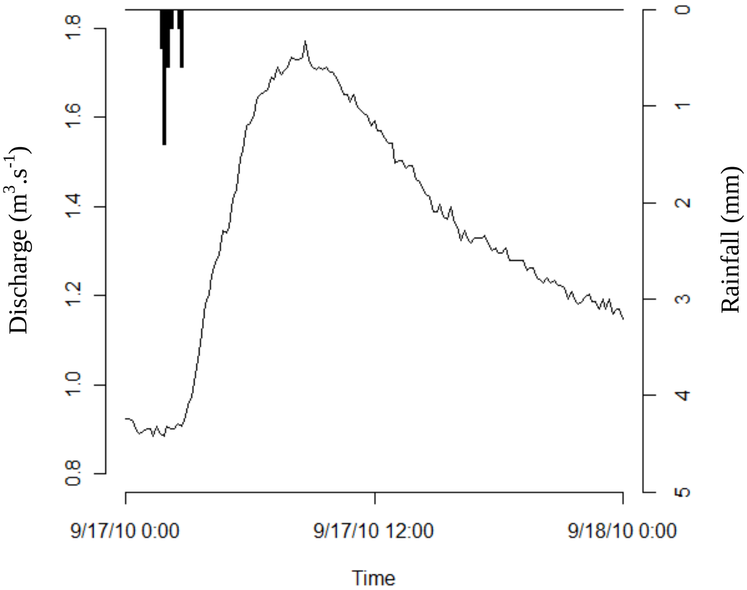
2. Application to the study area

Two storm events were recorded in the study area using Schlumberger divers (Mini-Diver and CTD-Diver). Measurements were carried during the dry season of the hydrological year 2010-2011 (August 2011).

Storm event 1 (RB1 outlet, sandy uplands): Total rainfall 21.6 mm, runoff coefficient: 3.9 %



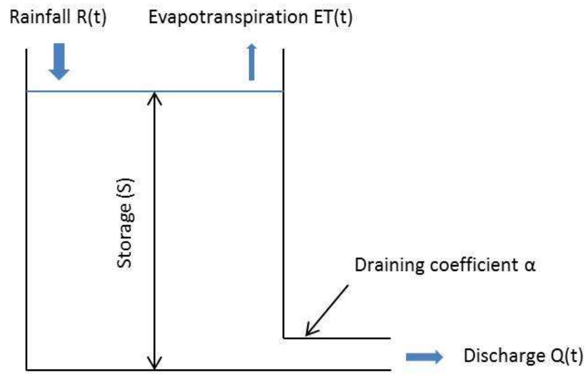
Storm event 2 (R2 outlet, sandy-loam lowlands) : Total rainfall 17.8 mm, runoff coefficient : 3.0 %



Appendix 3: Daily discharge reconstitution based on a reservoir model

1. Principle

In lumped reservoir models the watershed is considered as a whole system, performing the rain-flow conversion. This modeling approach has the advantage of taking account of the storage effect of the watershed, so it is adapted to an infiltrant system. The watershed is schematically represented in the form of a reservoir, where drainage is a linear function of water storage.



At each time step water storage is calculated as a function of rainfall, evapotranspiration and discharge calculated at the previous time step. Reservoir modeling is based on a simple mathematical equation (1):

$$WY_2(t) = S(t).\ \alpha \qquad (1)$$

The storage S(t) is determined as follows:

$$S(t) = S(t-1) + R(t) - ET(t) - Q(t-1)$$

WY_2 (t) = Daily water yield [L] $[T]^{-1}$

α = Draining coefficient $[T]^{-1}$

S(t) = Water storage [L]

R (t) = Rainfall [L]

ET (t)= Evapotranspiration [L]

This model provides water yield expressed as water depths (mm) at each time step, which has to consider the watershed contributive surface to be expressed as water fluxes Q ($m^3.s^{-1}$). The contributive zone represents the proportion of the watershed that effectively contributes to discharge at the outlet. It depends on the topography and on the presence of artificial draining pathways (e.g. ditches).

$$Q(t) = WI_2(t).Cz.A \qquad (2)$$

Q(t)= Discharge $[L]^3.[T]^{-1}$

Cz = Contributive proportion of the watershed area [dimensionless], the value of Cz is equal to1 when the draining watershed area equals the topographic watershed area.

A= Watershed topographic area $[L]^2$

2. Application to the study area

This model is a simple approach that requires few inputs data and calibration parameters and it takes account of the watershed storage (capacity). Thus, this model is thought to be adapted for daily discharge reconstitution from infiltrant watershed, where stream flow is dominated by baseflow from shallow groundwater.

2.1 Parameters and calibration

Input data were daily rainfall and evapotranspiration. Initial condition was initial water storage S(t=0) and the calibration parameters were the contributive proportion Cz and the draining coefficient α. Cz was derived from field knowledge and α from manual calibration based on (i) fitting daily simulation with punctual observations of baseflow occurring between storm events, (ii) finding coherence between the α values between watersheds: similar watersheds (soil, topography and land uses) were given similar α values.

Table 4.1. Model parameterization, calibration and validation

Watershed	Model Initial parameters			Model calibration criteria					Model output	Model validation
	S(t=0)*	α	Cz	RMSE	Slope β	Reference watershed**	R^2		AWY_2 ($mm.yr^{-1}$)	Difference between AWY_1 and AWY_2 (%)
Jernih										
JA1	53	0.06	0.50	0.01	0.79	JC1	0.72	n=23	1563	-1.6
JB1	53	0.06	0.50	0.01	0.79	JC1	0.79	n=18	1563	-1.6
JC1	53	0.060	0.50	0.01	0.79				1563	-1.6
Petapahan										
P0	69	0.055	1.00	0.37	1.00				1530	0.6
P1	71	0.055	1.00	1.01	0.96				1532	0.5
P2	77	0.050	0.90	1.67	1.00				1544	-0.3
P4	73	0.055	1.00	0.97	1.05				1546	-0.4
PB1	79	0.040	1.00	0.30	0.74				1533	0.4
PC1	56	0.080	1.50	0.37	0.93				1549	-0.7
PA1	56	0.080	1.50	0.37	0.93	PC1	0.78	n=15	1549	-0.6
PD1	15	0.060	0.80	0.12	0.82				1492	3.0

Table 4.1. (continued)

Watershed	Model Initial parameters			Model calibration criteria				Model output	Model validation
	S(t=0)*	α	Cz	RMSE	Slope β	Reference watershed**	R^2	AWY_2 ($mm.yr^{-1}$)	Difference between AWY_1 and AWY_2 (%)
Ramalah									
R1	53	0.080	1.00	0.36	0.44			1501	-1.9
R2	46	0.100	0.90	0.91	0.51			1509	-2.5
R3	72	0.050	0.80	0.65	0.65			1488	-1.0
RA1	53	0.080	0.80	0.23	0.09			1501	-1.9
RB1	53	0.080	0.70	0.28	0.64			1502	-1.9

* t=0 is Sept 1st 2009

* *For JA1, JB1 and PA1, there was insufficient data to calibrate the model, so a regionalization approach was used to select relevant model parameters from a reference watershed (i.e. having similar size and pedoclimatic conditions) (Parajka et al., 2005).

α: groundwater drainage coefficient

Cz: contributive area

RMSE: root mean square error between observed discharge and simulated daily discharge

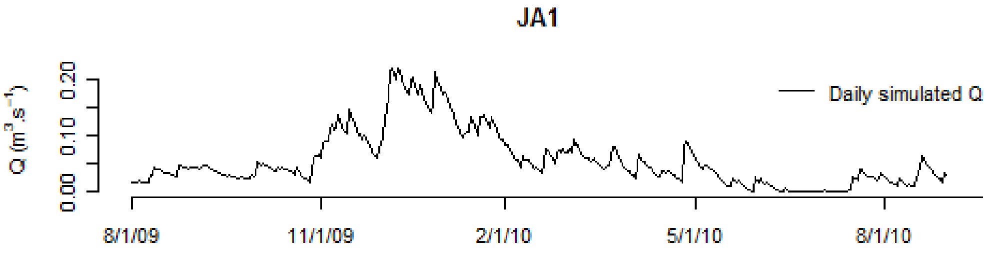
Slope β: slope for observed vs. simulated daily discharge

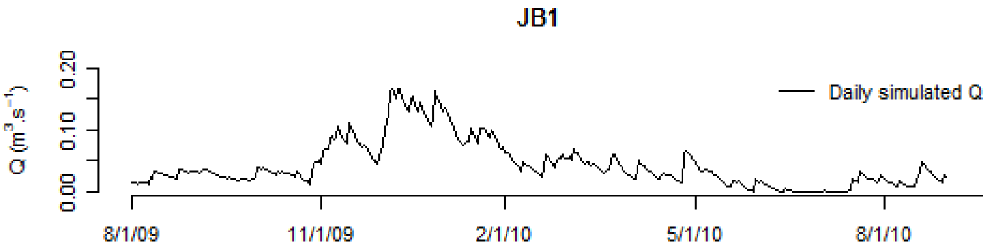
R^2 : coefficient of determination for observed discharge of JA1 vs. observed discharge of JC1, JB1 vs. JC1 and PA1 vs. PC1

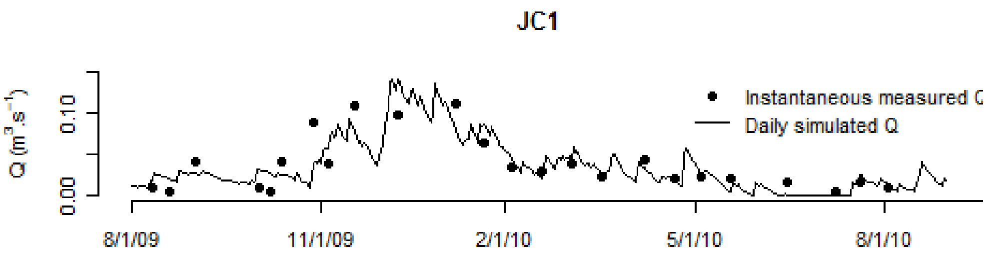
AWY_1 : Annual water yield deducted from annual water budget

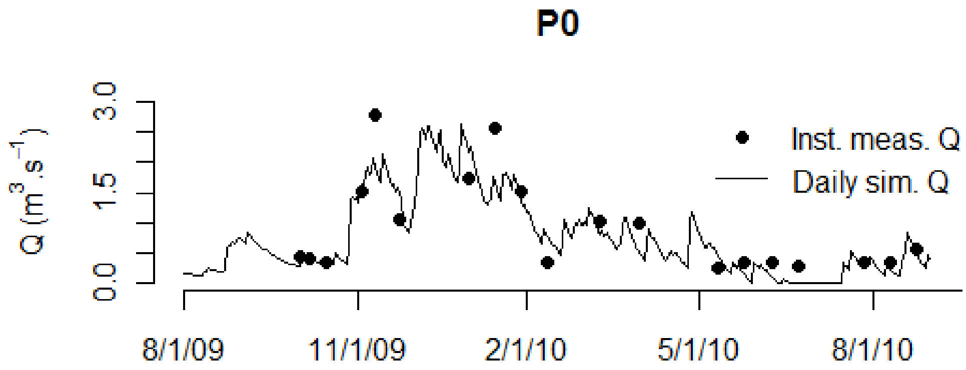
AWY_2 : Annual water yield calculed using the hydrological model.

2.2 Daily discharge reconstitution








P0
Q (m^3.s^-1)
0.0
1.5
3.0
Inst. meas. Q
Daily sim. Q
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11/1/09
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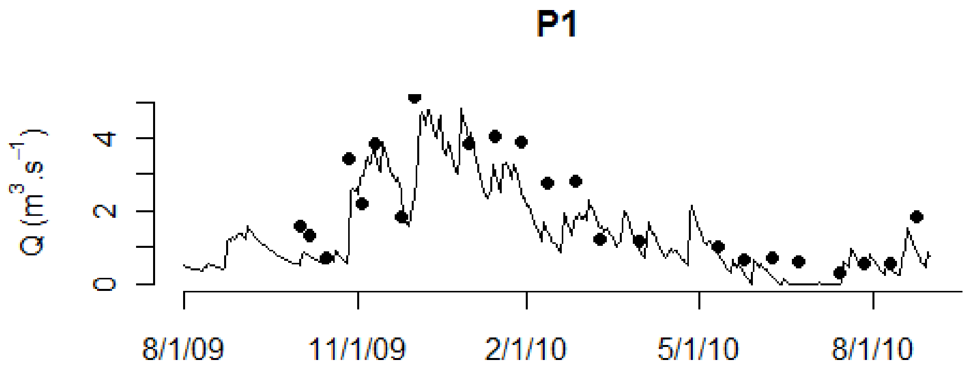
5/1/10
8/1/10


P1
Q (m^3.s^-1)
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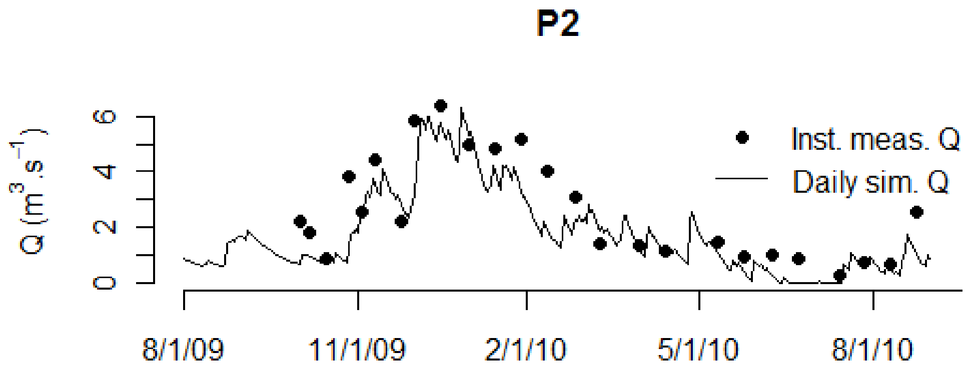
P2
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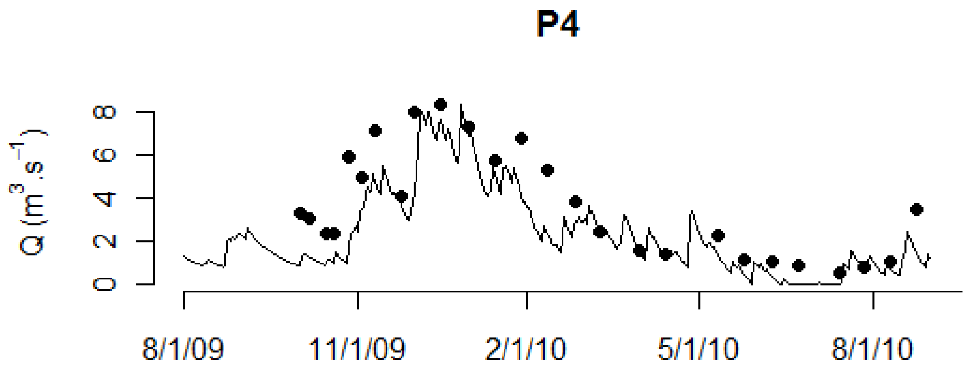
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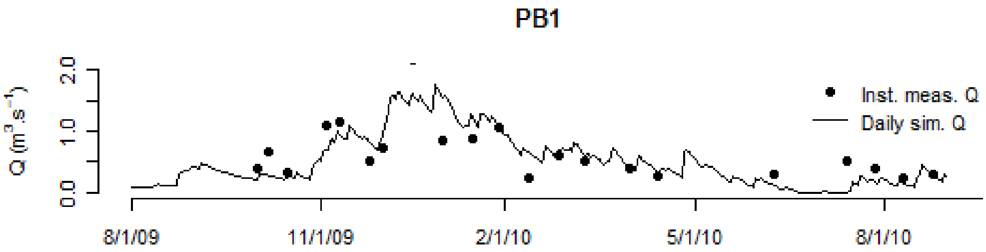
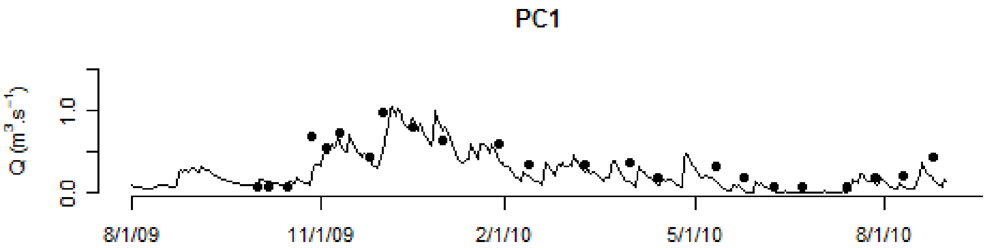
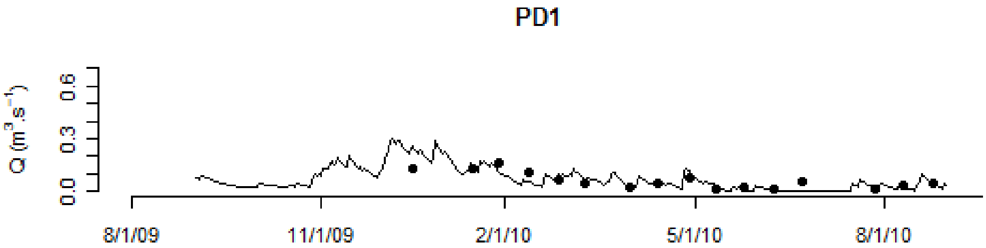
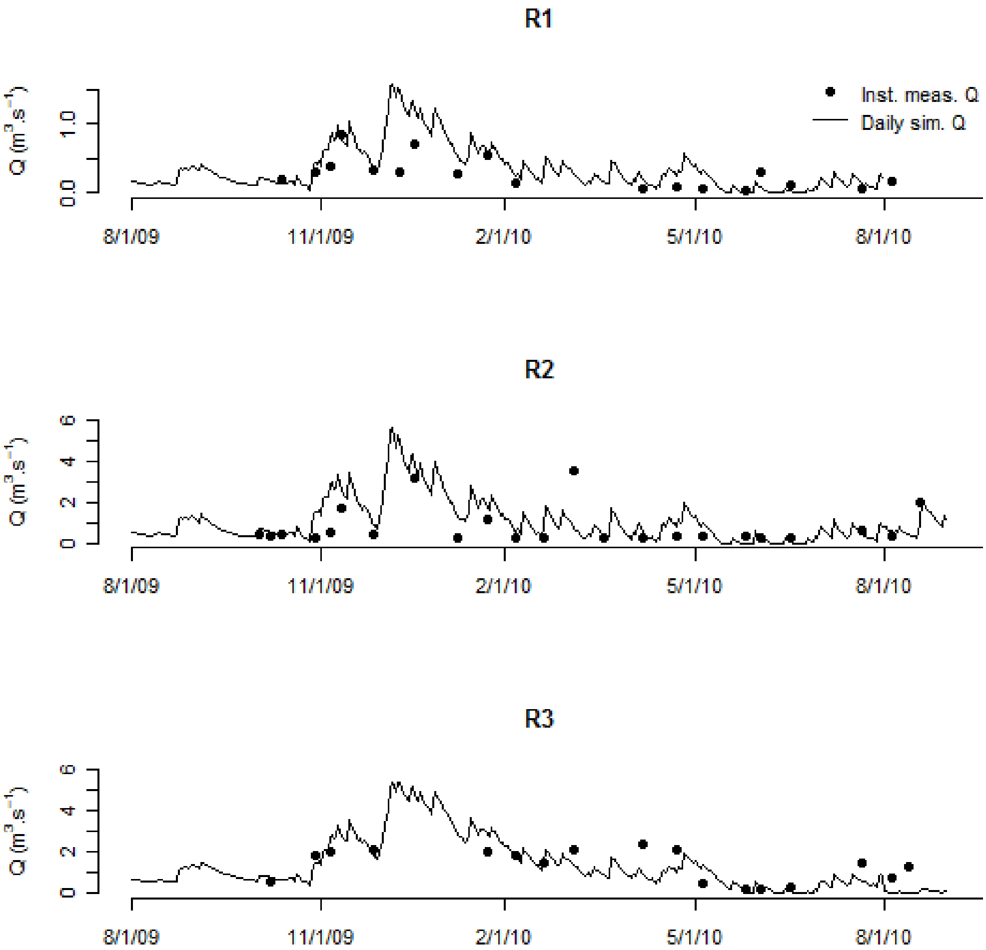
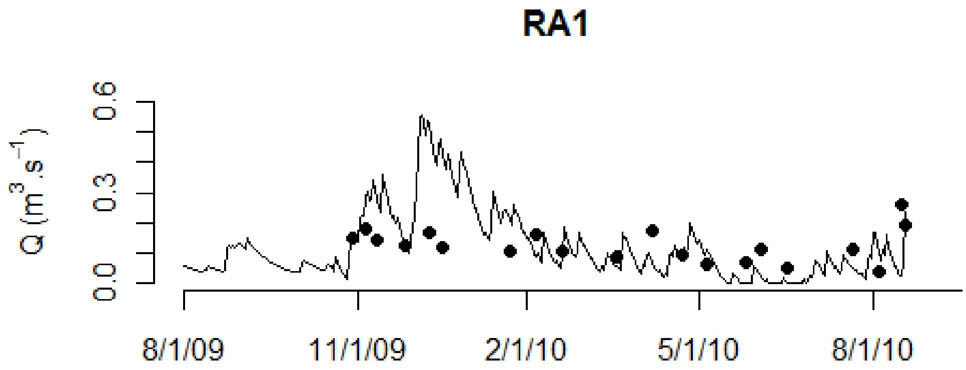
5/1/10
8/1/10

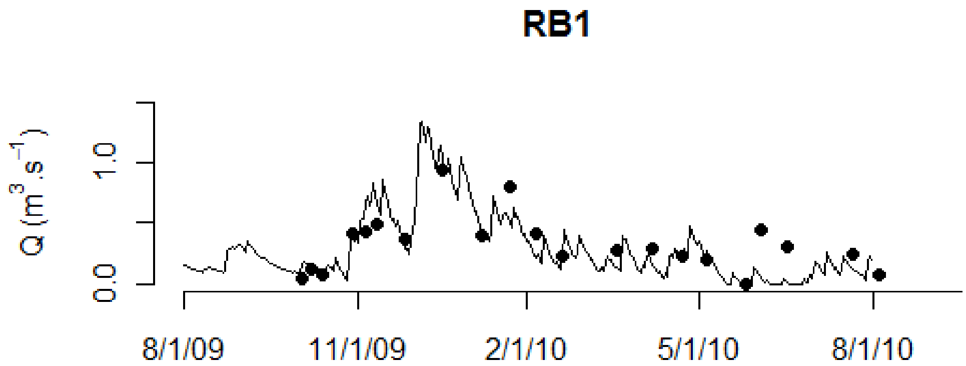

PB1
Q (m3.s-1)
0.0
1.0
2.0
Inst. meas. Q
Daily sim. Q
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10


PC1
Q (m3.s-1)
0.0
1.0
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10

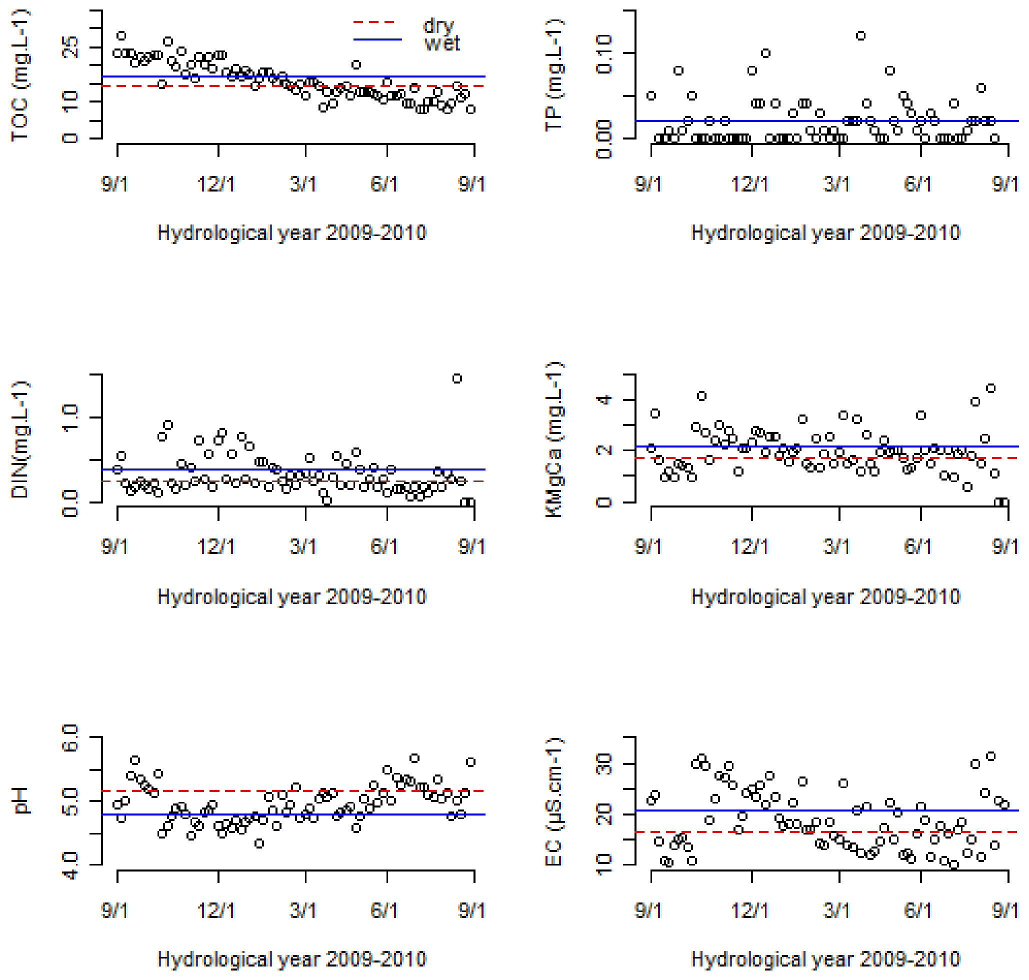

PD1
Q (m3.s-1)
0.0
0.3
0.6
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10


R1
Inst. meas. Q
Daily sim. Q
Q ($m^3.s^{-1}$)
0.0
1.0
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10
R2
Q ($m^3.s^{-1}$)
0
2
4
6
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10
R3
Q ($m^3.s^{-1}$)
0
2
4
6
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10

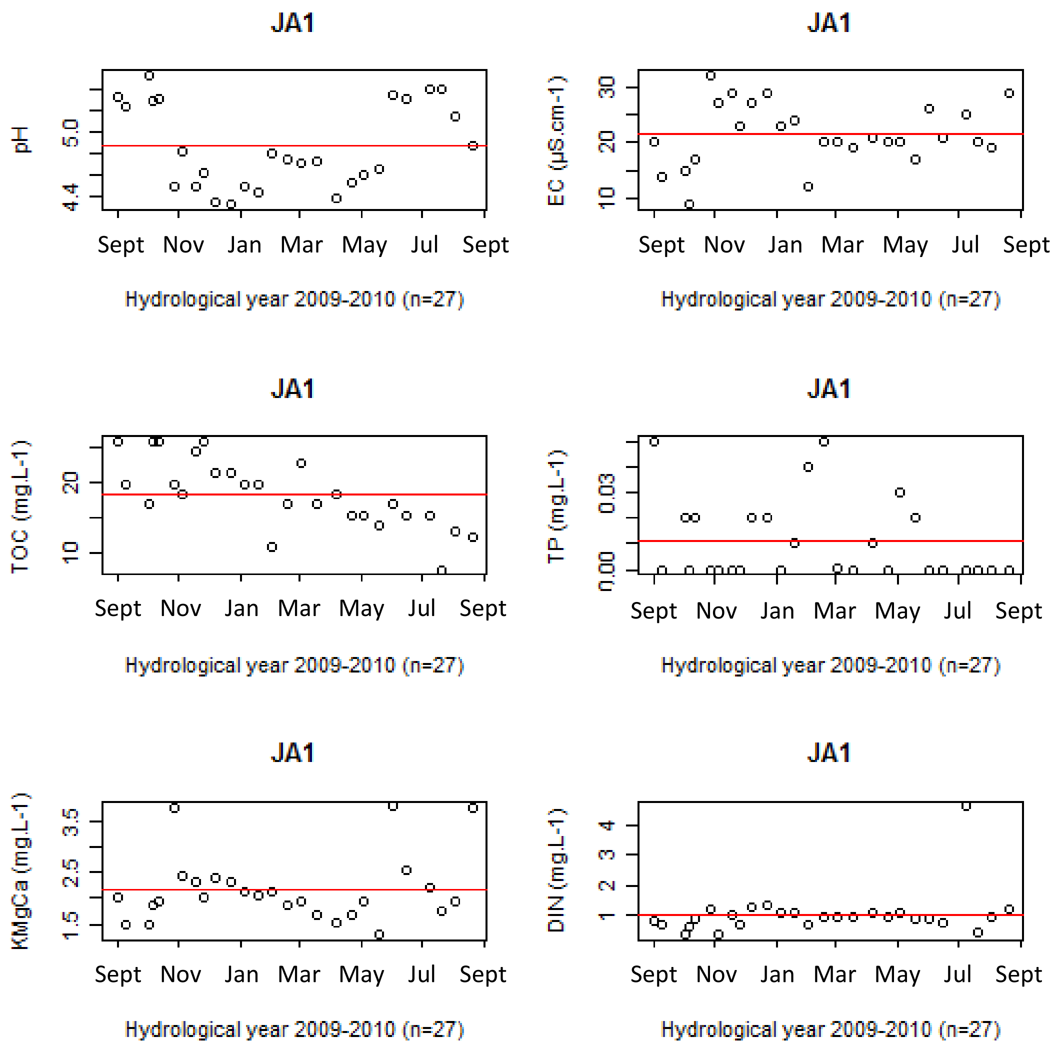

RA1
Q (m^3.s^{-1})
0.0
0.3
0.6
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10


RB1
Q (m^3.s^{-1})
0.0
1.0
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10

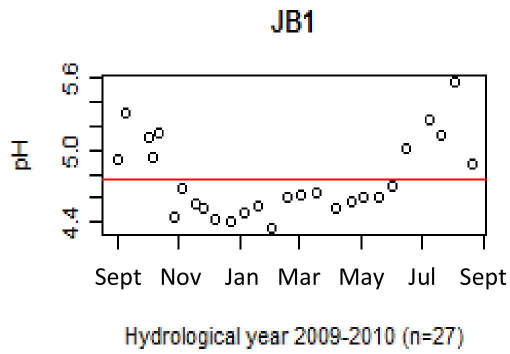
Appendix 4. Water quality parameters measured from September, 1st 2009 until August, 31st 2010 (n=78) in streams. Values are mean of all sites (n=16) during one sampling visit. TOC: Total organic C; TP: Total P; DIN: dissolved inorganic N; KMgCa: sum of K, Mg and Ca; EC: Electrical conductivity. Dotted red line represents the mean value during the dry season, the blue contiuous line represents the mean value during the wet season.

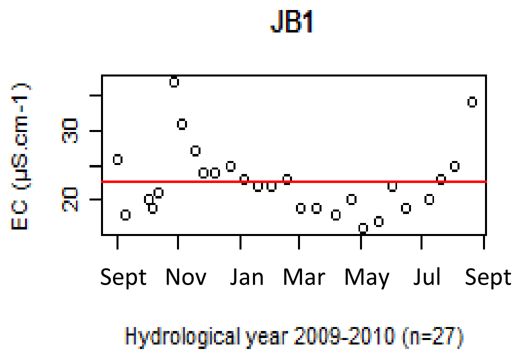


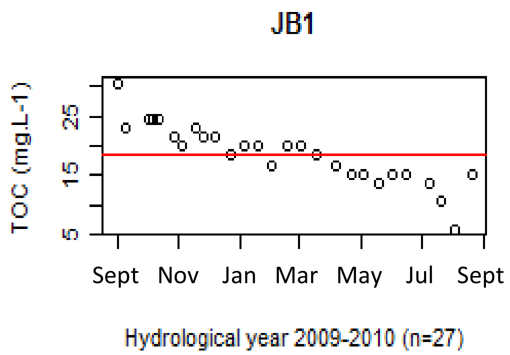
Appendix 5. Temporal variations of pH, electrical conductivity (EC), total organic Carbon (TOC), Total Phosphorus (TP), sum of K, Mg and Ca (KMgCa) and dissolved inorganic Nitrogen (DIN) at stream outlets. Lines represent mean annual values.

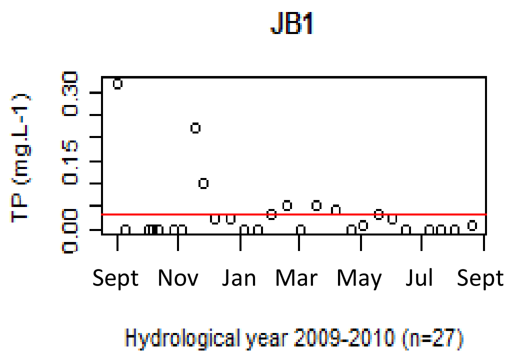


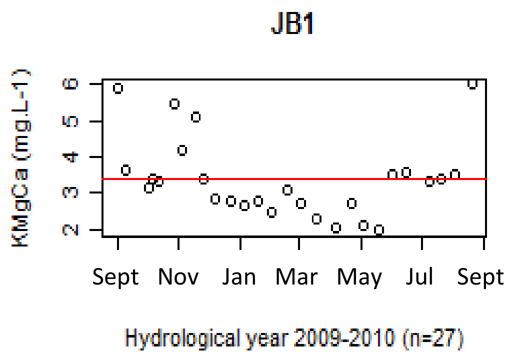
Appendix 5. (Continued)

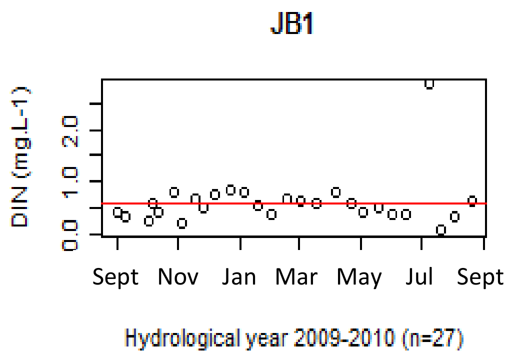




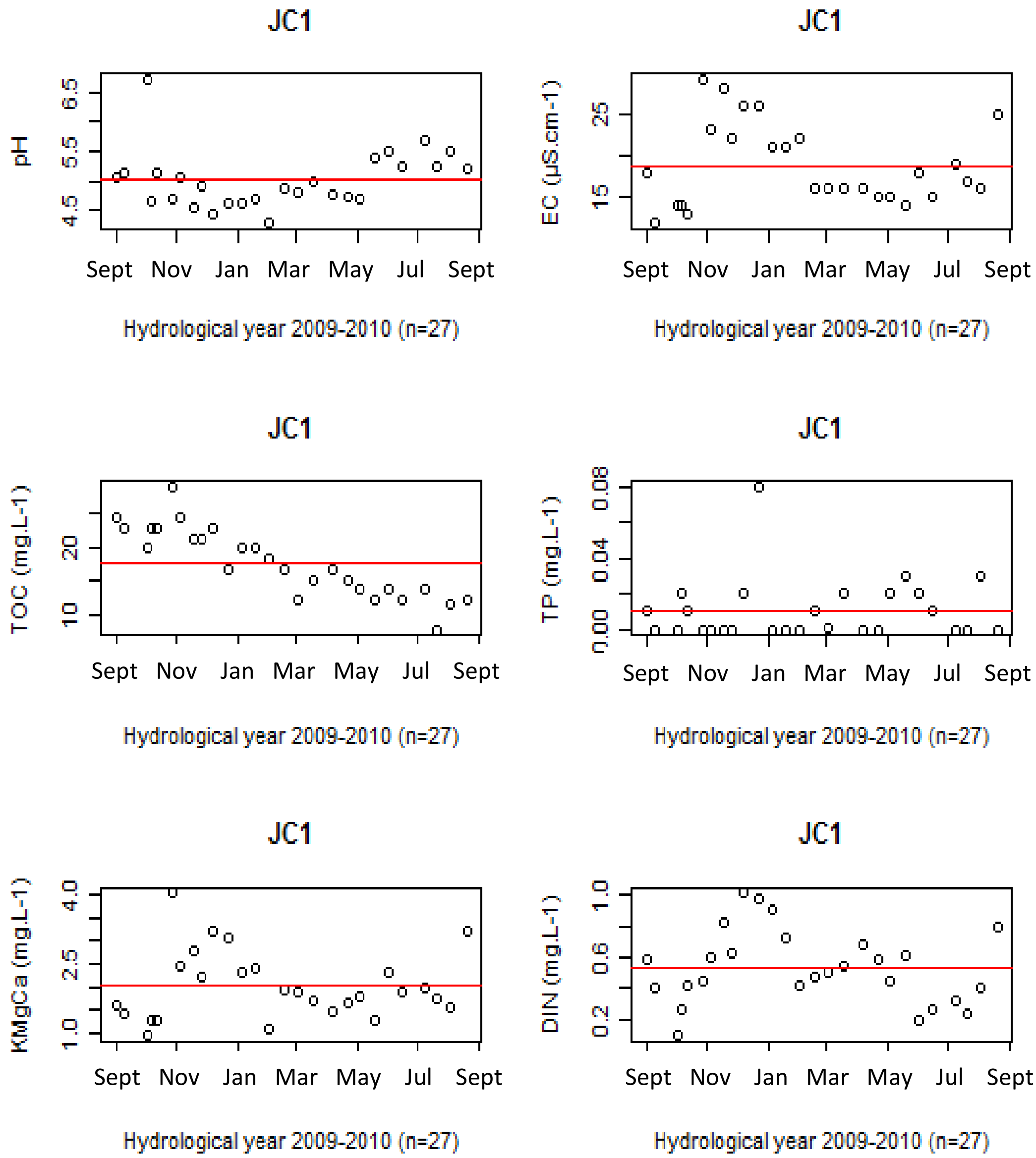




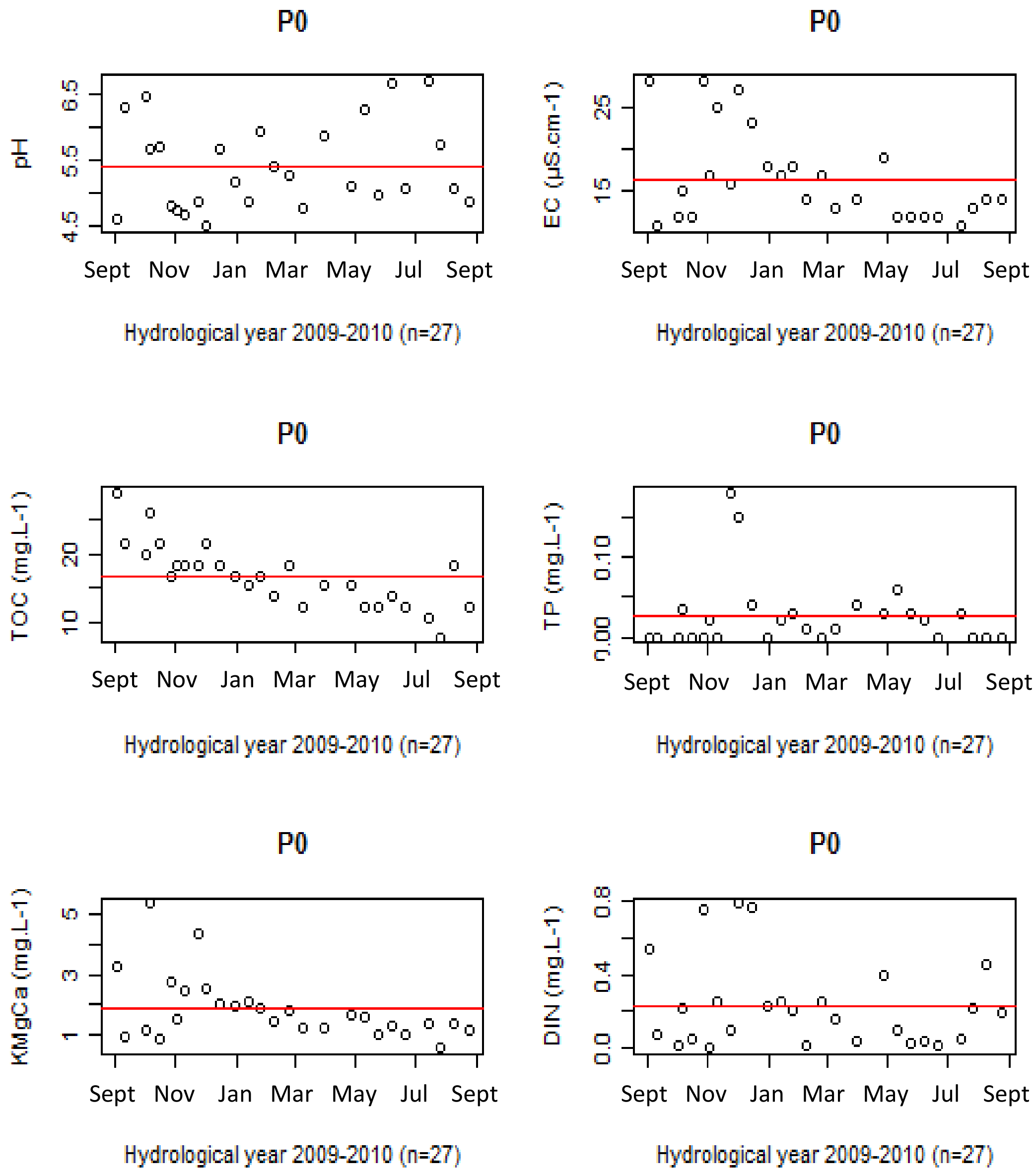




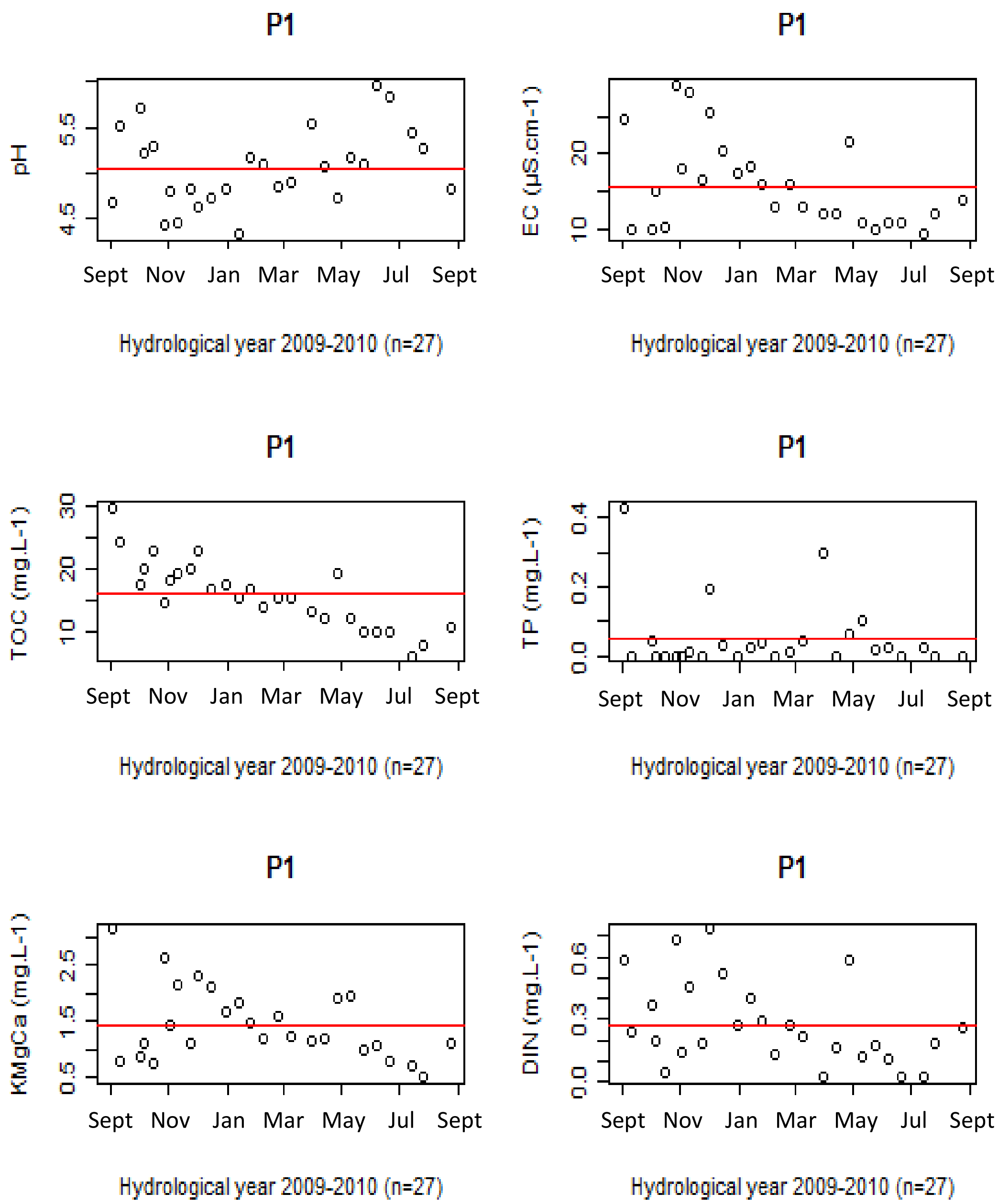
Appendix 5. (Continued)



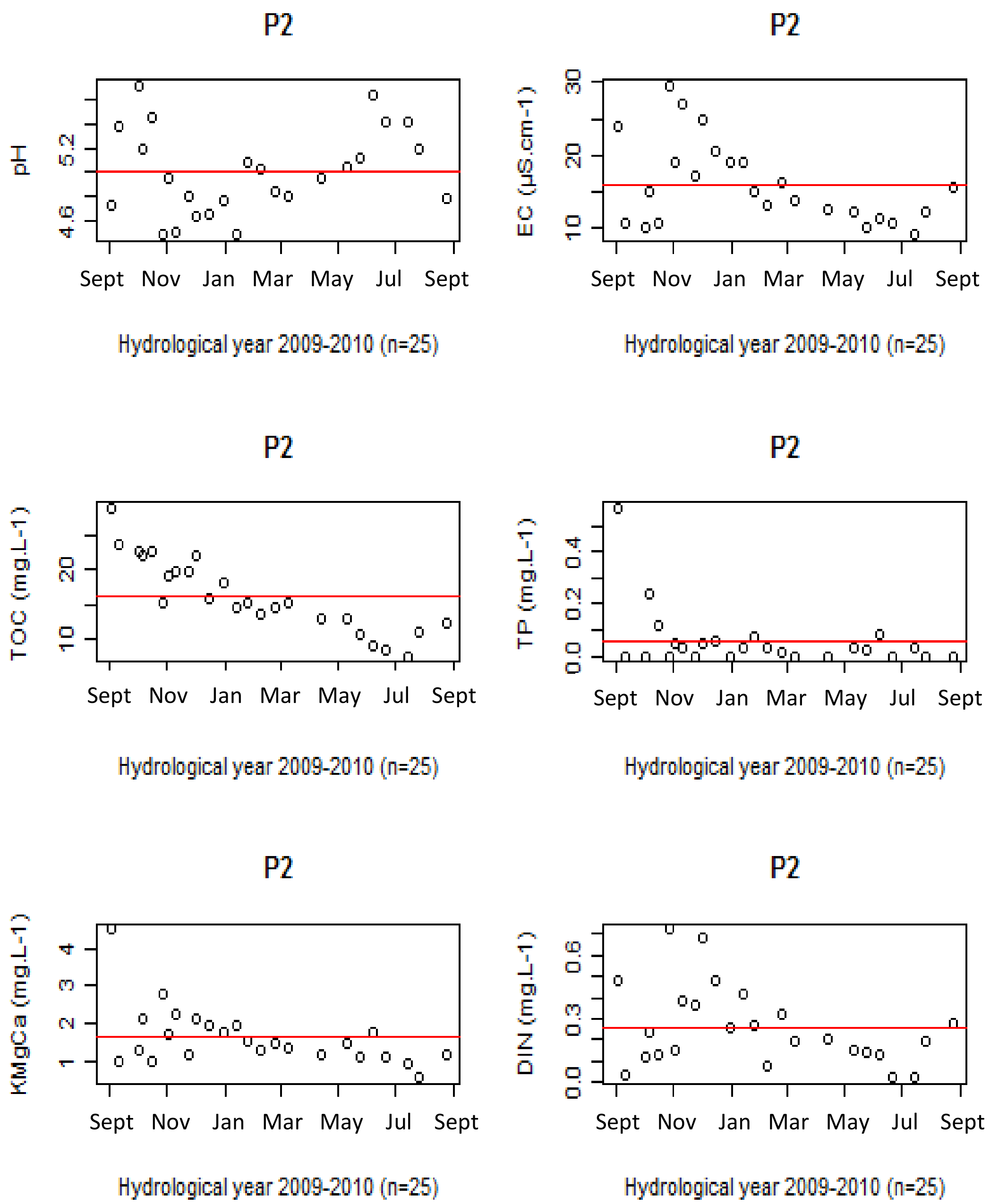
Appendix 5. (Continued)



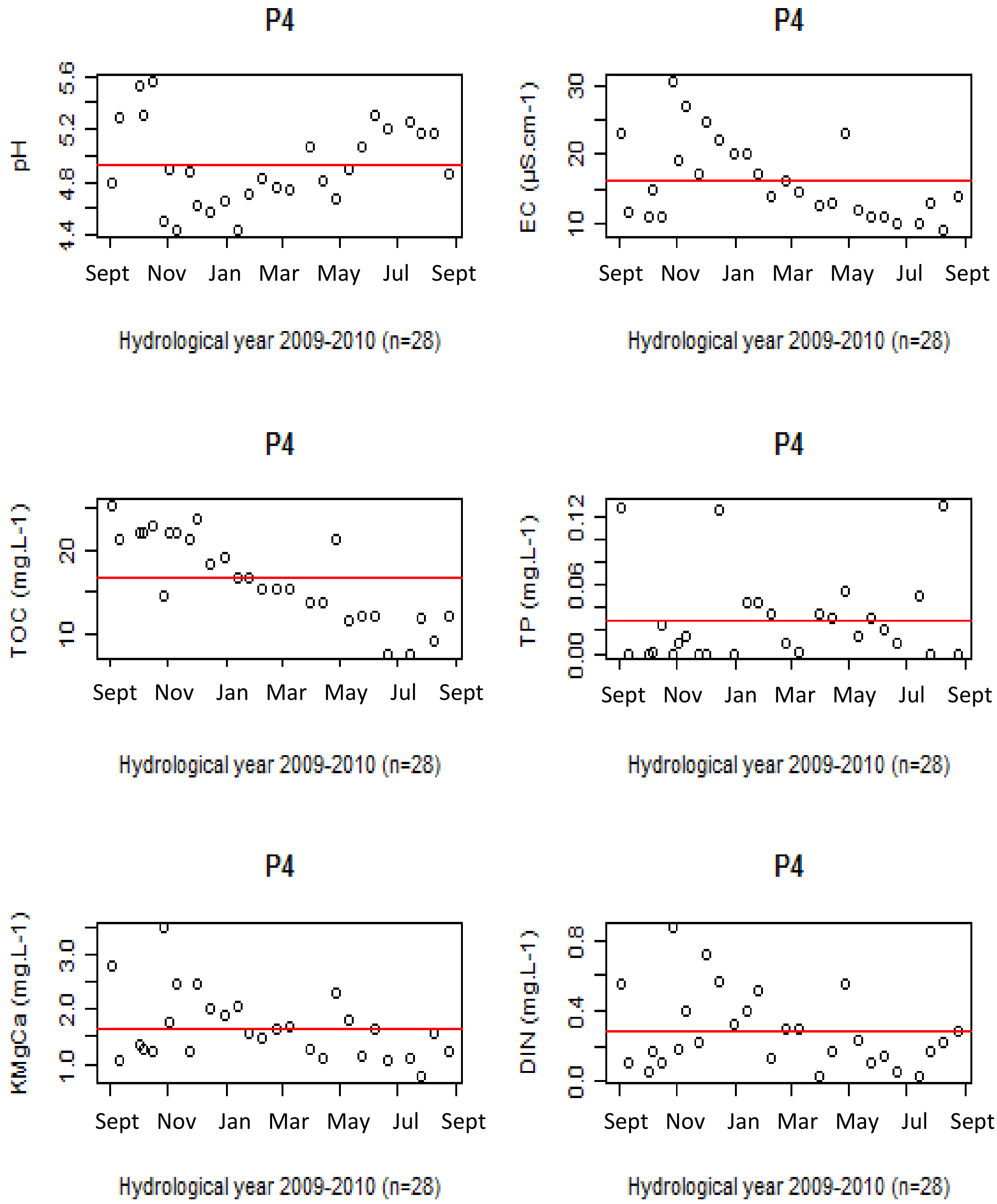
Appendix 5. (Continued)



Appendix 5. (Continued)



Appendix 5. (Continued)



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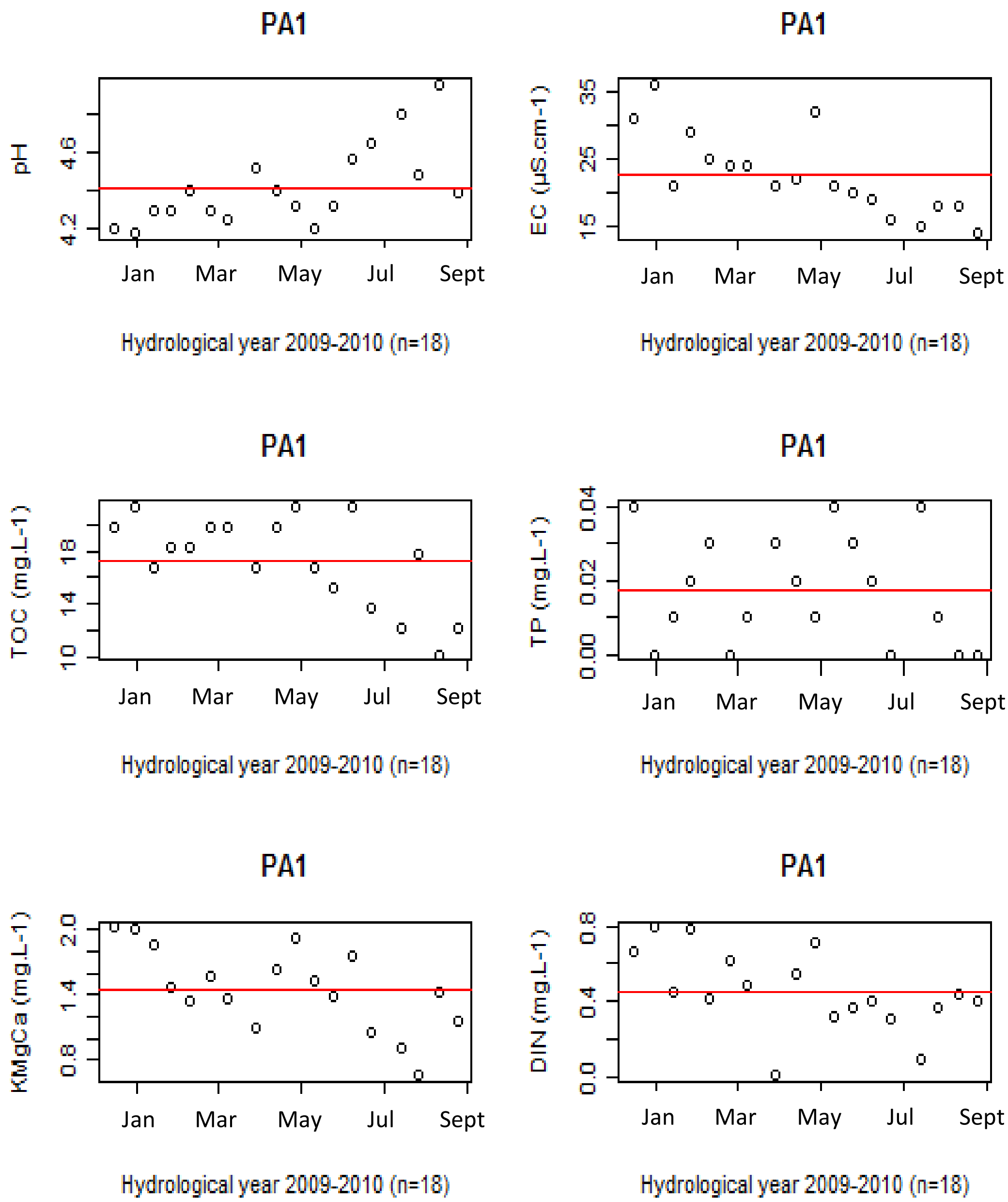

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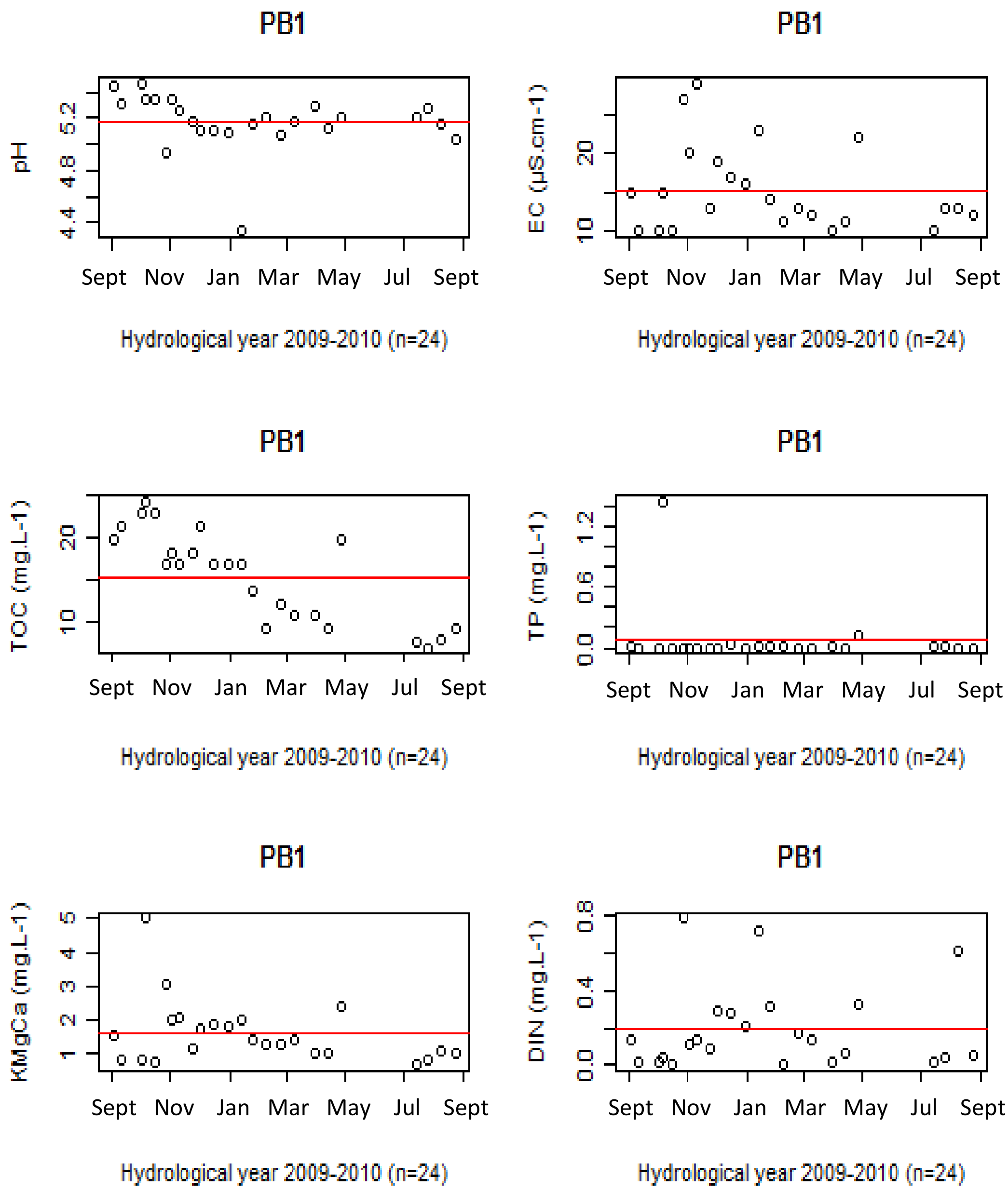

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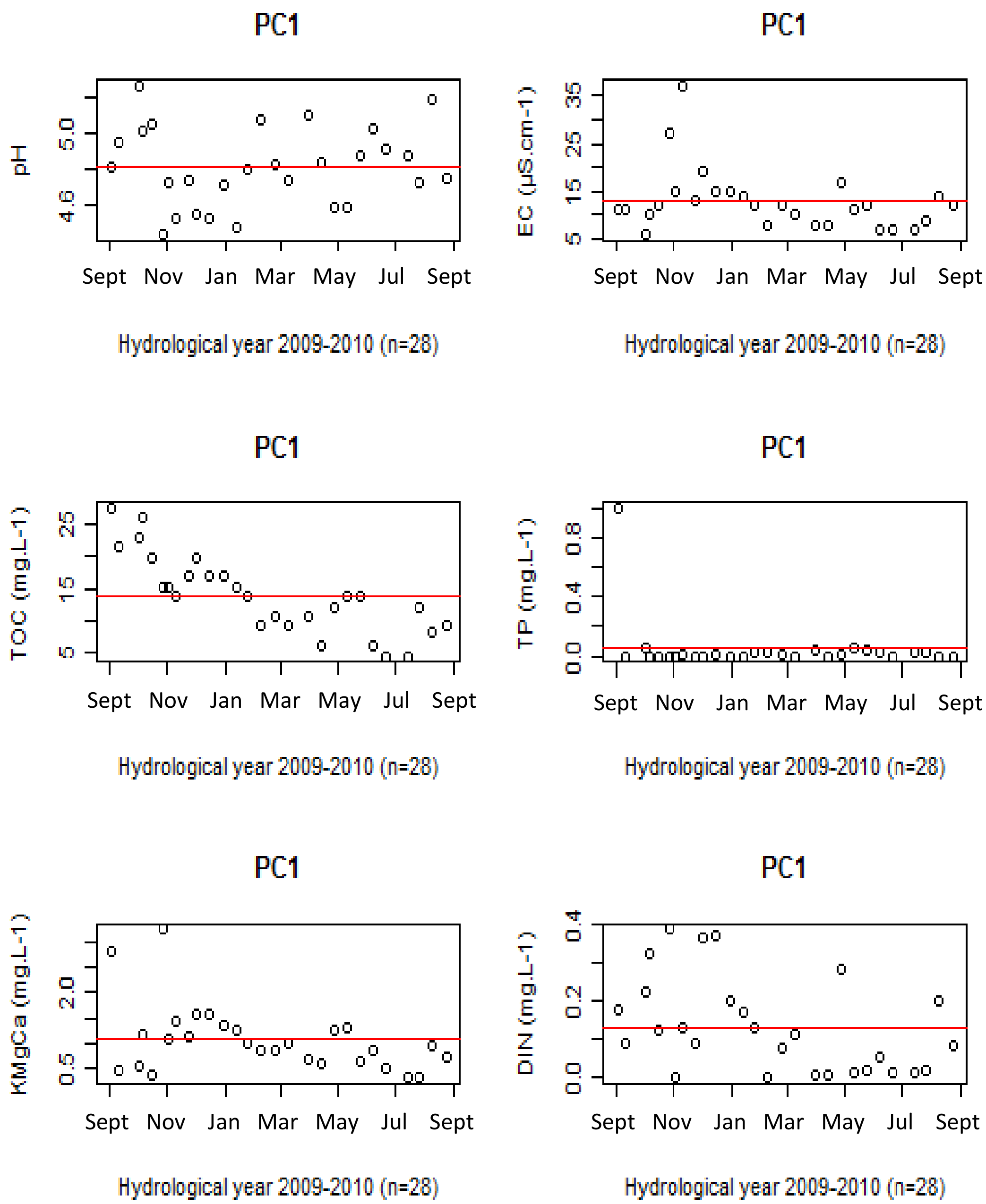

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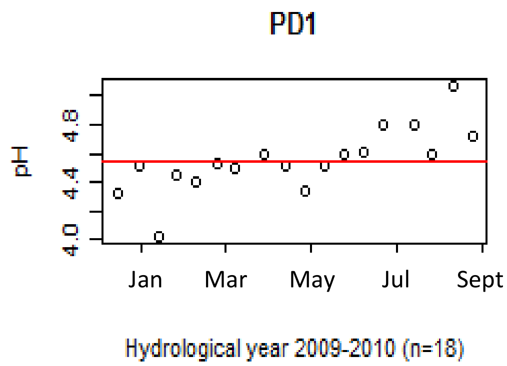

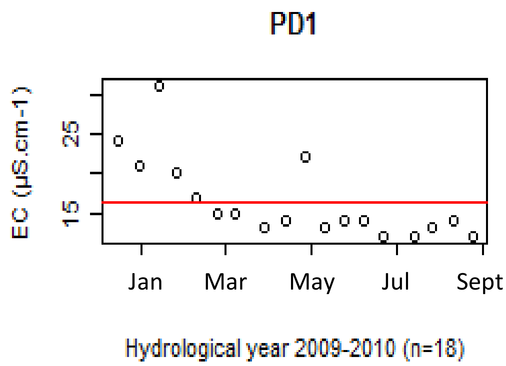

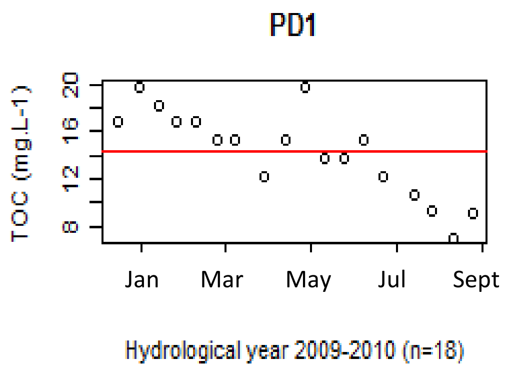

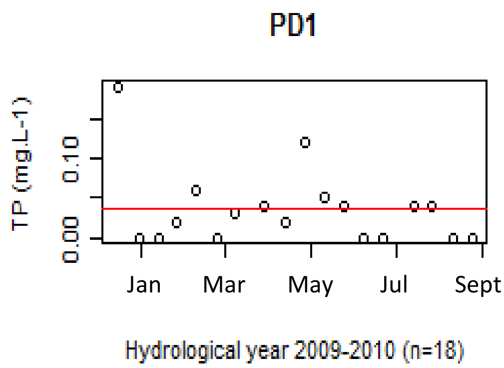

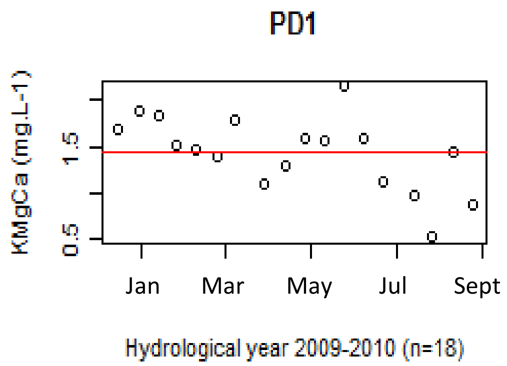

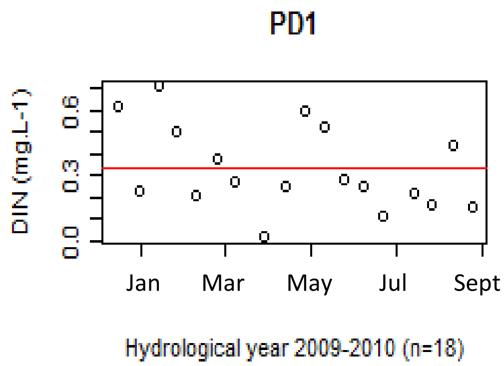

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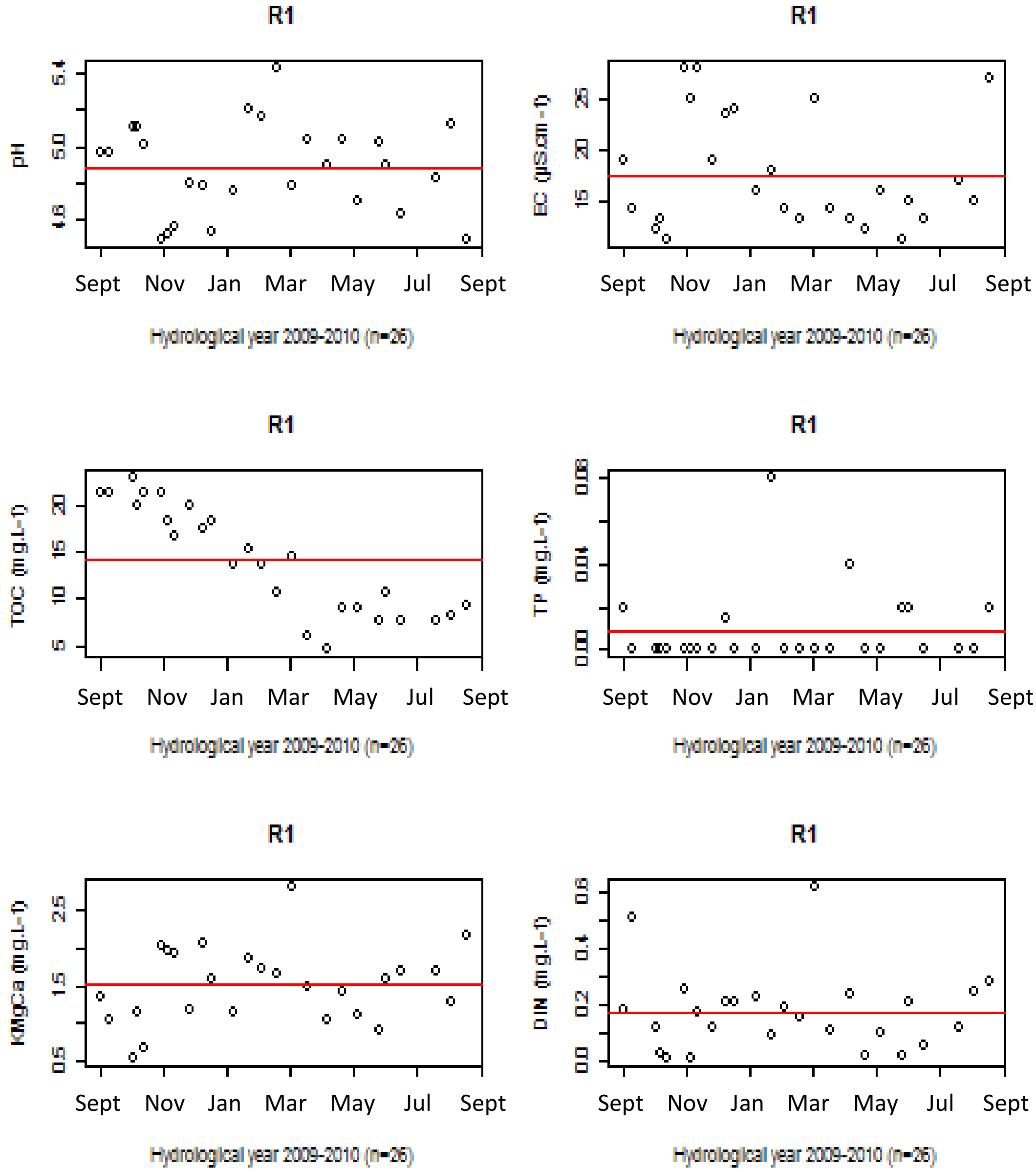

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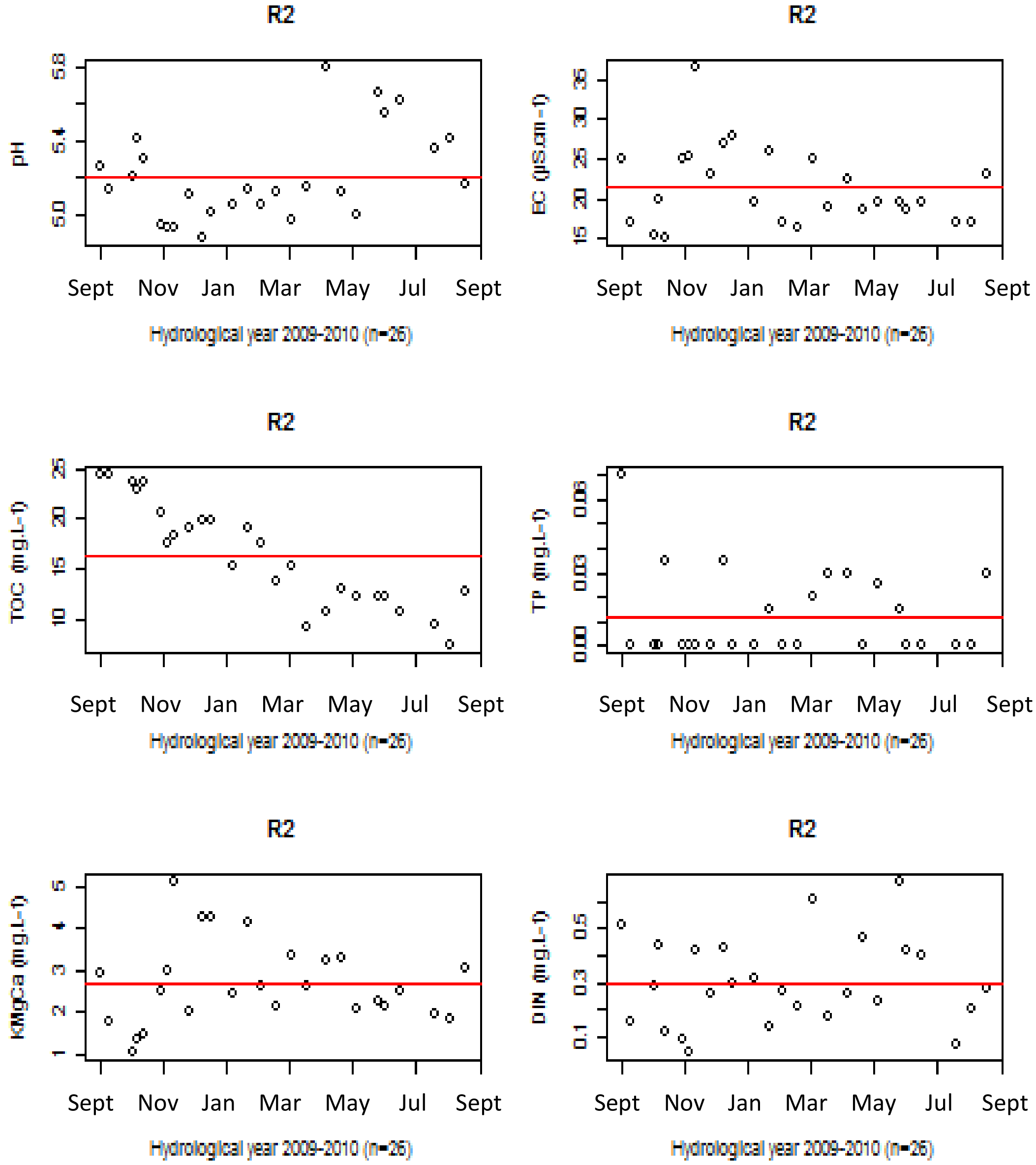

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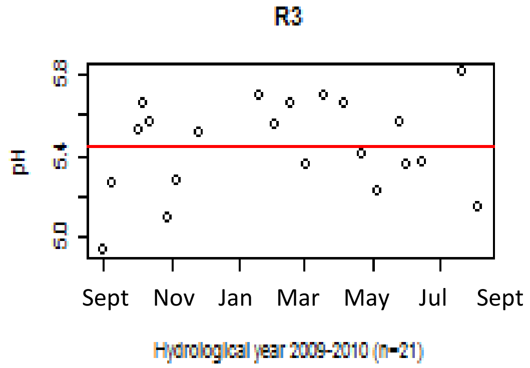

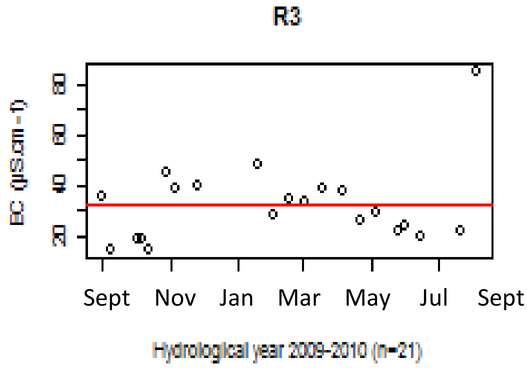

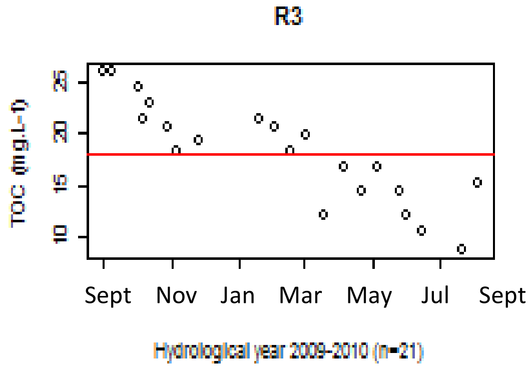

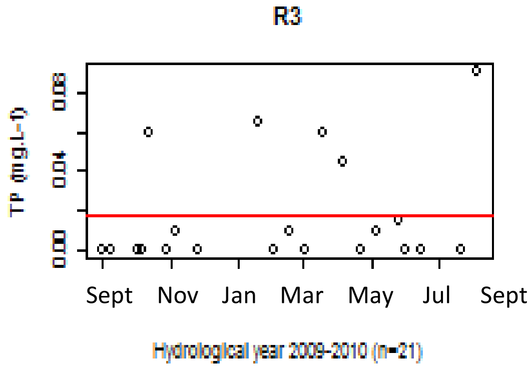

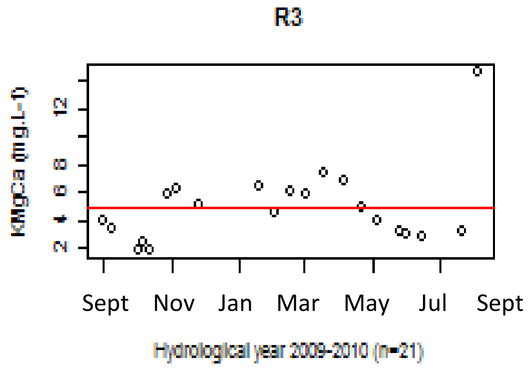

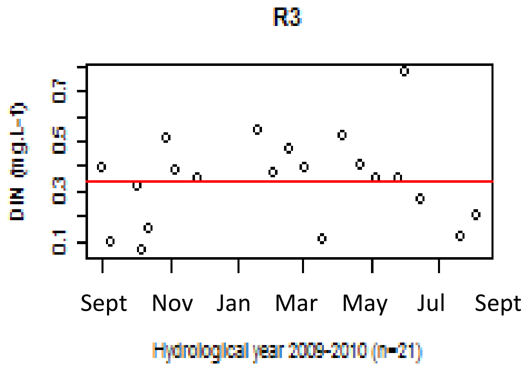

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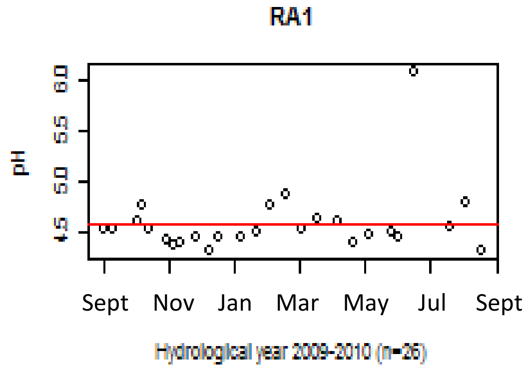
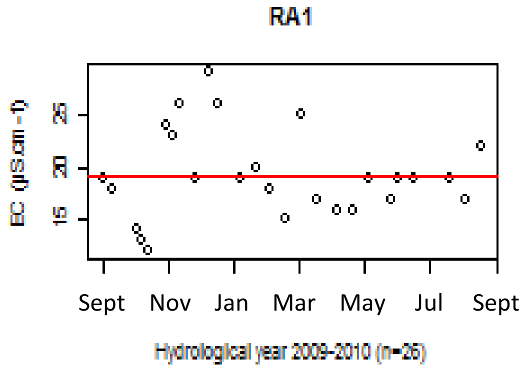
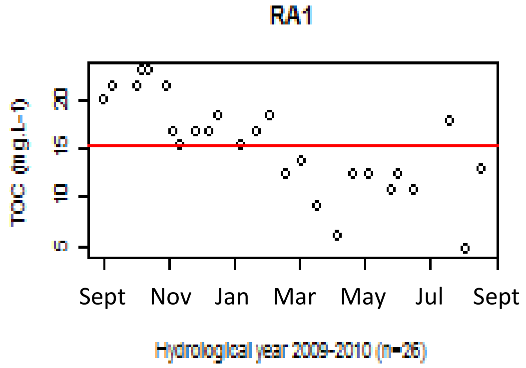
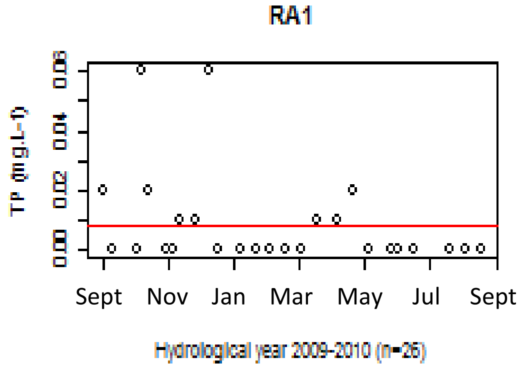
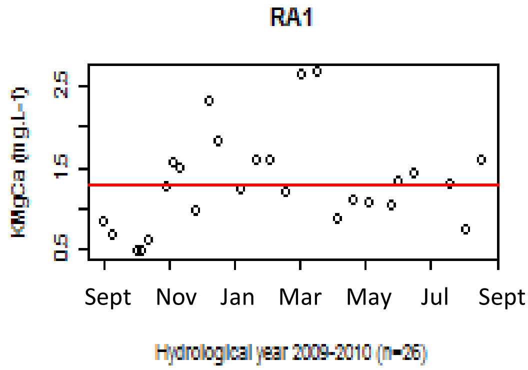
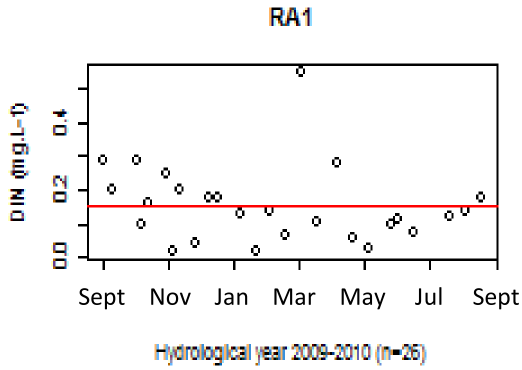




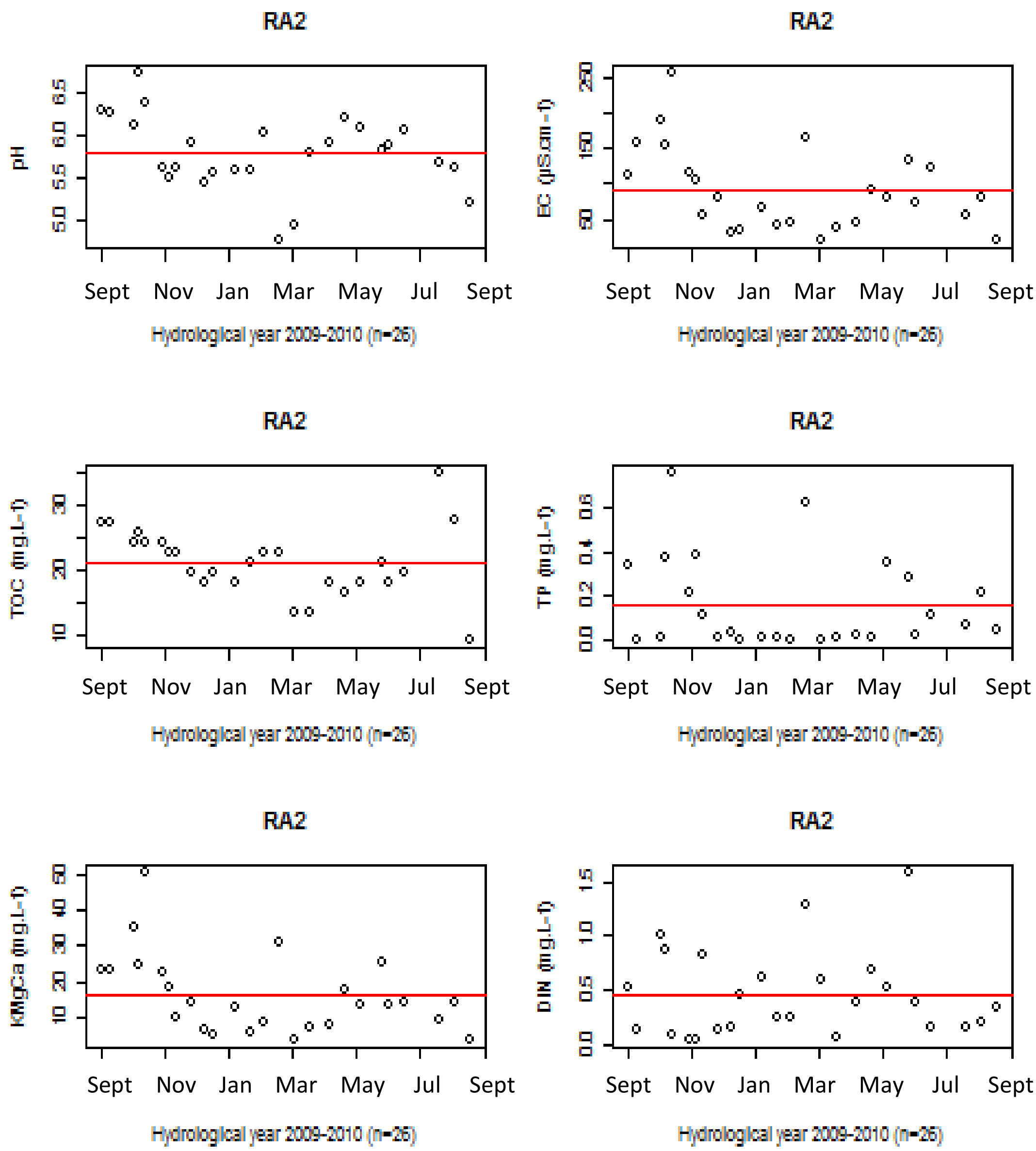








Appendix 5. (Continued). RA2 : sampling point immediately downstream the mill.



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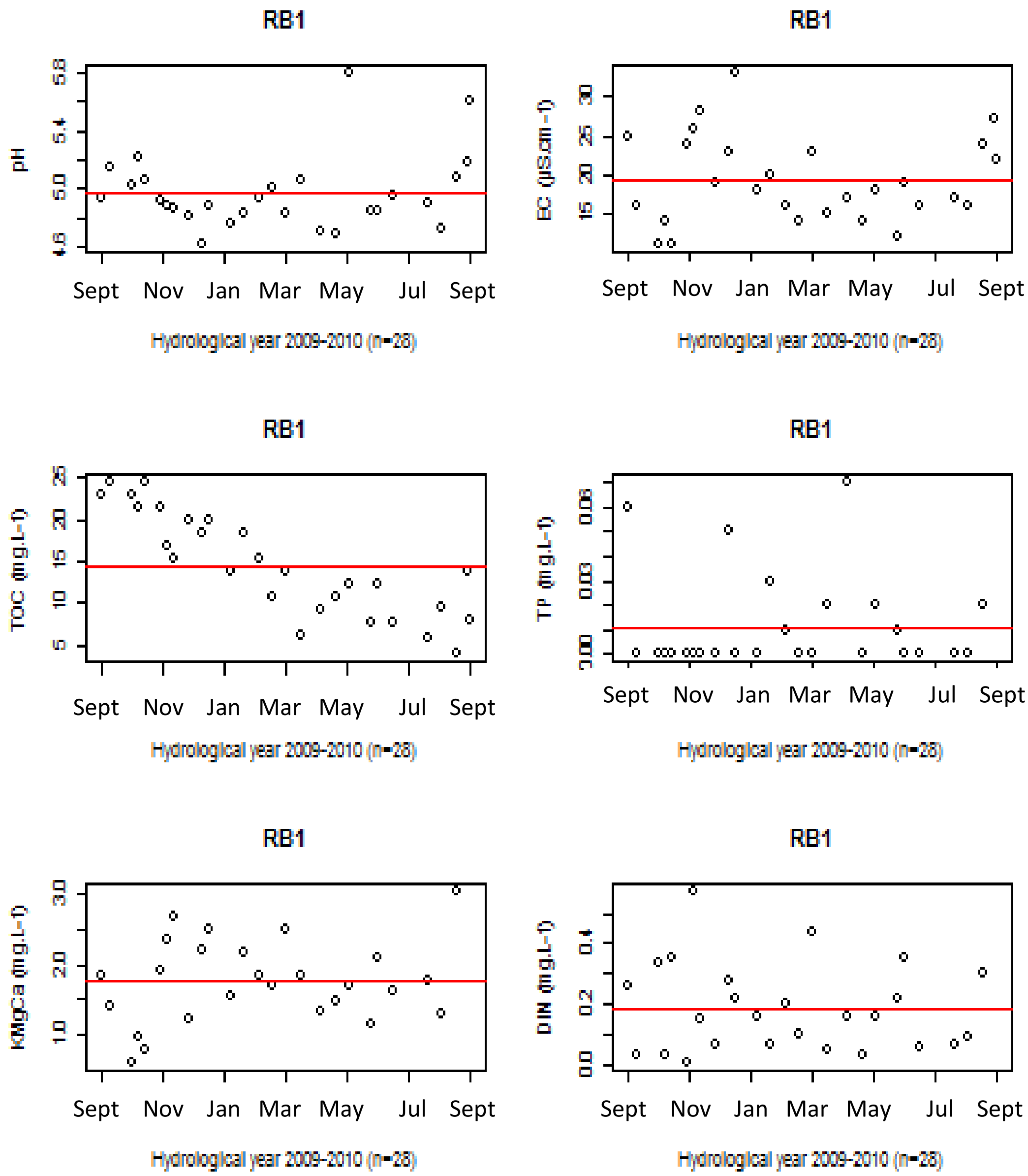
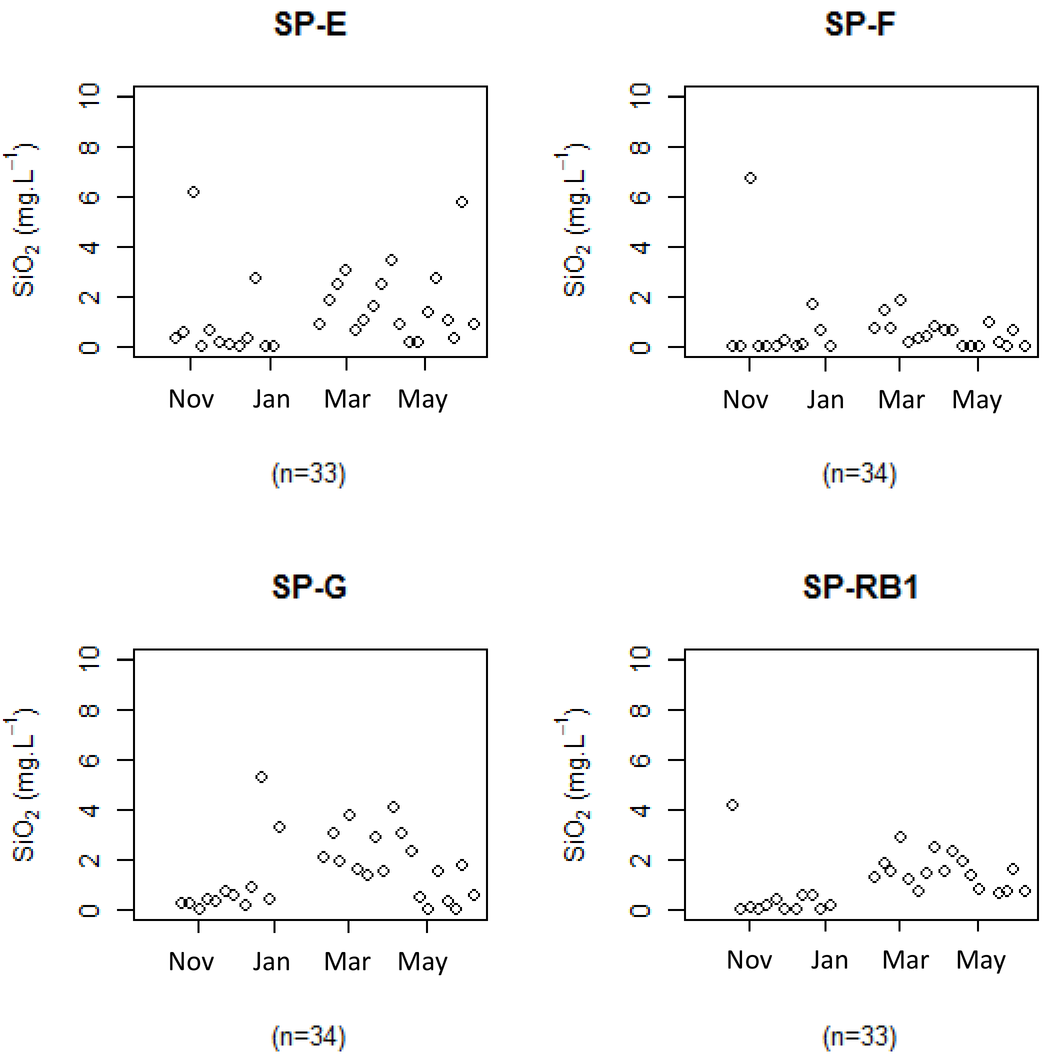


Appendix 6. Water quality parameters in 7 piezometers, in the Petapahan area, Sumatra, Indonesia. Values are the mean of n = 33 to 35 samples taken from September, 1st 2010 to June, 7th 2011.

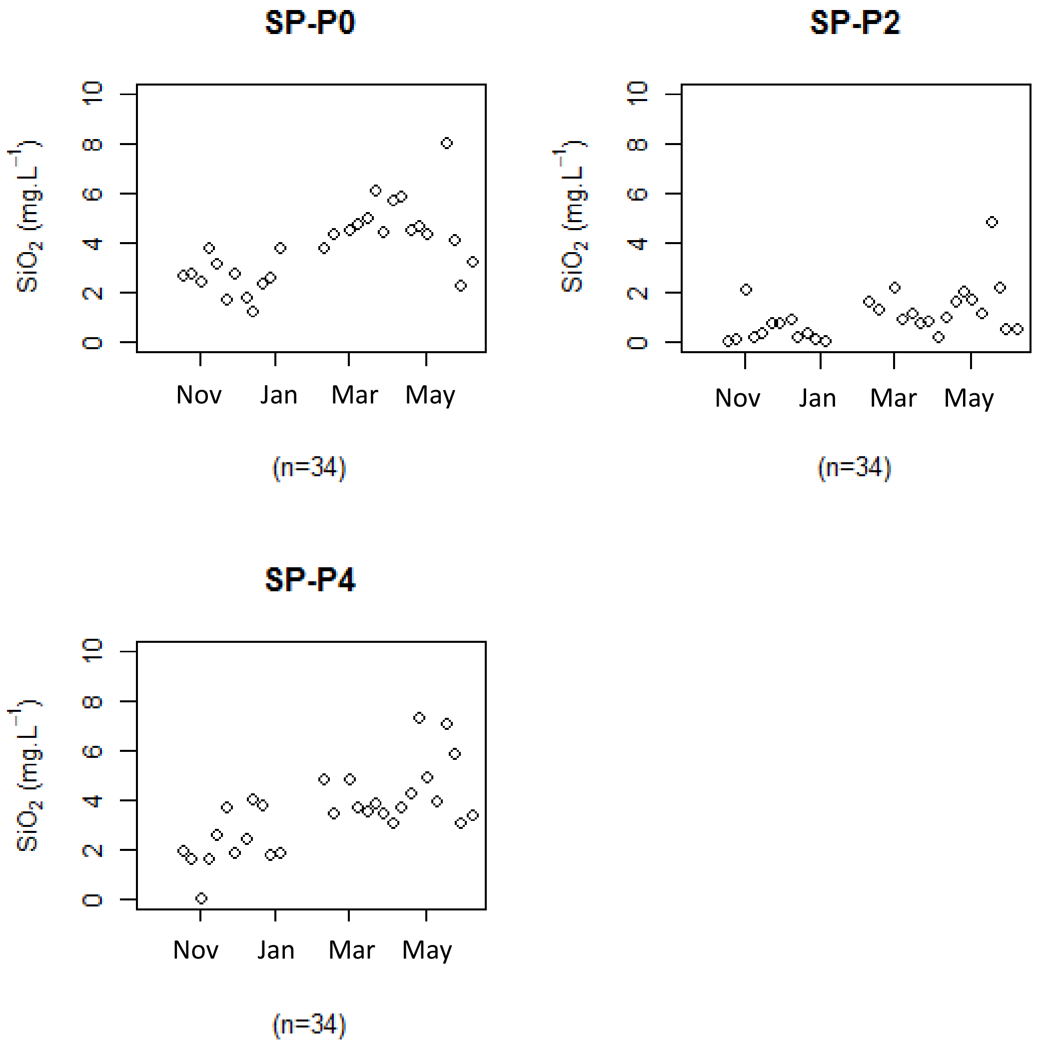
Land use	Site	pH	EC	TOC	TP	K	Mg	Ca	DIN	NO3-N	NO2-N	NH4-N	TDS	TA
			$\mu S\ cm^{-1}$	$mg\ L^{-1}$										
Loamy-sand uplands														
Unfertilized hevea	SP-P0	5.96	85.94	61.89	0.04	2.27	0.67	10.50	1.48	0.25	0.11	1.12	83.41	36.94
Mineral fertilized OP	SP-P2	5.39	55.49	13.51	0.06	1.86	0.73	6.00	1.00	0.44	0.01	0.55	58.25	15.77
forest	SP-P4	5.79	86.79	18.44	0.19	3.02	1.43	9.39	3.19	2.65	0.02	0.52	84.71	24.41
Loamy lowlands														
POME fertilized OP	SP-E	5.33	63.64	8.27	0.04	9.24	0.88	1.36	0.77	0.33	0.01	0.44	51.53	10.73
EFB fertilized oil palm	SP-F	5.08	27.26	12.02	0.03	2.55	0.43	1.17	0.71	0.29	0.01	0.41	37.44	7.24
Mineral fertilized OP	SP-G	4.54	54.32	17.00	0.04	3.49	0.79	2.61	1.02	0.37	0.01	0.63	56.11	5.62
Peat soil														
Mineral fertilized OP	SP-RB1	4.15	63.24	37.85	0.06	1.55	0.55	3.96	0.71	0.31	0.02	0.40	66.14	2.41

OP: Oil palm; EC: electrical conductivity; TOC: total organic Carbon; TP: total Phosphorus; DIN: dissolved inorganic Nitrogen; TDS: total dissolved solids; TA: total alkalinity

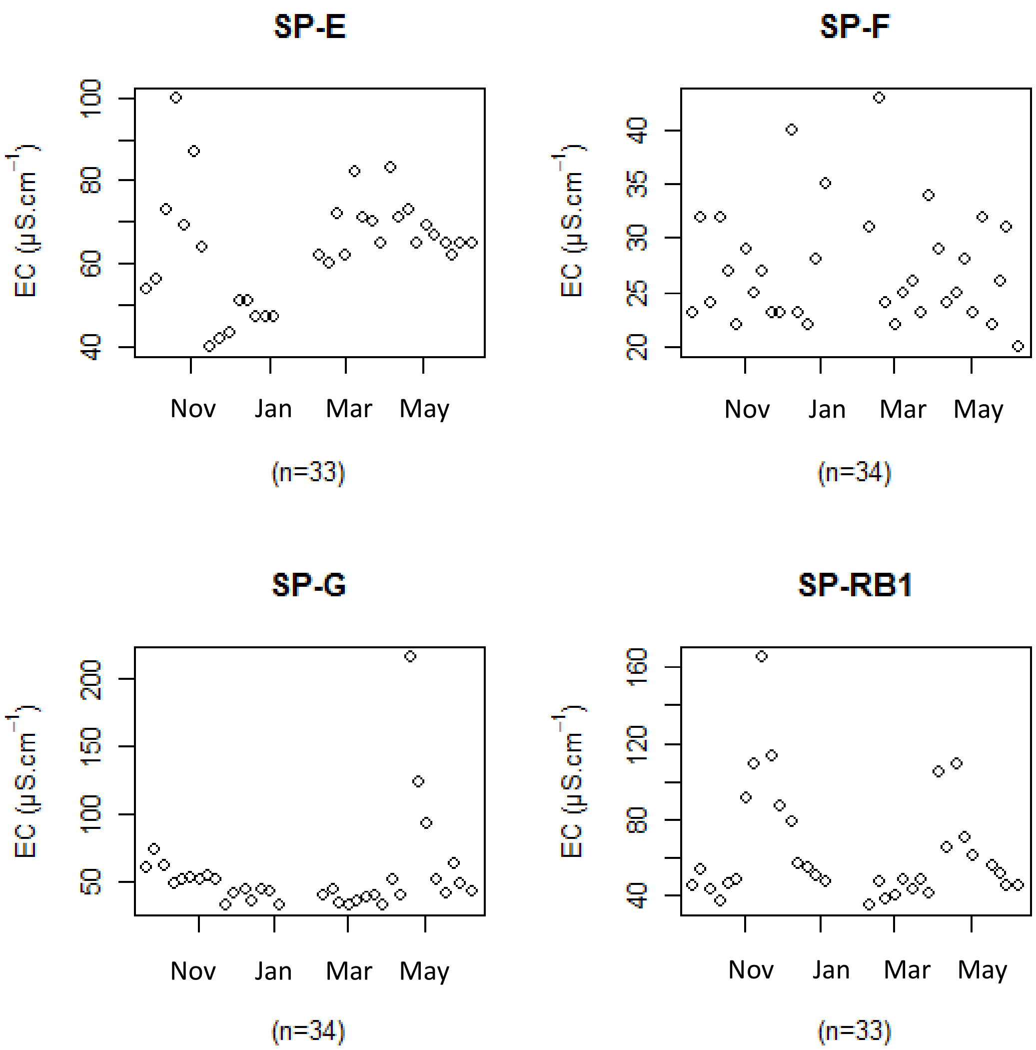
Appendix 7 Temporal variations of SiO_2 concentrations in piezometers during the hydrological year 2010-2011. a/ SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation.



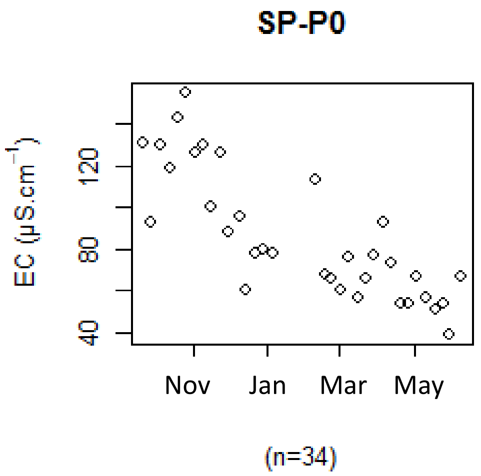
Appendix 7 (Continued). b/ SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under forest.

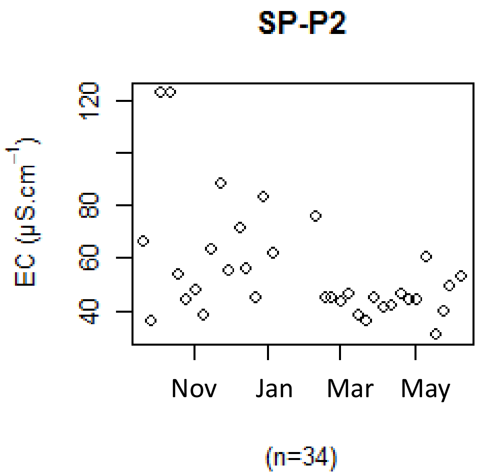


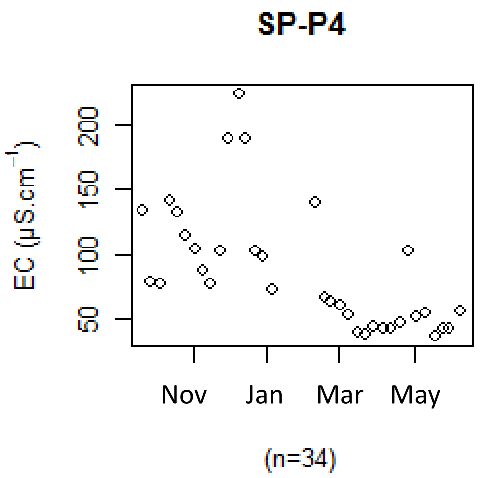
Appendix 8. Temporal variations of electrical conductivity (EC) in piezometers during the hydrological year 2010-2011. a/ SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation.



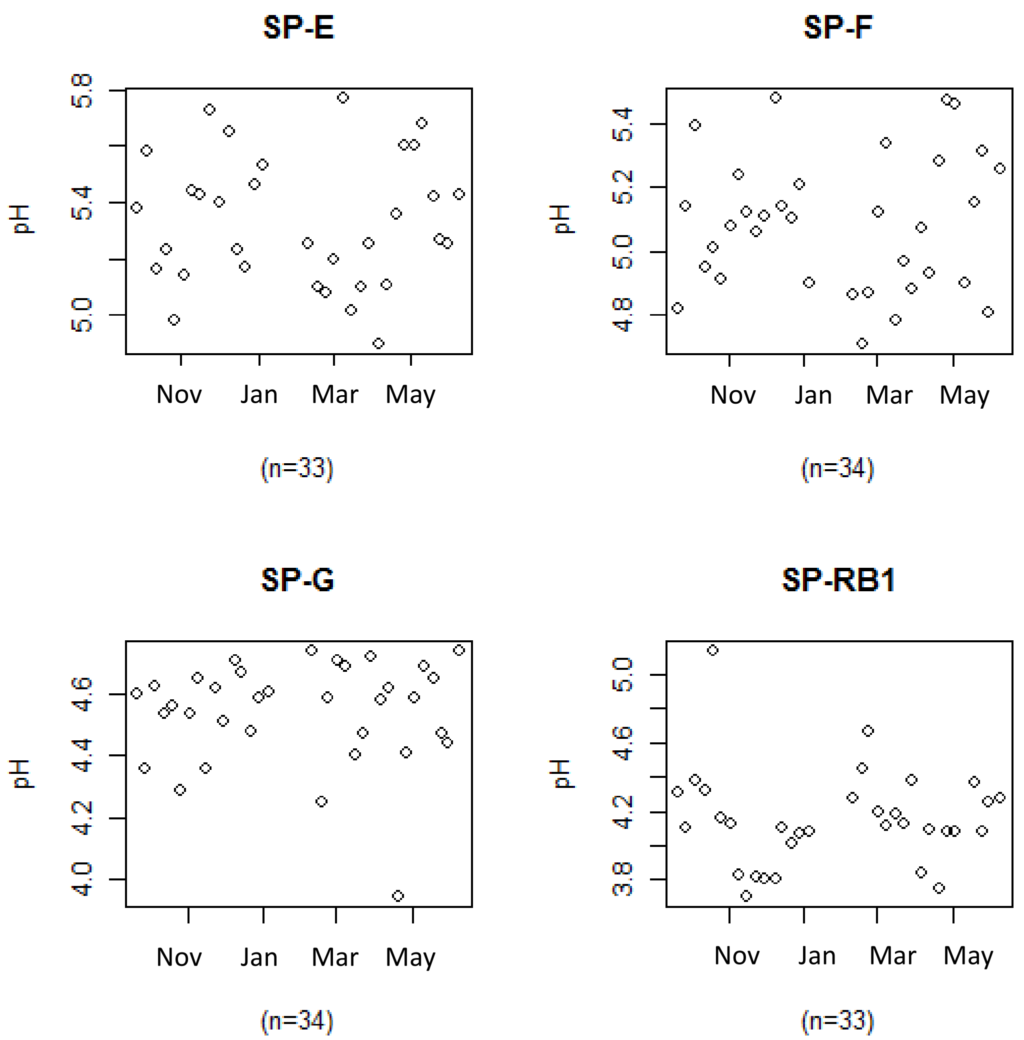
Appendix 8. (Continued) b/ SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under forest.



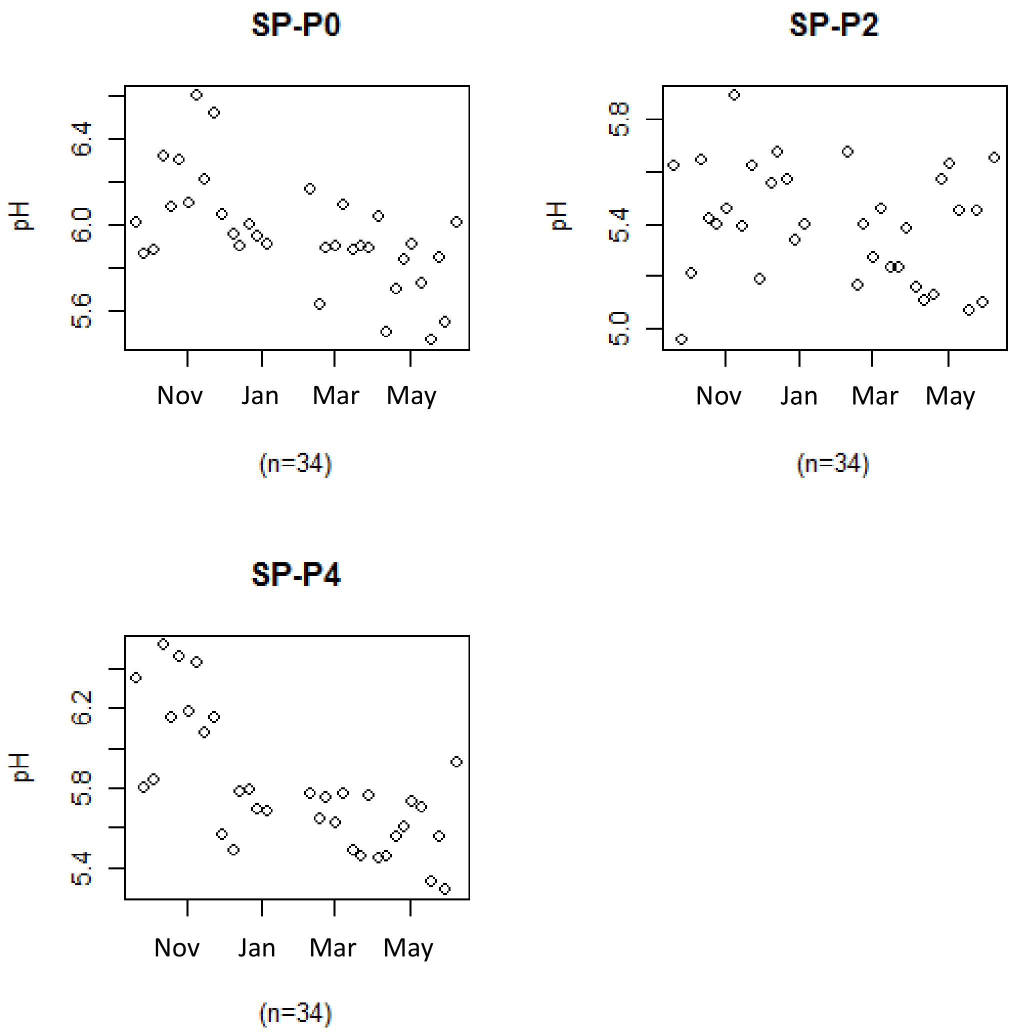




Appendix 9. Temporal variations of electrical conductivity (EC) in piezometers during the hydrological year 2010-2011. a/ SP-E: piezometer located in loamy lowlands under empty fruit bunch-fertilized oil palm; SP-F: piezometer located in loamy lowlands under palm oil mill effluent-fertilized oil palm. SP-G: piezometer located in loamy lowlands under mineral-fertilized oil palm; SP-RB1: piezometer located in a peatsoil patch over loamy-sand uplands, under mineral fertilized plasma oil palm plantation.



Appendix 9. (Continued) b/ SP-P0: piezometer located in loamy-sand uplands under unfertilized rubber plantation; SP-P2: piezometer located in loamy-sand uplands under mineral fertilized industrial oil palm plantation; SP-P4: piezometer located in loamy-sand uplands under forest;.



Appendix 10. Total organic carbon and nutrient fluxes exported to streams in the Petapahan area, Sumatra, Indonesia. a/ Cumulated fluxes (t yr^{-1}).

Site	TOC	TP	K	Mg	Ca	DIN	NO3-N	NO2-N	NH4-N
	t yr^{-1}								
JA1	35.6	0.02	2.16	0.47	1.29	1.78	1.69	0.02	0.07
JB1	26.9	0.05	3.23	0.36	0.80	0.85	0.81	0.01	0.03
JC1	22.5	0.02	1.64	0.35	0.94	0.87	0.78	0.02	0.07
P0	541.4	1.17	26.03	7.60	30.50	10.57	9.47	0.24	0.87
P1	823.8	2.26	37.84	11.94	45.17	15.45	14.09	0.34	1.16
P2	885.6	2.97	32.90	11.60	123.83	36.66	34.07	0.84	1.75
P4	1274.5	2.74	56.80	17.51	59.74	27.51	24.20	0.90	2.47
P1-P4*	450.6	0.48	18.96	5.57	14.56	12.06	10.11	0.56	1.31
PA1	46.0	0.04	1.51	0.78	1.76	1.36	1.29	0.02	0.05
PD1	34.8	0.11	1.55	0.51	1.65	0.61	0.56	0.03	0.04
PB1	258.9	1.30	9.59	3.45	13.59	4.18	3.46	0.23	0.48
PC1	115.8	0.19	3.03	1.46	5.03	1.38	1.22	0.05	0.11
R1	171.5	0.10	5.26	2.35	10.09	2.01	1.70	0.12	0.20
R2	521.7	0.23	48.40	9.31	33.81	10.17	6.61	1.81	1.78
R3**	772.5	0.60	115.27	20.52	59.07	13.58	9.25	0.42	3.91
R1-R2*	290.6	0.07	41.42	6.12	20.62	7.56	4.42	1.65	1.49
R1-R3**	409.0	0.31	103.35	14.75	35.27	9.28	5.59	0.11	3.50
RA1	59.6	0.05	1.72	0.84	3.10	0.60	0.49	0.04	0.09
RB1	132.4	0.13	4.93	2.58	10.61	1.69	1.46	0.15	0.12

* Section. Part of the watershed under industrial oil palm plantation. Fluxes are calculated as the differences between inflow fluxes and outflow fluxes

** Downstream the mill

Appendix 10. (Continued). b/ Specific fluxes (kg ha^{-1} yr^{-1}).

Site	TOC	TP	K	Mg	Ca	DIN	NO3-N	NO2-N	NH4-N
	kg ha^{-1} yr^{-1}								
JA1	153	0.09	9.28	2.03	5.55	7.64	7.29	0.07	0.28
JB1	150	0.26	18.01	2.03	4.48	4.74	4.54	0.06	0.15
JC1	148	0.12	10.79	2.27	6.16	5.70	5.12	0.12	0.47
P0	329	0.71	15.79	4.61	18.51	6.42	5.75	0.14	0.53
P1	273	0.75	12.55	3.96	14.98	5.12	4.67	0.11	0.39
P2	214	0.72	7.96	2.81	29.95	8.87	8.24	0.20	0.42
P4	266	0.57	11.85	3.65	12.46	5.74	5.05	0.19	0.52
P1-P4*	343	0.36	14.42	4.23	11.07	9.17	7.69	0.43	1.00
PA1	263	0.22	8.60	4.47	10.06	7.77	7.40	0.09	0.29
PD1	341	1.04	15.24	4.95	16.21	5.96	5.48	0.25	0.41
PB1	231	1.16	8.57	3.09	12.15	3.73	3.09	0.21	0.43
PC1	338	0.54	8.84	4.25	14.67	4.02	3.56	0.14	0.32
R1	235	0.14	7.21	3.22	13.82	2.76	2.33	0.17	0.28
R2	208	0.09	19.32	3.72	13.50	4.06	2.64	0.72	0.71
R3**	194	0.15	28.90	5.14	14.81	3.40	2.32	0.10	0.98
R1-R2*	200	0.05	28.49	4.21	14.18	5.20	3.04	1.14	1.03
R1-R3**	150	0.11	37.86	5.40	12.92	3.40	2.05	0.04	1.28
RA1	186	0.15	5.36	2.63	9.67	1.88	1.53	0.11	0.27
RB1	156	0.16	5.80	3.03	12.49	1.98	1.72	0.18	0.14

* Section. Part of the watershed under industrial oil palm plantation. Fluxes are calculated as the differences between inflow fluxes and outflow fluxes

** Downstream the mill