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Spécialité : Sciences de l'environnement

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par

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Modélisation du bilan azoté des plantations de palmiers à huile pour aider à la réduction des pertes dans l'environnement. Etude de cas à Sumatra, Indonésie.

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Modelling of the nitrogen budget of oil palm plantations to help reduce losses to the environment. Case study in Sumatra, Indonesia

Thesis submitted by

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(Master's Degree in Agronomy from AgroParisTech, Paris, France)

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Résumé long en français

L'humanité fait face aux défis urgents de réduire l'impact environnemental de l'agriculture, de changer les régimes alimentaires et d'accroître la production alimentaire. Le palmier à huile est une plante pérenne tropicale emblématique de ces défis. Alors que sa culture peut être à l'origine d'impacts environnementaux, le palmier à huile peut produire, en conditions optimales, 7 à 10 fois plus d'huile alimentaire que les cultures oléagineuses annuelles. Dans ce contexte, améliorer la durabilité de la production d'huile de palme est crucial, tant pour réduire les impacts environnementaux négatifs que pour garantir la sécurité alimentaire.

L'application de fertilisants azotés a été identifiée comme une source majeure d'impacts environnementaux dus à la culture du palmier. Des analyses de cycle de vie de l'huile de palme ont été réalisées pour quantifier les impacts et identifier des améliorations de pratiques agricoles. Cependant, les seuls modèles d'émissions disponibles pour estimer les pertes d'azote dans l'environnement sont généralement valides pour les cultures annuelles et en climat tempéré. L'utilisation de tels modèles dans l'analyse de cycle de vie peut mener à des résultats très incertains ou à une faible sensibilité aux pratiques.

L'objectif global de ce travail de recherche était d'aider à l'identification de pratiques pour réduire les pertes d'azote dans l'environnement. Le cœur du travail était le développement d'un modèle estimant toutes les pertes d'azote dans les plantations, tout en étant sensible aux pratiques et aux spécificités des plantations de palmiers à huile. L'étude s'est concentrée sur les flux d'azote dans les plantations de palmiers sur sols minéraux.

Nous avons réalisé quatre étapes pour mener à bien cette recherche. Premièrement, nous avons mené une revue de littérature de tout le savoir existant concernant les flux et pertes d'azote dans les plantations. Deuxièmement, nous avons comparé 11 modèles existants, pouvant être utilisés pour prédire les pertes d'azote dans les plantations. Troisièmement, nous avons réalisé une analyse de sensibilité de Morris approfondie du modèle mécaniste APSIM-Oil palm. Quatrièmement, nous avons construit IN-Palm, un indicateur agri-environnemental pour les pertes d'azote dans les plantations. Nous avons utilisé la méthode INDIGO® et l'approche de modélisation par arbres de décisions flous pour développer IN-Palm, et nous avons validé cet indicateur en utilisant des mesures de lixiviation d'azote d'une plantation à Sumatra, Indonésie.

Premièrement, la revue de littérature nous a permis d'estimer les principaux flux d'azote, les pertes d'azote, d'identifier leurs déterminants et de mettre en relief les manques de recherche

(Figure A). Il existe peu de connaissances approfondies concernant les calculs de bilan d'azote pour le palmier à huile, pour optimiser la fertilisation en tenant compte de la lixiviation et des émissions gazeuses d'azote. Nous avons synthétisé les connaissances sur tous les flux d'azote dans les plantations de palmiers à huile, selon les pratiques agricoles standard des plantations industrielles, sur sols minéraux, depuis la plantation jusqu'à l'abattage à l'issue d'un cycle de croissance de 25 ans. Les plus grands flux sont des flux internes, tels que l'absorption d'azote par le palmier, de 40-380 kg N ha^{-1} an^{-1}, et la décomposition des palmiers abattus à la fin du cycle, de 465–642 kg N ha^{-1}. Les pertes les plus importantes sont les émissions d'ammoniac (NH_3) et la lixiviation du nitrate (NO_3^-), correspondant respectivement à 0.1–42 % et 1–34 % de l'azote minéral appliqué. Les flux les plus incertains et les moins documentés sont les pertes d'azote, telles que les émissions de protoxyde d'azote (N_2O), d'oxydes d'azote (NO_x), et de diazote N_2, la lixiviation, la volatilisation de NH_3, et le ruissellement. Les conditions les plus critiques pour les pertes d'azote ont lieu au cours de la phase immature quand l'absorption de l'azote par les jeunes palmiers est faible, et au cours de la phase mature dans les zones avec une couverture du sol clairsemée ou recevant des quantités élevées de fertilisants. Des données manquent quant aux effets des pratiques agricoles sur la lixiviation du NO_3^- et sur les émissions de N_2O/NO_x dans ces conditions critiques.

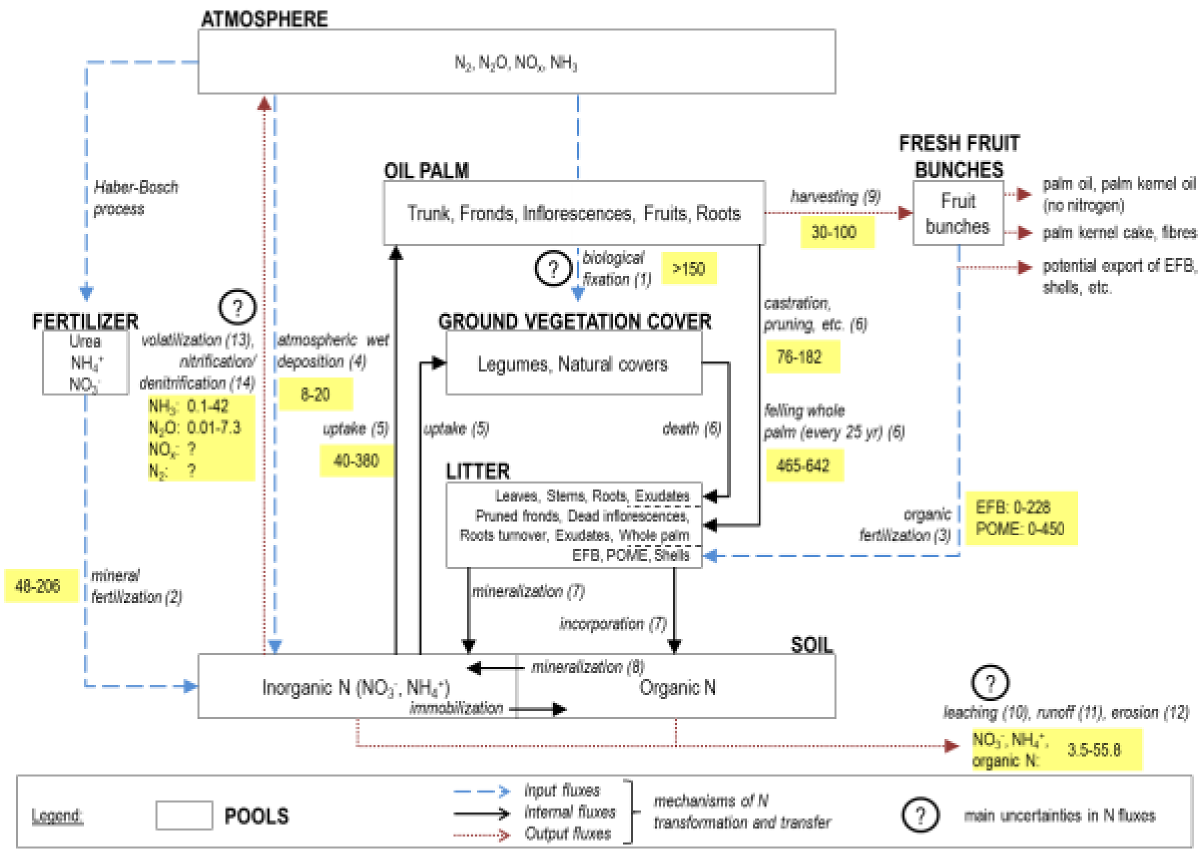

Figure A. Le bilan d'azote dans les plantations de palmiers, mettant en relief les principales incertitudes (Pardon et al., 2016a)

Les plus importants flux annuels d'azote sont principalement les flux internes, et les plus incertains et moins documentés sont les pertes d'azote. Les compartiments sont représentés par des rectangles et les principaux flux sont représentés par des flèches. Les principales incertitudes sont mises en relief par un point d'interrogation. Les valeurs des flux sont des fourchettes données en kg N ha^{-1} an^{-1}, et les pertes par ruissellement, lixiviation, érosion et volatilisation de NH_3 sont estimées en supposant une application de fertilisant minéral de 100 kg N ha^{-1} an^{-1}. EFB: rafles après extraction des fruits, POME: effluent liquide d'huilerie.

Deuxièmement, nous avons identifié la capacité des modèles existants à prendre en compte les particularités du palmier à huile, leurs limites, et les principales incertitudes dans la modélisation (Figure B). Alors que des modèles, nombreux et diversifiés, existent pour estimer les pertes d'azote de l'agriculture, très peu sont actuellement disponibles pour les cultures pérennes tropicales. De plus, il manque une analyse critique de leurs performances dans le contexte spécifique des systèmes de culture pérennes tropicaux. Nous avons évalué la capacité de 11 modèles et 29 sous-modèles à estimer les pertes d'azote dans une plantation de palmier typique tout au long d'un cycle de croissance de 25 ans, par lixiviation, ruissellement et émissions de NH_3, N_2, N_2O et NO_x. Les estimations de perte totale d'azote étaient très variables, allant de 21 à 139 kg N ha^{-1} an^{-1}. En moyenne, 31 % des pertes se sont produites dans les 3 premières années du cycle. La lixiviation du NO_3^- a constitué environ 80 % des pertes. Une analyse de sensibilité de Morris a montré que les plus influentes variables étaient le contenu du sol en argile, la profondeur d'enracinement et l'absorption de l'azote par le palmier. Nous avons aussi comparé les estimations des modèles avec des mesures de terrain publiées. De nombreux défis subsistent pour s'orienter vers une modélisation plus précise des processus liés aux spécificités des systèmes de cultures pérennes tropicaux tels que le palmier à huile.

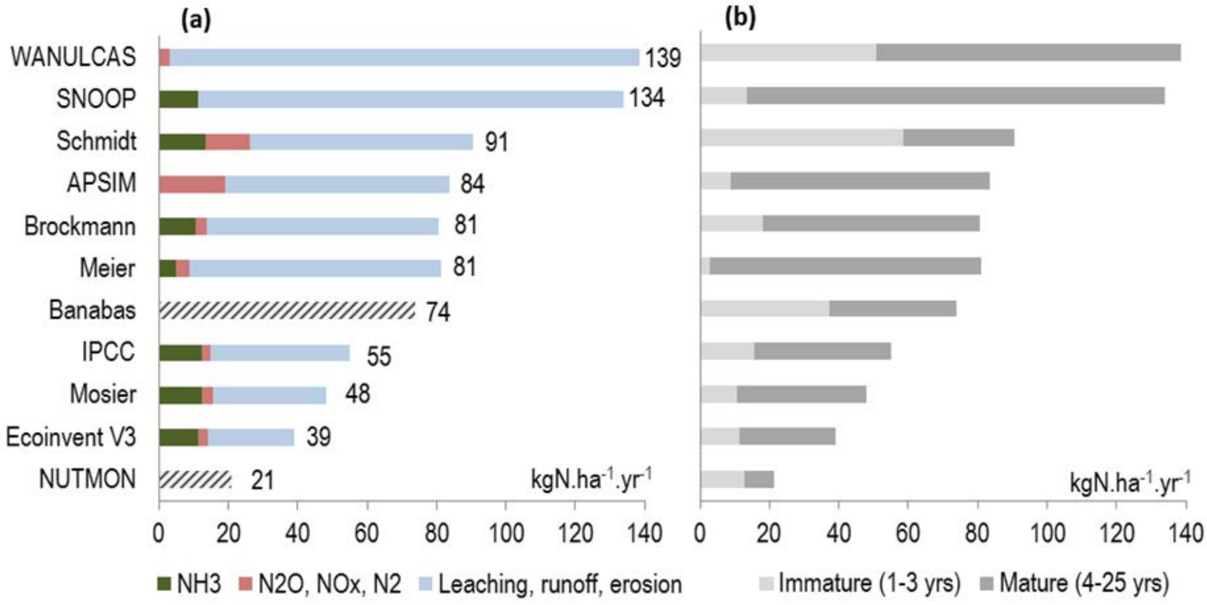

Figure B. Estimations de pertes d'azote par les 11 modèles (Pardon et al., 2016b)

(a) Distribution de la moyenne annuelle des pertes entre les trois groupes de perte: lixiviation et ruissellement, volatilisation de NH_3; émissions de N_2O, NO_x et N_2. Les pertes d'azote étaient globalement très variables, avec une moyenne de 77 kg N ha^{-1} an^{-1}, allant de 21 à 139 kg N ha^{-1} an^{-1}. Le groupe de perte par lixiviation et ruissellement était le plus important des trois, correspondant à environ 80 % des pertes. Les barres hachurées représentent les calculs incluant plusieurs groupes en même temps: Banabas a estimé les trois groupes conjointement, NUTMON a estimé conjointement toutes les émissions gazeuses et les émissions par lixiviation étaient négatives. SNOOP a estimé comme nulles les émissions de N_2, N_2O, et NO_x, et APSIM and WANULCAS n'ont pas modélisé la volatilisation de NH_3. (b) Distribution de la moyenne annuelle des pertes entre les phases immatures et matures, i.e. respectivement de 1 à 3 ans et de 4 à 25 après plantation. En moyenne, 31 % des pertes se sont produites pendant la phase immature, qui représente 12 % de la durée du cycle.

Troisièmement, nous avons mis en évidence les déterminants des pertes d'azote et du rendement dans l'un des modèles comparés, le modèle mécaniste APSIM-Oil palm (Figure C). Afin d'identifier les paramètres clés, parmi les pratiques agricoles et les caractéristiques des sites, qui déterminent le rendement et les pertes d'azote, tout au long d'un cycle de 25 ans, nous avons réalisé une analyse de sensibilité de Morris approfondie du modèle mécaniste APSIM-Oil palm, en utilisant 3 sites en Papouasie Nouvelle Guinée. Nous avons sélectionné 12 paramètres et 3 outputs: le rendement, les émissions de N_2O et la lixiviation de l'azote. L'influence des 12 paramètres sur les outputs a dépendu des caractéristiques des sites, de l'âge des palmiers et du climat. Les paramètres les plus influents pour les pertes d'azote étaient la fertilisation minérale en azote, le drainage et la fraction de légumineuse dans la couverture végétale du sol. Les simulations ont suggéré qu'APSIM-Oil palm est un outil utile pour l'évaluation de pratiques agricoles pour optimiser le rendement et les conséquences environnementales dans différents contextes. Les résultats peuvent aussi permettre d'identifier des besoins en données de terrain pour améliorer les estimations de perte d'azote, et guider de futurs développements de modèles et d'indicateurs de risque.

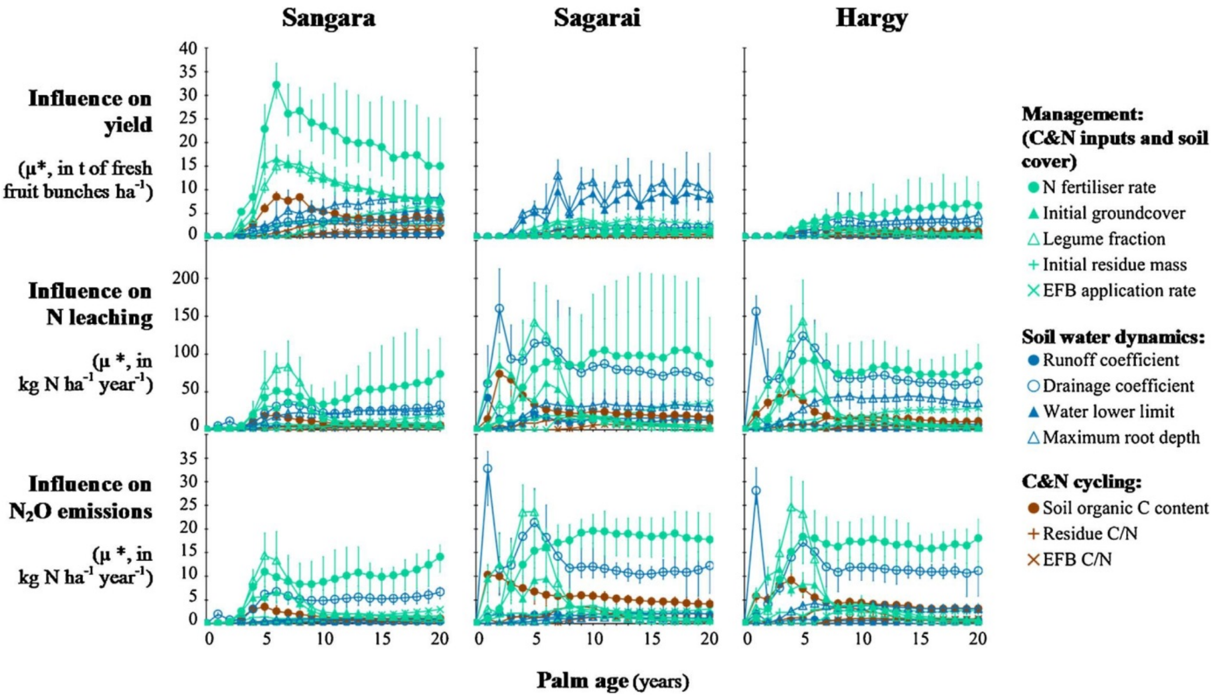

Figure C. Effet des caractéristiques des sites, de l'âge des palmiers et du climat sur l'influence de 12 paramètres sur le rendement et les pertes d'azote des plantations de palmiers (Pardon et al., 2017)

Les paramètres étudiés sont listés à droite des graphiques. μ* est l'influence moyenne du paramètre pour l'output choisi. Plus μ* est élevé, plus le paramètre est influent. Les barres d'erreur représentent les valeurs minimales et maximales parmi les scénarios correspondant aux 10 années de plantation, et illustrent donc l'effet du climat sur la valeur de μ*. La variabilité annuelle des moyennes n'est pas liée à la variabilité climatique inter-annuelle, car les simulations pour les 10 années de plantation sont moyennées sur la figure. EFB: rafles après extraction des fruits

Quatrièmement, nous avons utilisé toute l'information identifiée dans les chapitres précédents, ainsi que des dires d'experts, pour construire IN-Palm, un modèle pour aider les planteurs et les scientifiques à estimer les pertes d'azote dans l'environnement et à identifier les meilleures pratiques agricoles (Figure D). Le principal défi a été de construire un tel modèle dans un contexte de manque de connaissances. Etant donné ces objectifs et contraintes, nous avons développé un indicateur agri-environnemental, en utilisant la méthode INDOG® et l'approche de modélisation par arbres de décision flous. Nous avons effectué la validation du module de lixiviation de l'azote en utilisant des données de terrain d'une plantation à Sumatra, Indonésie. Nous avons aussi utilisé IN-Palm pour tester des changements théoriques de gestion de la fertilisation et des résidus. IN-Palm s'exécute dans un fichier Excel et utilise 21 variables d'entrée facilement accessible pour calculer 17 modules. Il estime des émissions annuelles et des scores pour chaque voie de perte d'azote et fourni des recommandations pour réduire les pertes d'azote. Les prédictions de lixiviation de l'azote par IN-Palm étaient acceptables selon plusieurs calculs statistiques effectués, avec une légère tendance à sous-estimer la lixiviation. IN-Palm s'est montré efficace pour tester des changements de pratiques dans un contexte donné, tout en tenant compte de l'incertitude climatique. Finalement, une validation complémentaire d'IN-Palm sera réalisée auprès des utilisateurs finaux dans une plantation à Sumatra.

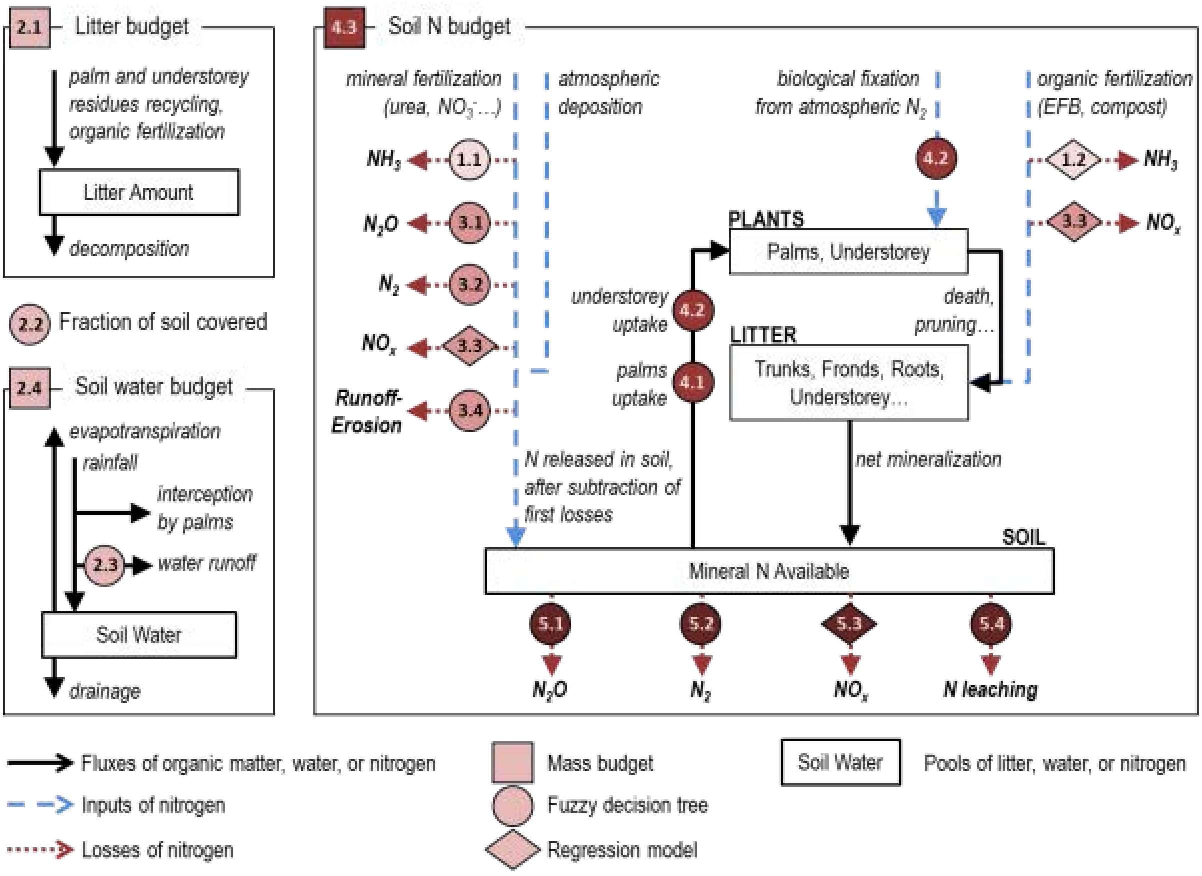

Figure D. Flux et pertes d'azote calculés par IN-Palm (Pardon et al., under review)

Cinq principales étapes de calcul sont réalisées pour un hectare de palmier et pour chaque mois d'une année choisi par l'utilisateur, entre 1 et 30 ans: ① la volatilisation de NH_3 due aux fertilisants minéraux et organiques; ② l'estimation de la couverture du sol du bilan hydrique; ③ La dénitrification due aux fertilisants minéraux et organiques, et les pertes d'azote dues au ruissellement et à l'érosion à partir des fertilisants minéraux et des dépôts atmosphériques d'azote; ④ l'estimation du contenu en azote minéral du sol après libération nette de l'azote dans le sol et de l'absorption d'azote par les plantes; et ⑤ les émissions de fond par dénitrification et la lixiviation, dues à l'azote minéral du sol. EFB: rafles après extraction des fruits

Cette recherche constitue donc une synthèse exhaustive des connaissances et modèles disponibles pour les flux et pertes d'azote dans les plantations. L'un des principaux résultats est un nouvel indicateur agri-environnemental, IN-Palm, sensible aux pratiques et conditions locales, de même que potentiellement utilisable en tant que modèle d’émission dans des approches holistiques. Cet indicateur peut être une base utile pour de futures adaptations à d’autres plantes pérennes tropicales.

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I also would like to thank all the members of the oral defence jury, the co-authors of our research articles, and anonymous reviewers, for their time and the thorough comments which really helped me to integrate new skills in research and scientific writing.

Finally, I warmly thank all my colleagues, family and friends for their support throughout this Ph.D.

Contribution of others and funding

Contribution of others: the main contributions for this research project are summarised below. A detailed description of the contributions is also provided at the beginning of each chapter.

Contribution types*	Contributors	Description
Conceptualisation	Cécile Bessou, Lénaïc Pardon, Paul Nelson, Benoît Gabrielle	Goals, scope and structure of the research
Methodology	Cécile Bessou, Paul Nelson, Benoît Gabrielle	Mentoring for bibliographic research, scientific writing, choice of methodology
Software	Lénaïc Pardon	Programming of the IN-Palm agri-environmental indicator
Validation	Ph.D. Board members: Cécile Bessou, Paul Nelson, Benoît Gabrielle, Jean-Pierre Caliman, Christian Bockstaller, Jean-Paul Laclau, Claudine Basset-Mens, Raphaël Marichal Specific topics : Nathalie Saint-Geours, Niel Huth	Validation of the scientific and operational quality of the work
Resources	CIRAD (Montpellier, France), SMART-RI (Sumatra, Indonesia), CSIRO (Toowoomba, Australia), JCU (Cairns, Australia)	Office, computational resources, field work, accommodation, travel
Writing - Initial draft	Lénaïc Pardon	Text, figures, tables
Writing – Review and editing	Co-authors, experts, anonymous journal reviewers, editors (see specific chapters for details)	Critical review, comments, re-phrasing, complementary references
Supervision	Cécile Bessou, Paul Nelson, Benoît Gabrielle, Neil Huth	Oversight and leadership responsibility for the research activity planning and execution
Project administration	Cécile Bessou, Paul Nelson, Benoît Gabrielle	Management and coordination responsibility for the research activity planning and execution
Funding acquisition	Cécile Bessou, Paul Nelson	Acquisition of the financial support

* Contributions typology is from Allen et al. (2014)

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- **SMART-Research Institute, in Indonesia,** which funded the nitrogen leaching and runoff-erosion trials whose data were used in the fourth chapter of the thesis;
- and **James Cook University, in Australia,** which partly funded the research travel in Australia leading to the third chapter of this thesis, and partly funded the expenditures of the oral defence in Montpellier, France.

Table of Contents

List of Tables

List of Figures

General introduction

Climate change, land-use change, biodiversity loss and nitrogen (N) flows were identified as four anthropogenic perturbations already exceeding the planetary boundaries beyond which the Earth system may be irreversibly altered (Rockström et al., 2009; Steffen et al., 2015). On the other hand, the global population is expected to increase to 9 billion people by 2050, raising the question of the optimal ways to feed the world (Godfray et al., 2010). Thus, humanity faces the challenges of urgently decreasing the environmental impact of agriculture, shifting diets and increasing food production (Foley et al., 2011; Galloway et al., 2013).

Oil palm is a tropical perennial crop emblematic of the challenges faced by humanity. Indeed, its cultivation can play a role in the four anthropogenic perturbations above-mentioned, while it is on the other hand a highly productive crop for edible oil. Rapid expansion of the area cultivated to oil palm over the period 1990-2010 was associated with deforestation and oxidation of peat soils, contributing to land-use change and greenhouse gases emission mainly, in Indonesia and Malaysia (Carlson et al., 2012; Gunarso et al., 2013; Koh et al., 2011; Miettinen et al., 2012). Despite its relatively small area of cultivation of 19 M ha (FAOSTAT, 2014), compared to cultivation areas of many other crops in the world, forest conversion to oil palm was associated with loss of biodiversity and reduction in ecosystem functions, as optimal production areas of oil palm are usually hotspots of biodiversity in the tropics (Dislich et al., 2016; Fitzherbert et al., 2008). When oil palm plantations are established, application of N fertilisers is a common practice to help achieve the yield potential of the crop (Corley and Tinker, 2015; Giller and Fairhurst, 2003). The use of fertilisers is one of the major causes of the increase of global anthropogenic N flows (Galloway et al., 2008). Yet, in optimal conditions, oil palm can produce 3 to 7 t oil ha^{-1} yr^{-1}, which is 7 to 10 fold higher than in annual oil crops (Corley and Tinker, 2015; Rival and Levang, 2014). In this context, increasing palm oil production sustainability is crucial for both reducing negative environmental impacts and ensuring food security.

Palm oil is the largest source of vegetable oil in the world, and 82 % of the production occurs in Indonesia and Malaysia (FAOSTAT, 2014). Globally, 40 % of the cultivated area belongs to smallholders and 60 % to industrial plantations (Rival and Levang, 2014). In recent years, research and actions related to environmental impacts of palm oil production were mainly focused on land-use change, climate change and biodiversity loss during establishment of plantations (Clough et al., 2016; Pirker et al., 2016; Sayer et al., 2012). However, the application of synthetic N fertilisers was also identified as a major source of environmental impacts associated with the cultivation of oil palms (Choo et al., 2011). Application of N fertilisers may be followed by N losses in the environment, such as ammonia (NH_3) volatilisation, nitrous oxide (N_2O) emissions, and nitrate (NO_3^-) leaching. These N losses lead to a 'cascade' of environmental impacts, such as climate change, terrestrial acidification and fresh water eutrophication (Galloway, 1998). As the largest increases in N flows over the coming decades are expected to occur in tropical areas, efforts to reduce N losses should particularly focus on these areas (Galloway et al., 2008). A reduction in N losses might be achieved by reducing N fertiliser rates, which would reduce expenditures in plantations, as fertilisers constitute 46 to 85 % of field costs (Caliman et al., 2001a; Goh and Härdter, 2003; Goh and PO, 2005; Silalertruksa et al., 2012). Therefore, in order to help reduce environmental impact of oil palm cultivation, this research work focused on N fluxes in oil palm plantations on mineral soils. The overall objective was to help identify management practices to reduce N losses in the environment.

In order to identify management practices that minimise the environmental impacts, it is important to account for the consequences of management changes throughout the supply chain, and for as many impact categories as possible. This approach avoids recommending management changes that would cause other adverse effects either elsewhere in the supply chain, or related with another type of environmental impact. Such a holistic approach is facilitated by the life cycle assessment conceptual framework (Brentrup et al., 2004). Life cycle assessments of palm oil have already been performed (Choo et al., 2011; Mattsson et al., 2000; Schmidt, 2010; Stichnothe and Schuchardt, 2011; Yusoff and Hansen, 2007). However, the default models used in such studies to estimate N losses to environment, such as IPCC models (2006), are generally valid for annual crops and temperate climate conditions and are not sensitive to management. The use of such general models may lead to life cycle assessments that are very uncertain and that do not provide useful indications of potentially superior management practices (Basset-Mens et al., 2010; Bessou et al., 2013b; Richards et al., 2016). For instance, some soil cover management practices may reduce N losses through runoff and erosion in oil palm, but standard life cycle assessments would not be sensitive enough to capture their effects. Thus, in order to be able to identify management practices that reduce environmental impact of oil palm cultivation, a model of N losses accounting for peculiarities of the oil palm system is needed. As a consequence, the core of this research work consisted of developing a model that estimates all N losses in oil palm plantations, while being sensitive to management practices.

The main challenge in building such a model is the lack of available knowledge about N fluxes, N losses and their drivers. Despite existing data on measurements over the last 50 years, the complex N dynamics and their environmental and management drivers in plantations are not fully understood. Agri-environmental indicators of the INDIGO® method (Bockstaller et al., 1997; Bockstaller and Girardin, 2008) are particularly suitable models for use in such contexts of knowledge scarcity. Indeed, they harness the most of readily accessible data from a whole range of sources, such as measured or modelled, qualitative or quantitative, empirical or expert knowledge (Girardin et al., 1999). In the INDIGO® indicators, the decision tree modelling approach (Breiman, 1984) is often used to tackle the lack of knowledge and allow for the combination of all available data. Moreover, the use of fuzzy logic (Zadeh, 2008) to design fuzzy decision trees facilitates generation of more realistic and sensitive output spaces without requiring extra knowledge (Olaru and Wehenkel, 2003). Therefore, in this research work, I used the INDIGO® method and the fuzzy decision tree modelling approach to develop a novel agri-environmental indicator of N losses specific to oil palm plantations.

I hence performed four steps, with the overall goal of helping to identify management practices that minimise environmental impacts associated with N losses from oil palm plantations (Figure 0). First, I conducted a literature review of all the existing knowledge about N fluxes and losses in plantations. This first step was important to estimate the main N fluxes and N losses, and identify their drivers and the research gaps. Second, I compared 11 existing models that may be used to predict N losses in plantations, and assessed their ability to capture oil palm system peculiarities, their limits, and the main uncertainties in modelling. Third, I focused on one of the existing models, the APSIM-Oil palm process-based model, which has been validated for yield (Huth et al., 2014). I performed a sensitivity analysis of this simulation model to identify the key drivers of N losses and yield. Fourth, I used all the information identified in the previous chapters, together with expert knowledge, to build IN-Palm, an agri-environmental indicator for N losses in oil palm plantations. I validated this indicator using a field dataset of N leaching from a plantation in Sumatra, Indonesia.

Finally, I discussed four key points of this research: (1) the potential management options identified to reduce N losses in oil palm, (2) the future use and development of IN-Palm, (3) the future field measurements to reduce knowledge gaps in N loss estimates, and (4) the INDIGO® framework and life cycle assessment.

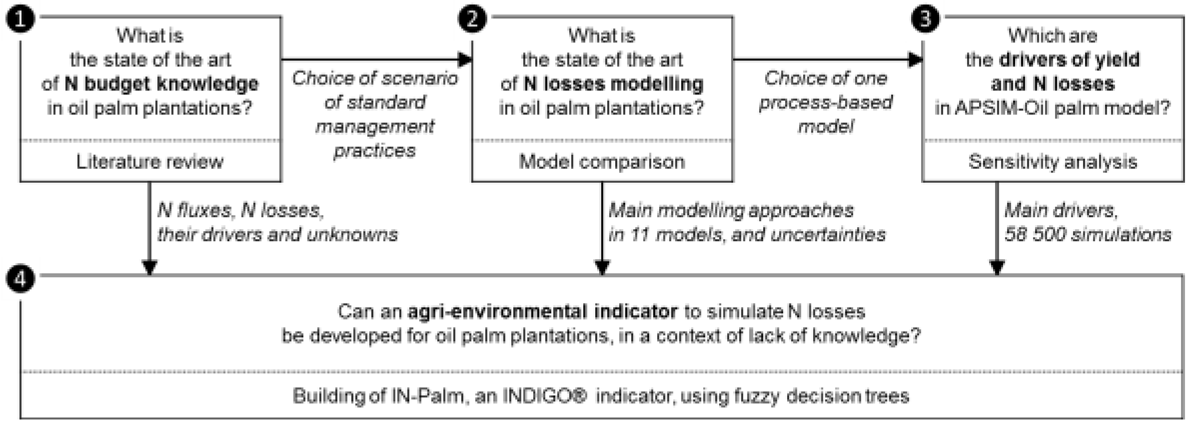

Figure 0. The four steps of this research work, each one related to a chapter of this thesis.
In each chapter, the research question is written in the upper rectangle, and the main method used is written in the lower rectangle. Links between chapters are represented by arrows.

1. Key unknowns in nitrogen budget for oil palm plantations: A review

Lénaïc Pardon, Cécile Bessou, Paul N. Nelson, Bernard Dubos, Jean Ollivier, Raphaël Marichal, Jean-Pierre Caliman and Benoît Gabrielle

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Contribution of co-authors:

Contribution types*	Contributors	Description
Conceptualisation	Lénaïc Pardon, Cécile Bessou, Paul Nelson	Goals, scope and main structure of the chapter
Methodology	Cécile Bessou	Mentoring for bibliographic research and scientific writing
Validation	Cécile Bessou, Paul Nelson, Benoît Gabrielle	Validation of the scientific quality
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* Contributions typology is from Allen et al. (2014)

Abstract

Nitrogen (N) losses in agroecosystems are a major environmental and economic issue. This issue is particularly pronounced in oil palm cultivation because oil palm production area is expected to increase to 12 M ha by 2050. N fertilisation in oil palm plantations is mainly provided by mineral fertilisers, palm oil mill by-products, and biological fixation using legume cover crops. N loss has a major environmental impact during cultivation. For instance, 48.7 % of the greenhouse gases emitted to produce 1 t of palm oil fruit are due to N fertilisation. Actually, there is little comprehensive knowledge on how to calculate N budgets in oil palm plantation in order to optimise fertilisation, taking into account N leaching and N gases emissions. Here we modelled knowledge about all N fluxes in an oil palm field following standard management practices of industrial plantations, on a mineral soil, from planting to felling after a 25-year-growth cycle. The largest fluxes are internal fluxes, such as oil palm uptake, with 40–380 kg N ha^{-1} yr^{-1}, and the decomposition of felled palms at the end of the cycle, with 465–642 kg N ha^{-1}. The largest losses are emissions of NH_3 and leaching of NO_3^-, corresponding to 0.1–42 % and 1–34 % of mineral N applied, respectively. The most uncertain and least documented fluxes are N losses such as N_2O, NO_x, N_2 emissions, leaching, NH_3 volatilisation, and runoff. The most critical conditions for N losses occur during the immature phase when young palms uptake is low and during the mature phase in areas with sparse soil cover or receiving high amounts of fertilisers. Data is lacking about the effects of management practices on NO_3^- leaching and N_2O/NO_x emissions in those critical conditions.

1.1. Introduction

The anthropogenic production of reactive nitrogen (Nr) is now two to three times that of natural terrestrial sources. Much of this nitrogen (N) is lost from the site of use to the surrounding environment, resulting in a cascade of negative environmental impacts (Galloway et al., 2013; Vitousek et al., 1997). In agriculture in particular, N losses are a key issue from both environmental and economic points of view. Agroecosystems receive about 75 % of the Nr created by human activity (Foley et al., 2011; Galloway et al., 2013, 2008).

In oil palm plantations, addition of N via legume cover crops and fertilisers is a common practice to achieve the yield potential of the crop. Fertilisers constitute 46 to 85 % of field costs in a plantation (Caliman et al., 2001a; Goh and Härdter, 2003; Goh and PO, 2005; Silalertruksa et al., 2012). Addition of N is also associated with pollution risks of ground and surface waters and emission of greenhouse gases (Choo et al., 2011; Comte et al., 2012). This raises environmental concerns as oil palm is the most rapidly expanding tropical perennial crop and is expected to keep expanding in the next decades up to an added 12 M ha area by 2050 (Corley, 2009), i.e., +64 % compared to current surface area (18.7 M ha in FAOSTAT, 2014). Hence, an accurate understanding of N dynamics and losses in plantations is important to optimise the management of N and use of N fertilisers.

N budgets are commonly used in palm plantations to make fertiliser management plans. The used approach may be more or less complex depending on how detailed the budget is in terms of N flux accounting. Oil palm is a perennial crop with a wide root network and a high production of biomass residues, which, coupled with management practices, generates spatial and temporal heterogeneity in soil dynamics over the long growing cycle. Hence, a precise assessment of N budget requires characterising and modelling numerous and diverse fluxes. Despite existing data on measurements over the last 50 years, there has been no comprehensive synthesis on the N cycle in oil palm plantations and the effects of environmental conditions and management practices on N losses. There is a need to compile such data and to highlight research needs in order to shed further light on N budgets in oil palm plantations and to improve fertiliser management in a sustainable way.

This paper focuses on oil palm industrial plantations on mineral soils after replanting. The objectives are to (a) assess current knowledge regarding the N cycle in oil palm plantations, (b) identify the remaining challenges for establishing complete N budgets and, in particular, quantify N losses, and (c) identify opportunities for the use of N budgets to improve production and environmental outcomes. This paper first reviews the budget approaches and highlights the peculiarities of oil palm plantations. It then reviews the existing literature, measurements, and knowledge gaps on N fluxes in plantations. It finally identifies dominant processes and critical conditions favoring N losses.

1.2. N budget within oil palm management

1.2.1. Standard oil palm management

In this paper, we consider predominant management practices in large industrial plantations, as they are generally related with highest environmental impacts (Lee et al., 2014a). Moreover, practices in independent smallholders' plantations may be more variable and are less characterised in the literature (Lee et al., 2014b). However, a large part of smallholders' plantations in Asia and South America are supervised by industrial plantations in the young age of the palms, and their practices are hence partly comparable to the industrial plantations. In industrial plantations, practices also vary, as for the choice of the planting material, the rate and placement of mineral and organic fertilisers, the weeding practices, etc. But some practices have a relatively lower variability, such as planting density, duration of the growth cycle, and sowing of a legume cover. Therefore, we considered the management practices being the most spread, which we referred to as standard management practices in this paper.

N cycling in oil palm plantations must be considered in the context of management systems, which we briefly summarise here. This summary is derived from (Corley and Tinker, 2015), and we refer readers to that book for more detailed insights. Palm plantations are generally grown on a cycle of approximately 25 years. Clearing and preparation practices may differ depending on the landform and previous land cover. Important variations for N cycling concern the amount of residues from the previous vegetation left to decompose in the field, as well as anti-erosion measures and drain density. One-year-old palms from a nursery are planted in equilateral triangular spacing with a planting density usually in the range of 120–160 palm ha^{-1}. A legume cover, e.g., Pueraria phaseoloides or Mucuna bracteata, is generally sown in order to provide quick ground cover and fix N from the atmosphere. The legume rapidly covers the whole area and is controlled with manual weeding around palms. It declines as the oil palm canopy grows and is at least partially replaced by more shade-tolerant vegetation around the sixth year when the palm canopy closes.

During the first 2–3 years of plantation, i.e., the immature phase, fruit bunches are not harvested and female inflorescences may be removed to improve growth and subsequent production at the beginning of the third year after planting. During the following 22 years, i.e., the mature phase, the plantation is harvested two to four times per month. For each fresh fruit bunch harvested, one or two palm fronds are pruned and left in the field, mostly in windrows in every second interrow. The alternate inter-row is used for the harvest pathway. The natural vegetation cover in the harvest path and in the circle around the palms is controlled three to four times a year with selective chemical or mechanical weeding. In the remaining area, vegetation is left to grow, except for woody weeds to avoid critical competition with the oil palms.

Fertiliser management varies greatly between plantations and through the life cycle. It generally consists of the application of various forms of mineral fertilisers containing N, P, K, Mg, S, B, Cl, but can be also complemented or substituted by organic fertilisers. Organic fertilisers come mainly from the palm oil mill. After oil extraction, the empty fruit bunches and the palm oil mill effluent may be returned, either fresh or after co-composting, to parts of the plantation, especially on poor soils or in the vicinity of the mill. Around 25 years after planting, the productivity of the palms declines due to higher fruit lost and higher harvesting cost, depending on the palms' height and stand per hectare. The old palms are felled and sometimes chipped and left in the field to decompose, and new seedlings are planted between them.

Based on this standard management, we identified three main peculiarities in N dynamics to be accounted for in the oil palm N budget. These characteristics are related both to the lifespan of the crop and the management practices. First, as a perennial crop, the palm grows continuously for around 25 years and develops a wide root network, whose extent and turnover will impact nutrient uptake efficiency. Practices are adapted to the plants' evolving needs and may vary from year to year. Thus, N dynamics may be impacted differently each year and may be influenced by both short- and long-term processes. Second, management practices are spatially differentiated and generate marked spatial heterogeneity across the plantation. For instance, mineral and organic fertilisers may be unevenly distributed and weeds are controlled in specific areas. Thus, the practices generate three main visible zones on the ground: the weeded circle, the harvest pathway, and the pruned frond windrows. These zones differ in terms of ground cover, soil organic matter content, bulk density, and soil biodiversity (Carron et al., 2015; Nelson et al., 2015), and the differences become more pronounced over the crop cycle. N dynamics must also be related to the distribution of fertiliser, which may or may not be associated with the visible zones. N fertiliser may be applied manually or mechanically usually as a band around the outside of the weeded circle. Empty fruit bunches are usually applied in piles adjacent to the harvest path. Temporal and spatial heterogeneity may both influence N dynamics and may also affect the measurement accuracy of N fluxes and stocks (Nelson et al., 2014). Third, internal fluxes of N within the plantation may be important. For instance, as a tropical perennial crop, oil palm produces a large amount of biomass that is returned to the soil, with large associated N fluxes such as pruned fronds, empty fruit bunches, and felled palm. There are also internal fluxes within the palm tree itself, notably from old to new fronds.

1.2.2. Application of N budgets to fertiliser management

N budgets or balances are based on the principle of mass conservation (Meisinger and Randall, 1991; O Legg and J Meisinger, 1982). In agroecosystems, this principle can be represented as follows: N inputs=N outputs +ΔN storage. This simple principle can lead to various approaches, whose complexity increases with the number of considered fluxes and the accuracy of the calculation (Figure 1.1). (Oenema et al., 2003; Watson and Atkinson, 1999) proposed a distinction between three basic approaches in nutrient budget studies: (1) farm-gate budgets, which record only the fluxes of purchased nutrients entering and fluxes of harvested nutrients leaving the system; (2) system budgets, which also include natural fluxes of nutrients entering and leaving the system such as biological N fixation or N leaching, but without looking at potential internal dynamics; (3) cycling models, which take into account all fluxes entering and leaving the system and also quantify internal fluxes and stocks, e.g., immobilisation in plants and mineralisation of residues.

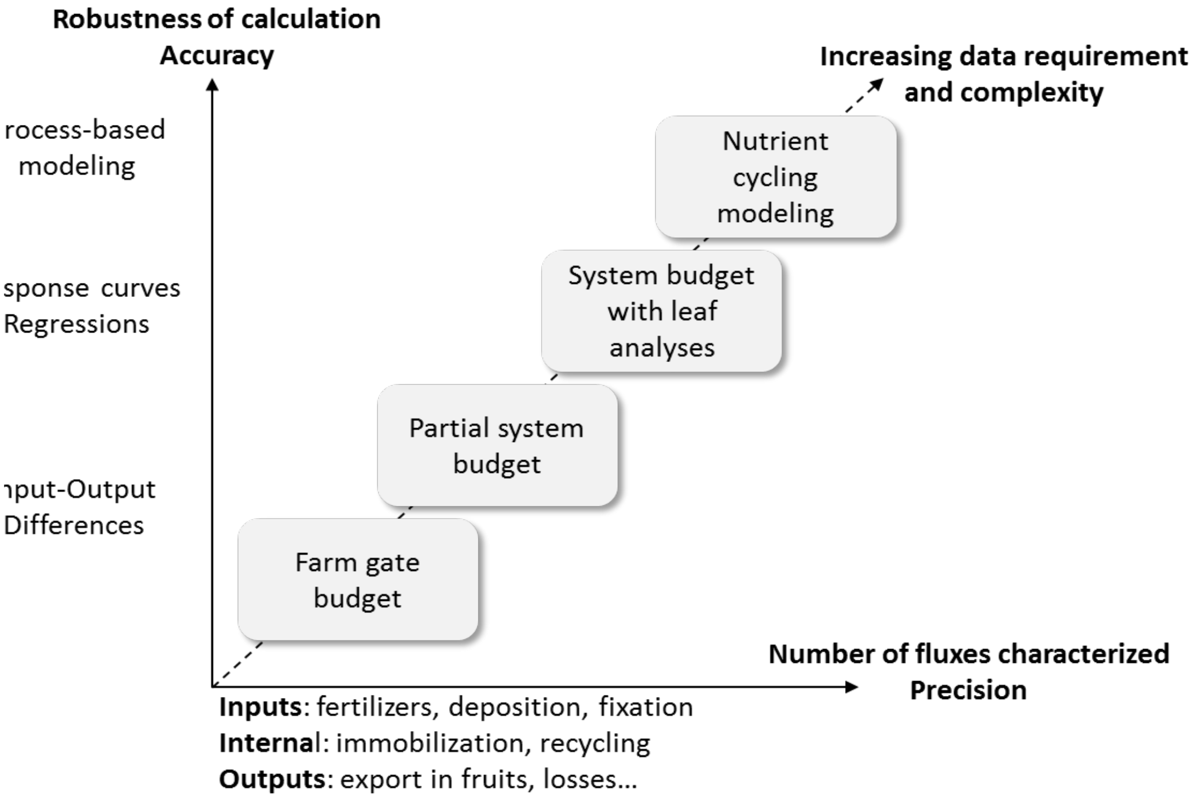

Figure 1.1. Nature of N budget to guide management.

Reliability increases when accuracy and precision increase, but applicability decreases with data requirement. The various approaches are adapted to oil palm management context.

N budgets are commonly used to determine crop fertiliser management. The reliability and applicability of N budget approaches in the case of oil palm management are shown in Figure 1.1. Reliability proceeds from a combination of accuracy and precision, which increase with the level of knowledge and data availability. On the contrary, applicability is usually limited by knowledge and data availability. Applying one of these approaches to fertiliser management hence implies some trade-off between reliability and applicability. In oil palm plantations, only the first two approaches are currently commonly used, i.e., farm-gate or system budgets, or an intermediate partial budget approach. A comprehensive nutrient cycling approach exists, i.e., the WANULCAS model (Noordwijk et al., 2004), but is still not yet widespread in practice. In the partial budget approach, normally using a time step of 1 year, the fertiliser rates are estimated as the amounts required, nutrient by nutrient, to compensate the amounts of nutrients exported, immobilised, and lost (Corley and Tinker, 2015).

Several levels of precision are possible. Some approaches, closer to Farm-gate budgets, take into account only the export in fruit bunches with or without accounting for immobilisation in the palm tissues. Some other approaches, closer to System budgets, also take into account atmospheric deposition and major losses of nutrients (Ng et al., 1999; Ollivier, 2011) or nutrients from the pruned fronds recycled to the soil (e.g., Goh and Härdter, 2003). However, nutrient budgets alone are not adequate to guide fertiliser applications if there is an existing nutrient deficiency because an investment of nutrients in palm tissues or soils may be necessary (Corley and Tinker, 2015).

In a more comprehensive budget approach, leaf analysis can help to identify nutrient deficiency in palms and hence better account for part of the internal stocks and fluxes that are not discriminated in the in-out budget approach. Leaf analysis is used to modulate recommendations of fertiliser rates based on critical levels derived from fertiliser rate experiments. This empirical method was developed from the work of Prévot and Ollagnier (1957) and is based on the relationship that exists between leaf nutrient content and yield. First, fertiliser rate trials are implemented to provide response curves for the main nutrients required. Second, leaf analyses are carried out in the same plots, and the response curves are used to adapt the fertiliser application in order to drive the leaf content to the optimal rate and hence improve the yield (Caliman et al., 1994). However, the leaf analysis method still need to be improved by integrating more knowledge of internal nutrient fluxes within the plant and the soil-plant system as well as better accounting for the specificities of various planting materials in these internal nutrient dynamics (Ollivier et al., 2013). Indeed, in tree crops, storage and relocations of nutrients may occur between different plant tissues. It is therefore important to understand the fluxes inside the plant over the cycle, in order to link more efficiently the nutrient content, the rate of fertilisers to apply, and the targeted yield. These relationships also depend on soil and climate conditions, notably in the case of palm oil (Foster, 2003).

Depending on the precision and accuracy of the measurements and calculations, N budgets may also be used to identify dominant processes or knowledge gaps and to estimate N losses as a performance indicator in nutrient management or in environmental impact assessment. As an example, in the greenhouse gas calculator, PalmGHG (Bessou et al., 2014), developed by Roundtable on Sustainable Palm Oil (RSPO), a partial N budget approach based on the IPCC guidelines was applied in order to estimate the N losses in a plantation. As part of these losses, N_2O emissions are calculated based on a statistical model that correlated N_2O losses to the total mineral and organic N fertilisers applied (see "Response curves, Regressions" in Figure 1.1).

While the simplest forms of budget may be easy to implement for fertiliser management, they neither show where N is stored nor the time scale of its availability, e.g., for the organic N in soil (Watson and Atkinson, 1999). On the contrary, the cycle modelling approach encompasses all fluxes including internal N dynamics and N losses at any time. In the following sections, we investigate the available knowledge to characterise all fluxes within a cycle modelling approach and highlight research needs to fill in knowledge gaps and improve fertiliser management based on comprehensive cycling models or derived budget approaches.

1.2.3. System boundaries and accounted fluxes

The fluxes were investigated within the system boundaries of an oil palm field on a mineral soil, including the following components: palms, ground vegetation cover, litter, and soil where the roots are. The production of agricultural inputs, transport-related fluxes, and the process of milling were not included in the system. The pools, stocks, and fluxes of N considered are shown in Figure 1.2.

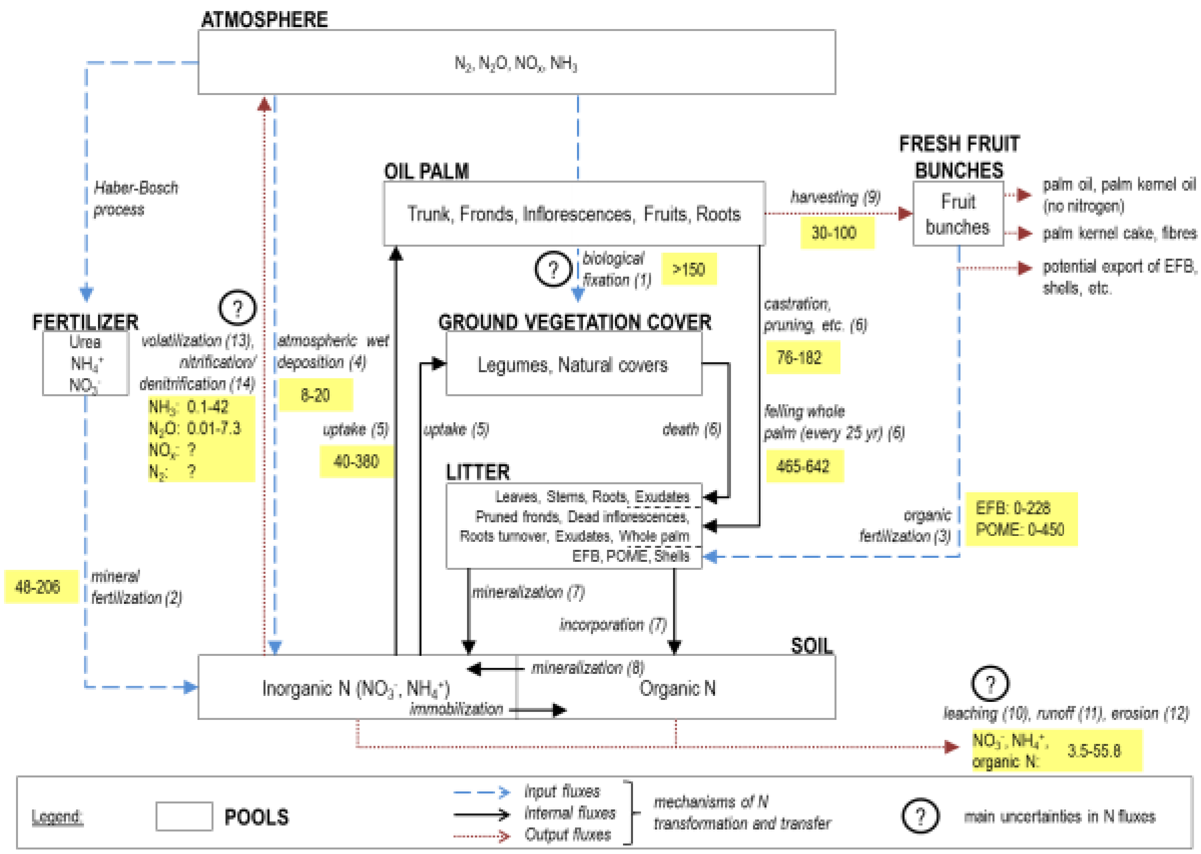

Figure 1.2. The N budget in oil palm plantations, highlighting the main uncertainties.
The largest annual N fluxes are mainly internal fluxes, and the most uncertain and least documented fluxes are N losses. The pools are represented by the rectangles and the main fluxes are represented by the arrows. The main uncertainties are highlighted with a question mark. Flux values are ranges given in $\mathrm{kg\ N\ ha^{-1}\ yr^{-1}}$, and runoff, leaching, erosion, and volatilisation of NH_3 are estimated assuming an application of 100 $\mathrm{kg\ N\ ha^{-1}\ yr^{-1}}$ of mineral N fertiliser (see Tables 1.1, 1.2, and 1.3 for sources). EFB: empty fruit bunches, POME: palm oil mill effluent.

Spatially, the system was defined as having homogeneous palm and ground vegetation cover types and age, soil, climate, and management. Regarding the root zone, roots were measured down to 3–5 m depth (Jourdan and Rey, 1997; Schroth et al., 2000; Sommer et al., 2000). But most of the root biomass and root activity is found in the top 1 m (Corley and Tinker, 2015; Ng et al., 2003), with for instance 75 % of root activity estimated at 0.8 m depth in Papua New Guinea (Nelson et al., 2006) and 0.22 m in Malaysia (Lehmann, 2003 using data from IAEA, 1975).

Temporally, the system included the whole growth cycle of the palms, from planting to felling, excluding the nursery stage and previous land use. The typical 25-year-growth cycle is split into two main phases: the immature phase that starts when previous palms are felled and ends

2–3 years later and the mature phase from then until the end of the cycle when the palms are felled.

Several inputs, internal fluxes and outputs or losses occur along with transformations to the form of N. Inputs to the system consist of biological N fixation; mineral and organic fertiliser application such as empty fruit bunches, palm oil mill effluent, or compost; atmospheric deposition of ammonia (NH_3) and N oxides (NO_x); and deposition of eroded N containing soil and litter coming from outside of the system. Internal fluxes comprise N uptake by palms; legumes and other vegetation; N transfer to the litter and soil via residues from palms such as pruned fronds, removed inflorescences, frond bases, root exudates, roots turnover, and the whole palm at the end of the cycle; legumes and other vegetation such as leaves, stems, roots, and root exudates; and litter and soil N mineralisation. Outputs from the system consist of export of the N in harvested products; volatilisation of NH_3; emissions of nitrate (NO_3^-), ammonium (NH_4^+), and organic N through leaching, runoff, and erosion; emissions of nitrous oxide (N_2O), NO_x, and nitrogen gas (N_2) through nitrification and denitrification.

1.3. N fluxes and variability in plantations: state-of-the-art

We reviewed the knowledge available in the literature for all the input, internal, and output fluxes identified in Figure 1.2.

1.3.1. Inputs

1.3.1.1. Biological N fixation

One input is the biological fixation of N from the atmosphere (flux no. 1 in Figure 1.2), which is carried out by specific bacteria. Three types of fixation were mentioned in oil palm plantations: endophytic fixation inside the tissue of a palm colonized by bacteria (e.g., *Azospirillum*, Reis et al., 2000), non-symbiotic fixation which takes place in the litter or soil (e.g., *Azobacter*, Aisueni, 1987), and symbiotic fixation in the nodules of the roots of legumes (e.g. *Rhizobia*). Regarding endophytic fixation, Amir et al. (2001) reported an uptake of fixed N by palm seedlings in the greenhouse following inoculation with *Azospirillum* bacteria and (Om et al., 2009) reported higher leaf protein and chlorophyll content in 280-day-old oil palm plants inoculated with *Acetobacter*. These results suggested that endophytic fixation is a flux of N input not negligible in oil palm systems, but other studies are necessary to obtain estimates of the magnitude of this flux.

The results regarding non-symbiotic fixation have so far been inconsistent or difficult to replicate in the field (Tinker and Nye, 2000 in Corley and Tinker, 2003). The magnitude of such inputs from non-symbiotic fixation might be similar to those in tropical forest ecosystems, which are on average 3.3–7.8 kg N ha^{-1} yr^{-1}, with a tendency to increase with temperature, soil moisture, and soil N scarcity (Reed et al., 2011).

Finally, for symbiotic N fixation, recent reviews were done on oil palm plantations (Giller and Fairhurst, 2003; Ruiz and López, 2014). Most of the quantifications of N fixation were made in Malaysia in the 1980s and 1990s, mostly with *P. phaseoloides*, and also *M. bracteata*, *Calopogonium pubescens*, and *Calopogonium muconoides*. Two main methods were reported: 15N isotope labelling and deduction from other fluxes with N budget approaches. The estimates of N fixed by legumes were very similar, with an average of 150 kg N ha^{-1} yr^{-1} over the first 5 years (Agamuthu and Broughton, 1985; Broughton, 1977; Zaharah et al., 1986). A more recent work reported amounts of N biologically fixed of 0.3 to 34.2 kg N ha^{-1} in legume covers under oil palm in shoots and litter, but more research would be needed to take into account fixed N in roots (Pipai, 2014). However, Giller and Fairhurst (2003) noted that most estimates of fixation are likely to be underestimates, as they were all based on harvested legume plants without taking into account the biologically fixed N continually added to the litter through residue cycling.

1.3.1.2. N fertilisers

The other main N input is via the application of mineral (flux no. 2 in Figure 1.2) and organic fertilisers (flux no. 3 in Figure 1.2) such as empty fruit bunches and palm oil mill effluent. Several studies were done on fertiliser efficiency and several papers propose fertiliser recommendations, but few data are easily available on actual amounts of mineral and organic fertilisers applied in plantations. The amount of mineral fertiliser applied is very variable and ranges from 48 to 90 kg N ha^{-1} yr^{-1} for immature palms (Banabas, 2007; Choo et al., 2011; Henson, 2004) and from 56 to 206 kg N ha^{-1} yr^{-1} for mature palms (Carcasses, 2004, unpublished data; FAO, 2004; Foster, 2003; Hansen, 2007; United Plantations Berhad, 2006; Wicke et al., 2008). It seems to be a common practice to reduce or even stop fertiliser application over the 2–3 years before felling (Choo et al., 2011), despite evidence that effects of N fertiliser on yield do not always persist from 1 year to the next (Caliman et al., 1994). The amount of fertiliser applied is adapted over time mainly on the basis of foliar N contents. This amount hence depends indirectly on the age of the palms, the soil and climate conditions, and the planting material which influences the potential yield.

The main types of N fertilisers used in oil palm are urea, containing 46 % of N, used everywhere; ammonium sulfate, 21 % of N, mainly used in Southeast Asia; and ammonium nitrate, 34 % of N, used in Africa and South America (Banabas, 2007; Corley and Tinker, 2015; Goh and Härdter, 2003). The main factors governing the choice of fertiliser type are the availability, e.g., related with legal framework; the cost per unit N, including transport; and the local soil and climate conditions. The choice of the type of fertiliser is critical for N cycling processes and there might be trade-offs between these selection factors. For instance, urea is less costly than other types, but it may produce high gaseous losses of NH_3 in dry conditions (Goh et al., 2003). A common practice is to manually apply the fertilisers in an arc around the palm, using calibrated containers to deliver the required amount to each tree. For immature palms, it is applied close to the palm (Caliman et al., 2002; Goh et al., 2003). For mature palms, application practices vary. Applications can be made manually on the weeded circle, on the edge of the weeded circle, and even on the frond piles where more feeding roots are found and fewer losses may occur through runoff (Banabas, 2007). Broadcast mechanical applications by tractors using spreaders with deflectors are now often used where labour is expensive or in short supply (Goh and Härdter, 2003). Aerial application is also a developing practice but mainly used on peat soils and steeply sloping areas where mechanical application is not possible (Caliman et al., 2002). It is a common practice to split the application of N fertilisers in 2 or 3 per year, depending on soil type and rainfall distribution, to reduce the risk of nutrient losses. In immature palms, the splitting is usually increased to 4 to 5 applications per year because of the use of various fertilisers that cannot be systematically combined together (Banabas, 2007; Goh et al., 2003). The optimal frequency is therefore a compromise between the need to meet nutrient demand, labour cost, risk of nutrient losses, and logistical issues for transport and storage (Goh et al., 2003). Fertilisers are normally applied after rainfall when the soil is wet, especially for urea to limit volatilisation, but not during heavy rain periods to avoid losses through leaching, runoff, and erosion. However, there are situations where labour availability is also an important factor which influences the timing of applications (Banabas, 2007).

Empty fruit bunches are commonly returned directly to the plantation from the mill after oil extraction, with an addition of supplementary mineral N (Corley and Tinker, 2015). A plantation yielding 22 t of fresh fruit bunches per hectare would produce empty fruit bunches for only about 10 % of the mature plantation area. This estimate results from the assumptions that the weight of empty fruit bunches produced is 20 to 25 % of the weight of fresh fruit bunches processed (Corley and Tinker, 2015; Redshaw, 2003) and that the application rate of empty fruit bunches is 50 t.ha^{-1} (Redshaw, 2003). Thus, there is not enough empty fruit bunches for the whole plantation area and the preferential areas for spreading are those close to the mill and on relatively flat terrain, for reasons of cost and feasibility (Redshaw, 2003). Soils with low carbon content are also favoured because empty fruit bunch inputs increase their organic matter content (Carcasses, 2004, unpublished data). This uneven distribution of empty fruit bunches creates a spatial heterogeneity of organic N input at the plantation scale.

Under immature palms, empty fruit bunches are applied in a single layer immediately around the palms. Annual applications of 15 to 60 t ha^{-1} are common, and even larger rates of 80 t ha^{-1} may be used on an 18-month or 2-year cycle (Redshaw, 2003). Under mature palms, empty fruit bunches are usually spread in the harvest pathway or in some cases in between palms in the row in order to keep the weeded circle easily accessible for harvest. Application rates of 30 to 60 t ha^{-1} are common (Banabas, 2007; Redshaw, 2003). The empty fruit bunches contain from 0.26 to 0.38 % N in fresh matter (0.65 to 0.94 % in dry matter) (Caliman et al., 2001b; Corley et al., 1971; Gurmit et al., 1999, 1990; Singh, 1999; Singh et al., 1982). Empty fruit bunch application rates vary widely. Hence, the associated inputs of N are also very variable ranging from 39 to 228 kg N ha^{-1} yr^{-1} under immature palms and from 78 to 228 kg N ha^{-1} yr^{-1} under mature palms. In addition to direct application to fields, empty fruit bunches are also used to produce compost, with the advantage of reducing the volume of biomass to transport for field application. Empty fruit bunches are commonly mixed with palm oil mill effluent or urea, and the final N content of compost ranges from 1.5 to 2.7 % in dry matter (Lord et al., 2002; Schuchardt et al., 2002, in Redshaw, 2003; Siregar et al., 2002).

Palm oil mill effluent is often spread in the plantations following treatment in ponds. The treatment ponds are designed to decrease biological oxygen demand. Depending on the treatment, palm oil mill effluent contains from 0.92 to 1.2 kg N t^{-1} (Corcodel et al., 2003; Corley and Tinker, 2015; Redshaw, 2003; Schmidt, 2007). The rate and frequency of application depend mainly on the maximal rate legally allowed and on the application system, but one reported application rate was about 375 t ha^{-1} yr^{-1} split in three applications (Carcasses, 2004, unpublished data). At that rate, the inputs of N generated are rather high at approximately 345 to 450 kg N ha^{-1} yr^{-1}. As for the empty fruit bunches, palm oil mill effluent is spread onto only a small portion of the whole plantation area, dictated by the application system and the distance between the mill and the field. Several application systems are used, such as gravity flow, pipe irrigation with a pump, or application by a tractor with a tanker (Lim, 1999; Redshaw, 2003).

1.3.1.3. N depositions

The N inputs that are the most difficult to quantify and least well known are those from atmospheric (flux no. 4 in Figure 1.2) and sediment depositions. At a global scale, production of Nr, such as NH_3 and NO_x, by lightning and volcanic activity is small (Galloway et al., 1995; Mather et al., 2004), but it may be significant in some oil palm-growing regions. To our knowledge, only measurements of wet deposition have been done in oil palm systems, i.e., for N contained in rain water (possibly including aerosols). Depositions were reported to range from 14.6 to 20 kg N ha^{-1} yr^{-1} in Malaysia (Agamuthu and Broughton, 1985; Chew et al., 1999) and were measured at 8 kg N ha^{-1} yr^{-1} in Brazil (Trebs et al., 2006).

N inputs also result from the deposition of eroded particles of soil coming from upslope of the system studied. This flux concerns mainly lowland areas where the eroded soil from upper areas accumulates and hence it depends on the local topography. To our knowledge, no specific measurements of N deposition have been done to estimate this input flux in palm plantations. Finally, input of N to ecosystems from weathering of rocks is usually considered to be negligible. However, it is possible that it constitutes a significant input if the geology consists of fine sedimentary rocks (Holloway and Dahlgren, 2002), given the intense weathering conditions of oil palm-growing regions.

In summary, N inputs were estimated, in kg N ha^{-1} yr^{-1}, at 150, 0–206, 0–450, 8–20, for biological N fixation, mineral fertiliser, organic fertilisers, and atmospheric deposition, respectively. The results and references are synthesized in Table 1.1.

Table 1.1. Summary of N inputs estimates from the reviewed experimental data

Fluxes	Estimates kg N ha^{-1} yr^{-1} or % of N applied	Variability Ratio max/min	Main controls identified in literature	References
Biological N fixation	Endophytic: needs confirmation	–	–	(Reis et al. 2000); (Amir et al. 2001)
	Non-symbiotic: 3.3–7.8	2.4	Increasing with temperature, soil moisture, soil N scarcity	(Reed et al. 2011) (tropical forest)
	Symbiotic: >150 (average over the first 5 years)	1	N content in soils	(Giller and Fairhurst 2003)[a]; (Ruiz and López 2014)[a]; (Broughton et al. 1977); (Agamuthu and Broughton 1985); (Zaharah et al. 1986)
Fertiliser application	Mineral: 48–90 in 4–5 applications (immature) 56–206 in 2–3 applications (mature) 0 (2–3 years before replanting)	4.3 –	N foliar content (indirect factors: age, soil and climate, planting material)	(Henson 2004) (Banabas 2007) (Choo et al. 2011) (Foster 2003) (FAO 2004) (Carcasses 2004, unpublished data) (Hansen 2005) (United Plantations Berhad 2006) (Wicke et al. 2008)
	Empty fruit bunches: 0 in most fields 39–228 (immature) 78–228 (mature)	– 5.8	Age, distance to the mill, slope, soil fertility	(Banabas 2007) (Redshaw 2003)
	POME: 0 in some plots 345–450	– 1.3	Distance to the mill, laws	(Carcasses 2004, unpublished data)
Atmospheric deposition	8 in Brazil 14.6–20 in Malaysia	2.5	Rainfalls, proximity of industries and volcanic activity	(Agamuthu and Broughton 1985) (Chew et al. 1999) (Trebs et al. 2006)
Sediment deposition	No data available			
Weathering of rocks	No data available			

[a] Review articles that may be helpful for readers to have a quick overview of each flux

1.3.2. Internal fluxes

1.3.2.1. N uptake

A major internal flux is the N uptake from soil by palms, legume cover crops, and other plants, mainly as inorganic N (NH_4^+ and NO_3^-) (flux no. 5 in Figure 1.2). Uptake by plants other than palms and legumes may be significant because it is known to compete with palms and affect fresh fruit bunches production (Corley and Tinker, 2015). However, to our knowledge, no measurements of such uptake terms are available. For the legume cover, Agamuthu and Broughton (1985) estimated that 149 kg N ha^{-1} yr^{-1} was taken up from the soil over the first 3 years of the oil palm cycle. For palms, two main reviews have reported estimates of N uptake (Goh and Härdter, 2003; Xaviar, 2000), with most of the work done on Dura palms in Malaysia and Nigeria between the 1960s and 1990s. Other work was done more recently on Tenera palms in Sumatra (Foster and Parabowo, 2003). In all cases, estimates reported are not direct measurements of N uptake by roots but indirect estimates inferred from a nutrient budget approach. Thus, over the whole growth cycle, the net N uptake is considered to be equal to the

N immobilised in the palm, above- and belowground biomass; the N released in palm residues such as pruned fronds, removed inflorescences, frond bases, dead roots; and the N exported in harvested bunches.

The results reported by Xaviar (2000) and Goh and Härdter (2003) showed that uptake rate mainly depends on the age of the palms, with estimates of 40 kg N ha^{-1} yr^{-1} for 0 to 3-year-old palms (Tan, 1977, 1976) and ranging from 114 to 267 kg N ha^{-1} yr^{-1} for 3 to 9-year-old palms (Henson, 1999; Ng et al., 1999, 1968; Ng, 1977; Ng and Thamboo, 1967; Pushparajah and Chew, 1998; Tan, 1977, 1976). However, recent work has resulted in considerably higher estimates of uptake by Tenera palms, up to 272 kg N ha^{-1} yr^{-1} in 10-year-old palms and even 380 kg N ha^{-1} yr^{-1} in adult palms (Foster and Parabowo, 2003). Both studies considered only above-ground biomass in the budgets. This difference could be explained by the higher yields now obtained with current genotypes (Goh and Härdter, 2003). Recent measurements in trials in Indonesia showed uptake rates by above- g round biomass ranging from about 221 to 272 kg N ha^{-1} yr^{-1}, depending on the planting material. In addition to genotype, variability of uptake seems to be linked with soil and climate conditions. For example, uptake was estimated at 149 kg N ha^{-1} yr^{-1} in Nigerian conditions with a production of 9.7 t of fresh fruit bunches ha^{-1} yr^{-1} (Tinker and Smilde, 1963) and at 191 kg N ha^{-1} yr^{-1} in Malaysian conditions with a production of 24 t of fresh fruit bunches ha^{-1} yr^{-1} (Ng et al., 1968; Ng and Thamboo, 1967).

1.3.2.2. N from plant residues to the litter

Another major internal flux is the N contained in plant residues, which goes from the plants to the litter (flux no. 6 in Figure 1.2). Residues come from the palms, legume cover crops, and other vegetation. For plants other than palms and legumes, to our knowledge no data is available. For legume cover, Agamuthu and Broughton (1985) estimated an amount of 123 kg N ha^{-1} yr^{-1} going from the living plants to the litter over the first 3 years under oil palm and Pushparajah (1981) estimated an amount of about 120–160 kg N ha^{-1} yr^{-1} over the first to the third years and less than 40 kg N ha^{-1} yr^{-1} over the fourth to the seventh years under rubber trees. In both cases, root turnover was not taken into account. For palms, several residues are distinguished: those produced throughout the crop cycle, mostly in the mature phase such as pruned fronds, removed inflorescences, frond bases, root exudates, and dead roots and those produced only once before replanting, i.e., the whole palm when it is felled.

For pruned fronds, the flux of N depends on the quantity of fronds pruned and their N content. Frond production rate stabilizes after 8–12 years at about 20–24 fronds yr^{-1} (Corley and Tinker, 2015). Several publications estimated the annual flux of N going to the litter, with values ranging from 67 to 131 kg N ha^{-1} yr^{-1} (Carcasses, 2004, unpublished data; Redshaw, 2003; Schmidt, 2007; Turner and Gillbanks, 2003). Therefore, this flux is uncertain and the reasons for the variability are not well defined; they may depend on the soil, climate, and planting material which influence frond production and frond weight and on the methods of measurement of N content. For male inflorescences, the flux of N going to the litter has been ignored in most N cycling studies. We found only two estimates, being 6 and 11.2 kg N ha^{-1} yr^{-1} (Carcasses, 2004, unpublished data; Turner and Gillbanks, 2003, respectively). These estimates suggest that this flux is lower than the uncertainty of the concomitant N flux via pruned fronds. For frond bases, which rot and fall naturally from the trunk, the only estimate we found was of 3 kg N ha^{-1} yr^{-1} going to the litter (Carcasses, 2004, unpublished data).

For root exudates and transfers into the soil via Mycorrhizae, no estimate of N flux is available to our knowledge. Roots themselves are continuously dying and being replaced by new ones. This death of roots constitutes a flux of N going from the palm to the litter pool and depends on the rate of root turnover and on the N content of roots when they die. Root turnover is very difficult to measure. Corley and Tinker (2003) reviewed several methods to estimate it such as deduction from measurements of soil carbon balance or measurements of the growth of roots after extracting soil cores and refilling the holes with root-free soil. Estimates of average turnover ranged from 1.03 to 11.5 t of dry matter ha^{-1} yr^{-1} for adult palms (Dufrêne, 1989; Henson and Chai, 1997; Jourdan et al., 2003; Lamade et al., 1996), and turnover was reported to be zero for 3–4-year-old palms (Henson and Chai, 1997). Thus, with an average root N content of 0.32 % of dry matter measured by Ng et al. (1968) in 8–15-year-old palms in Malaysia, the average N flux from root turnover would range from 3.3 to 36.8 kg N ha^{-1} yr^{-1}. Carcasses (2004, unpublished data) also proposed the value of 7.5 kg N ha^{-1} yr^{-1} based on data from Henson and Chai (1997). Therefore, this flux is highly uncertain. Moreover, Corley and Tinker (2003) noted that root turnover measured in Malaysia was much lower than that in Africa, which could be explained by the death of a larger part of the root system in Africa during the annual dry season (Forde, 1972).

Finally, the estimate of the N contained in the felled palms must take into account above- and below-ground biomasses. Several publications estimated the weight of dry matter of above-ground biomass of old palms at felling and the N content of their different tissues, i.e., trunk, fronds, inflorescences, and frond bases (see for e.g., Corley and Tinker, 2003). Some of them reviewed available data to estimate the total N content of palms at felling and reported values ranging from 400 to 577 kg N ha^{-1} (Khalid et al., 1999a; Redshaw, 2003; Schmidt, 2007). Fewer studies estimated the below-ground dry matter of palms, but Khalid et al. (1999b) reported a value of 65 kg N ha^{-1}. Therefore, the total N contained in palms at felling and going to the litter has been estimated at 465 to 642 kg N ha^{-1}.

1.3.2.3. N from the litter to the soil

Another important internal flux is the mineralisation or incorporation of N from the litter to the soil (flux no. 7 in Figure 1.2). The litter is composed mostly of plant residues but also contains active microorganisms and fauna. To our knowledge, no data is available regarding the decomposition of residues from plants other than oil palm or legumes in the oil palm system.

For legume litter decomposition, Chiu (2004) measured losses of about 70 % of dry matter after about 2–3 months in leaves and stems of *P. phaseoloides* and *M. bracteata*. But the net N release follows a slower dynamic due to the immobilisation of the N by the microbial fauna and flora involved in decomposition and the partial uptake of the N released by growing legumes. For instance, Vesterager et al. (1995) measured in a pot experiment with *P. phaseoloides* a net release of about 25 % of the N of the legume litter after 2 months, using a 15N labelling technique. In an oil palm field, Turner and Gillbanks (2003) reported that net N release from legume litter occurred between the 24^{th} and the 30th months after planting.

For palm residues, no data was found for frond bases. For pruned fronds and felled and chipped trunks, Khalid et al. (2000) observed a loss of 50 % of dry matter after 6–8 months and a total decomposition after 12–18 months. For roots, Khalid et al. (2000) observed a loss of 50 % of dry matter after 10 months and a total decomposition after about 25 months. These decomposition rates were considered as approximately linear by Khalid et al. (2000), but Moradi et al. (2014) observed an exponential decrease with a faster decomposition over the first 5 months. Khalid et al. (2000) identified rainfall distribution as the main climatic factor controlling the rate of decomposition and observed that shredded residues decompose faster than un-shredded residues. For empty fruit bunches, when mineral N fertiliser was also added, losses of 50 % of dry matter were reported after 2–3 months (Lim and Zaharah, 2000; Rosenani and Hoe, 1996; Turner and Gillbanks, 2003), and total decomposition occurred within 6 to 12 months (Caliman et al., 2001b; Henson, 2004; Rosenani and Hoe, 1996). The decrease followed an exponential dynamic (Lim and Zaharah, 2000); the decomposition was faster when empty fruit bunches were applied in one layer than in two layers (Lim and Zaharah, 2000) and was slower without addition of mineral N (Caliman et al., 2001b). However, for all of these palm residues, the dynamics of N release is more complex than the dynamics of decomposition due to immobilisation by the microbial fauna and flora involved in decomposition. For instance, for trunks, Kee (2004) observed that the net release of N occurred only 12 months after felling. For empty fruit bunches, Zaharah and Lim (2000) observed a complete N immobilisation over their experimental period of about 8 months, and Caliman et al. (2001b) reported a N release of only 50 % at about 6 months, without adding mineral N.

The last internal flux considered is the mineralisation of soil organic N (flux no. 8 in Figure 1.2). Only few data are available, and they involve various soil depths, which hampers comparison. Schroth et al. (2000) estimated the net mineralisation in the top 10 cm of a central Amazonian upland soil at approximately 157 kg N ha^{-1} yr^{-1} after 15 years of oil palm production without any N fertiliser inputs. Khalid et al. (1999c) estimated the N mineralisation after replanting in Malaysia at about 312 kg N ha^{-1} yr^{-1} in fields without residues from the previous cycle except dead roots and at about 421 kg N ha^{-1} yr^{-1} in fields where the palm residues from the previous cycle were left on the soil. Finally, Allen et al. (2015) estimated the N mineralisation in the top 5 cm of soil in Sumatra at about 920 kg N ha^{-1} yr^{-1} in loam Acrisol and up to 1528 kg N ha^{-1} yr^{-1} in clay Acrisol. However, those measurements were done under more than 7-year-old oil palms established after logging, clearing, and burning of either forest or jungle rubber.

In summary, internal fluxes were estimated, in kg N ha^{-1} yr^{-1}, at 149, 40–380, 0–160, 76–182, and 157–1528, for legume uptake, oil palm uptake, legume residues decomposition, oil palm residues decomposition, and soil N mineralisation, and 465–642 for the decomposition of the felled palm at the end of the cycle. The results and references are synthesized in Table 1.2.

Table 1.2. Summary of N internal inputs estimates from the reviewed experimental

Fluxes	Estimates kg N ha^{-1} yr^{-1} or % of N applied	Variability Ratio max/min	Main controls identified in literature	References
Uptake by other plants	No data available			
Uptake by legume cover	149 (1–3 years)	–	–	(Agamuthu and Broughton 1985)
Uptake by palms	40 (palms of 0–3 years) 114–380 (palms of more than 3 years)	9.5	Age, soil and climate, genotype	(Xaviar 2000)[a]; (Goh et al. 2003)[a]; (Tan 1976) (Tan 1977) (Ng 1977) (Pushparajah and Chew 1998) (Henson 1999); (Ng et al. 1999); (Ng and Thamboo 1967); (Ng et al. 1968); (Foster and Parabowo 2003)
Transfer to the litter through plant residues	Legume residues: 120–160 (1–3 years) <40 (4–7 years)	1.3 –	–	(Agamuthu and Broughton 1985); (Pushparajah 1981)
	Pruned fronds: 67–131	2.1	Soil and climate, planting material	(Corley and Tinker 2003); (Redshaw 2003); (Carcasses 2004, unpublished data); (Turner and Gillbanks 2003); (Schmidt 2007)
	Male inflorescences: 6–11.2	1.8	–	(Carcasses 2004, unpublished data); (Turner and Gillbanks 2003)
	Frond bases: 3	–	–	(Carcasses 2004, unpublished data)
	Root exudates	No data available		
	Roots turnover: 0 (palms of 3–4 years) 3.3–36.8 (adult palms)	– 11.2	Age, climate (the dry season increases roots death and turnover)	(Corley and Tinker 2003)[a] (Dufrêne 1989) (Lamade et al. 1996); (Henson and Chai 1997); (Jourdan et al. 2003); (Carcasses 2004, unpublished data)
	Whole palm: 400–577 (above-ground) 65 (below-ground)	 1.4 –	–	Khalid et al. 1999a, b; (Redshaw 2003);(Schmidt 2007)
Litter N mineralisation	Legume: Net release of N between the 24-30th months	–	–	(Turner and Gillbanks 2003)
	Sawn trunks: Net release of N between 12–18 months	–	Rainfall distribution, shredding	(Khalid et al. 2000)
	Pruned fronds: Total decomposition after 12–18 months	–	Rainfall distribution	(Khalid et al. 2000)
	Roots: Total decomposition after 25 months	–	Rainfall distribution	(Khalid et al. 2000)
	Empty fruit bunches: Total decomposition after 6–12 months	–	Number of layers, adding mineral fertiliser	(Rosenani and Hoe 1996) (Henson 2004) (Caliman et al. 2001b)
Soil N mineralisation	157–1528	9.7	Fertiliser application, presence of residues, soil type	(Schroth et al. 2000) (Khalid et al. 1999c) (Allen et al. 2015)

[a] Review articles that may be helpful for readers to have a quick overview of each flux

1.3.3. Outputs

1.3.3.1. N exported in fresh fruit bunches

A major output is the N contained in fresh fruit bunches and exported during harvest (flux no. 9 in Figure 1.2). The N content of the fresh fruit bunches was reported to be around 2.89–

2.94 kg N t^{-1} of fresh fruit bunches in fresh weight (Hartley, 1988; Ng et al., 1968; Ng and Thamboo, 1967; in Corley and Tinker, 2003 and Goh et al., 2003) but some higher values were also reported, as much as 6.4 kg N t^{-1} fresh fruit bunches (Ng et al., 1999). In general, the fresh fruit bunches production starts at about 2–3 years of age and increases rapidly until levelling off at yields around 10–34 t of fresh fruit bunches ha^{-1} yr^{-1} after the tenth year (Tinker, 1976; Corley and Tinker 2003). Some very high yields were also reported at around 40 t of fresh fruit bunches ha^{-1} yr^{-1} (Kee et al. 1998). Thus, the yield depends on the age of the palm, but it also differs with the type of planting material, soil, and climate conditions. For instance, yields were reported to be lower in Nigeria (9.6 t FBB ha^{-1} yr^{-1}) than in Malaysia (24 t FBB ha^{-1} yr^{-1}) (Tinker, 1976). Therefore, for adult palms more than 10 years old producing 10 to 34 t of fresh fruit bunches ha^{-1} yr^{-1}, we deduced an export of N through harvest of around 30 to 100 kg N ha^{-1} yr^{-1}, consistent with other estimates done for Nigeria (Tinker and Smilde, 1963) and Malaysia (Ng et al., 1968; Ng and Thamboo, 1967).

1.3.3.2. N leaching

Soluble forms of N (NO_3^- and NH_4^+) can be lost by leaching out of the root zone (flux no. 10 in Figure 1.2). Tropical soils may have significant anion exchange capacity and thus retain NO_3^- (Rasiah et al., 2003), but such anion exchange capacity is usually not significant within the root zone. As most of the oil palm root activity is located within 1 m depth (Ng et al., 2003; Corley and Tinker 2003) and rainfalls are high in the tropics, this suggests a high potential risk of nutrient leaching under oil palm.

Many studies investigated the losses of N through leaching in plantations and were reviewed by Corley and Tinker (2003) and Comte et al. (2012). Most of the research was done in the 1980s and 1990s in Malaysia. Different plot-scale methods were used, such as lysimetric measurements, suction cup, and soil core sampling, and some studies were done at a larger scale with catchment sampling (e.g., Ah Tung et al., 2009). The age of the palms is one of the main control variables which can be identified. The measured values varied over a wide range, from 1 to 34 % of N applied (Ah Tung et al., 2009; Chang and Abas, 1986; Foong, 1993; Foong et al., 1983; Henson, 1999; Ng et al., 1999; Omoti et al., 1983). Of the fertiliser N applied, 10.9 to 26.5 % was lost with palms less than 4 years old (Foong et al. 1983; Foong 1993) versus 1 to 4.8 % for palms older than 5 years (Foong et al. 1983; Foong 1993; Ah Tung et al. 2009). Only Omoti et al. (1983) reported losses of 34 % of N applied in Nigeria for palms from 4 to 22 years old.

In the conditions studied and despite very large variability, measurements hence showed that high losses through leaching are restricted to the first years of the palms, when the root systems are not fully developed and N inputs from decomposing plant residues are large. Moreover, fertiliser placement may have a significant effect on leaching because of the spatial variability of application rate, rainfall as through fall and stem flow, and N uptake (Banabas et al., 2008; Schroth et al., 2000). However, there is little information about the spatial distribution of NO_3^- leaching within the plantation.

1.3.3.3. N losses through runoff and erosion

N can also be lost through runoff (flux no. 11 in Figure 1.2) and erosion (flux no. 12 in Figure 1.2) as a solute (NO_3^- and NH_4^+) or as eroded particles of soil containing N. Corley and Tinker (2003) and Comte et al. (2012) reviewed measurements of N losses through runoff and erosion from oil palm plantations. Research was done in Malaysia from the 1970s to the 1990s (Kee and Chew, 1996; Maena et al., 1979) and more recently in Papua New Guinea (Banabas et al. 2008) and Sumatra (Sionita et al., 2014). The main variables studied were the effect of soil type, slope, and spatial heterogeneity resulting from management practices, such as soil cover management. The variability of reported values is less than for leaching, ranging from 2 to 15.6 % of N applied lost through runoff, and from 0.5 to 6.2 % of N applied lost through erosion (Kee and Chew, 1996; Maena et al., 1979). Spatial heterogeneity of soil cover seems to have an important effect on losses. Maena et al. (1979) reported losses through runoff of 2 % of N applied in frond piles, but 16 % of that applied in the harvest pathway. Sionita et al. (2014) showed that 10 to 37 t of soil ha^{-1} yr^{-1} were lost through erosion of bare soil, depending on slope, but this reduced to 2 to 4 t of soil ha^{-1} yr^{-1} with a standard vegetation cover and the same slopes.

These results indicated that soil cover has a significant effect on both runoff and erosion under oil palm. However, data is lacking concerning the transition between the felling of palms and the early development of young palms when the soil is not yet covered by the legume. Finally, it can be noted that in a given situation, there is a balance between runoff/erosion losses and leaching losses, in which soil permeability plays an important role. For instance, in Papua New Guinea, Banabas et al. 2008 estimated losses through leaching at about 37–103 kg N ha^{-1} yr^{-1} and negligible runoff, even with a high rainfall of 3000 mm yr^{-1}. The authors suggested that the high permeability of volcanic ash soils could favour leaching over runoff.

1.3.3.4. N gaseous losses

A potentially important gaseous output is the volatilisation of NH_3 (flux no. 13 in Figure 1.2), which can occur directly from the leaves and from soil after fertiliser application, especially urea. Regarding emissions from palm fronds and other vegetation in the system, to our knowledge, no measurements have been reported. For emissions from soil following fertiliser application, several studies were done into urea efficiency under oil palm (e.g. Tarmizi et al., 1993) but only a few measured NH_3 volatilisation. Most of them were done in Malaysia between the 1960s and the 1980s, and they often compared urea and ammonium sulphate, the most commonly used fertilisers in oil palm plantations. Two studies were done in Malaysia using different fertiliser rates (125 and 250 kg N ha^{-1} yr^{-1}) and on different soil types. Reported volatilisation rates from urea ranged from 11.2 to 42 % of N applied (14 to 105 kg N ha^{-1} yr^{-1}), and volatilisation from ammonium sulphate ranged from 0.1 to 0.4 % of N applied (0.1 to 0.5 kg N ha^{-1} yr^{-1}) (Chan and Chew, 1984; Sinasamy et al., 1982). Another experiment was carried out in Peru by Bouchet (2003, unpublished data) with a lower fertilisation rate (85 kg N ha^{-1} yr^{-1}). The study found that 4 to 16 % of N applied in urea was volatilised (3.4 to 13.6 kg N ha^{-1} yr^{-1}), with higher volatilisation under vegetation cover and no volatilisation from ammonium sulphate. Therefore, given the few studies done and the high variability of the results, the magnitude of losses and the reasons for variations are uncertain. For urea, the highest values were in sandy loam soils with high application rates, and for ammonium sulphate the highest values were in clay soils with high application rates, but they did not exceed 1 % of N applied.

Gaseous emissions of N_2O, NO_x, and N_2 are produced by soil microorganisms, principally through nitrification and denitrification (flux no. 14 in Figure 1.2). Tropical soils are considered as important sources of N_2O due to rapid N cycling (Duxbury and Mosier, 1993). As N_2O and NO_x emissions are difficult to measure and have a very high variability, very few measurements were carried out in oil palm (Corley and Tinker 2003; Banabas et al. 2008; Nelson et al., 2010). Maybe due to the recent growing concern about greenhouse gases emissions, most of the measurements available were done in the 2000s and most of them involved peatlands (e.g. Melling et al., 2007). To our knowledge, only two trials were carried out under oil palm on mineral soils. They focused on N_2O emissions and showed very variable results whose average values ranged from 0.01 to 7.3 kg N ha^{-1} yr^{-1}. Emissions tended to decrease with the age of palms and to be higher in poorly drained soils. Potential N_2O emissions are high in poorly drained soils due to limited N uptake by plants and conditions that are conducive for denitrification.

The first study showed N_2O emissions ranging from 0.01 to 2.5 kg N ha^{-1} yr^{-1} in Indonesia (Ishizuka et al., 2005). The highest values were reported for young palms while the lowest were reported for old palms. Ishizuka suggested that the high emissions under young palms could result from the low uptake of young palms being concomitant with the application of fertiliser and the fixation of N by the legume cover. Conversely, the low emissions under old palms could result from the higher N uptake by palms and the absence of legume cover. The results also indicated that in this area, the N_2O emissions were mainly determined by soil moisture. The second study showed emissions ranging from 1.36 to 7.3 kg N ha^{-1} yr^{-1} on two different soil types in Papua New Guinea (Banabas 2007). Banabas explained the highest emissions as being related to poor drainage of the soil.

Despite the limited number of measurements in oil palm plantations on mineral soils and the high variability of results, emissions seem to be higher over the first years of the palms. In addition, they seem to be of the same order of magnitude as those under oil palm in peatlands, e.g., average of 1.2 kg N ha^{-1} yr^{-1} (Melling et al. 2007); under other crops in tropical conditions, e.g., average of 1.2 kg N ha^{-1} yr^{-1} (Bouwman et al., 2002a); and under tropical forest, e.g., average of 3 kg N ha^{-1} yr^{-1} (Keller et al., 1986). However, data is lacking on the effect of spatial heterogeneity of N_2O emission drivers, such as fertiliser application, soil water content, and organic matter content. Moreover, no measurements of NO_x and N_2 emissions have been reported for oil palm.

In summary, N outputs were estimated at 0–100 and 0.01– 7.3 kg N ha^{-1} yr^{-1} through harvest and N_2O emissions, respectively, and in percentage of mineral N applied, 1–34, 2–15.6, 0.5–6.2, and 0.1–42, for leaching, runoff, erosion, and NH_3 volatilisation, respectively. The largest losses are volatilisation of NH_3 and leaching of NO_3^-. The results and references are synthesized in Table 1.3.

Table 1.3. Summary of N outputs estimates from the reviewed experimental data

Fluxes	Estimates kg N ha^{-1} yr^{-1} or % of N applied	Variability Ratio max/min	Main controls identified in literature	References
Export in fresh fruit bunches	0 (0–2 years) 30–100 (>10 years)	– 3.3	Age of the palms, planting material, soil, and climate conditions	(Tinker 1976); (Corley and Tinker 2003)
Leaching	10.9 to 34 % (0–4 years) 1 to 4.8 % (>5 years)	34	Palms age, spatial repartition of fertiliser placement, rainfalls, and N uptake rate	(Corley and Tinker 2003)[a] (Comte et al. 2012)[a]; (Omoti et al. 1983); (Foong et al. 1983);(Chang and Abas 1986); (Foong 1993); (Ng et al. 1999); (Henson 1999); (Ah Tung et al. 2009)
Runoff and erosion	2 to 15.6 % (runoff) 0.5 to 6.2 % (erosion)	7.8 (runoff) 12.4 (erosion)	Soil permeability, slope, spatial heterogeneity (soil cover)	(Corley and Tinker 2003)[a] (Comte et al. 2012)[a]; (Maena et al. 1979) (Kee and Chew 1996) (Banabas et al. 2008) (Sionita et al., 2014)
NH_3 volatilisation	4–42 % (urea) 0.1–0.4 % (ammonium sulphate)	420	Fertiliser type, soil texture, soil cover	(Sinasamy et al. 1982) (Chan and Chew 1984); (Bouchet 2003)
NH_3 emissions from fronds and vegetation cover	No data available			
N_2O emissions	0.01 to 7.3	730	Soil moisture, soil drainage, palms age	(Ishizuka et al. 2005) Banabas (2007)
NO_x, N_2 emissions	No data available			

[a] Review articles that may be helpful for readers to have a quick overview of each flux

1.4. Important fluxes and critical conditions for N losses

1.4.1. The most important and most uncertain fluxes

Among the characterised fluxes, some are continuous, such as biological N fixation, N uptake, transfer of residues from plant to litter, and some are discontinuous. The discontinuous fluxes may occur one or several times per month, such as for export of fresh fruit bunches, pruning of fronds, leaching, runoff, and erosion during rainfall events; one or several times per year, such as for mineral and organic fertiliser application, NH_3 volatilisation after fertiliser application; or only once in the cycle, as for the felling of the whole palm (Figure 1.3). Therefore, when performing an N budget analysis in oil palm, the choice of the timescale influences the precision of the mechanisms taken into account. Moreover, the magnitude of some fluxes differs between the crop phases, e.g., mineral fertiliser application rate is about 48–90 kg N ha^{-1} yr^{-1} on immature palms, 56–206 kg N ha^{-1} yr^{-1} on mature palms, and may be zero on the oldest palms. Some fluxes occur only in one phase, such as the fluxes related to legume cover growth, which occur mainly over the first 5–7 years after planting. Thus, the crop phase should be taken into account to obtain a precise budget analysis.

The magnitude of some fluxes varies within fields because of the spatial heterogeneity of practices. For example, pruned fronds are placed in the windrows, and mineral fertiliser input depends on the method of fertiliser application but are usually spread around the weeded circle when applied manually. The effects of this spatially differentiated management on fluxes were evidenced in particular for runoff and erosion (Maena et al. 1979; Sionita et al., 2014). Similar effects might be expected for leaching and N_2O/NO_x emissions but data is lacking. Moreover, the value of some fluxes varies between fields of the same plantation. This is the case for the application of empty fruit bunches, which is applied to only about 10 % of the mature area (Redshaw 2003). Thus, consideration of spatial heterogeneity of practices between and within fields is useful to obtain a precise budget analysis, but more research is needed for some of the fluxes.

On average, the largest N fluxes, of about 160–640 kg N ha^{-1} yr^{-1}, are the felling of palms at the end of the cycle, application of palm oil mill effluent, and soil N mineralisation. The next largest fluxes, about 60–270 kg N ha^{-1} yr^{-1}, are uptake by the palms, application of empty fruit bunches, mineral fertiliser application, transfer of legume residues to litter, biological N fixation, and transfer of pruned fronds to litter. Although some of those fluxes occur only in some fields, e.g., palm oil mill effluent, only in one crop phase, e.g., biological N fixation and residues of legumes or only once in the cycle, e.g., felling of palms, we can note that the largest fluxes are internal fluxes. Moreover, there is a delay of about 6–30 months in the release of N from one pool to the next through microbial decomposition, e.g., for empty fruit bunches, pruned fronds, legume residues, whole palm, and dead roots. Therefore, internal fluxes and their dynamics may have important impacts on the availability of N for uptake or losses to the surrounding environment.

The most uncertain and least documented fluxes are N losses: N_2O, NO_x, N_2 emissions, leaching, volatilisation, and runoff. These high uncertainties are partly due to the difficulty of measuring these fluxes which are gaseous emissions or below-ground flux. Studies also suggested that their variability was related to soil biogeochemical properties and may therefore be significantly controlled by the spatial heterogeneity of soil properties and soil cover. An appraisal of the magnitude and uncertainty of N losses are presented in Figure 1.4.

In summary, the largest fluxes are internal fluxes, and the most uncertain and least documented fluxes are N losses: N_2O, NO_x, N_2 emissions, leaching, volatilisation, and runoff. When compiling the N budget of oil palm systems, it is hence important to quantify the size and uncertainty of the most important fluxes, especially the internal fluxes. To reduce uncertainty, it is also important to characterise soil conditions and practices that induce high spatial variability in fluxes and understand the interactions between fluxes and between fluxes and management practices. In the following section, we focus on the main losses and their determinants.

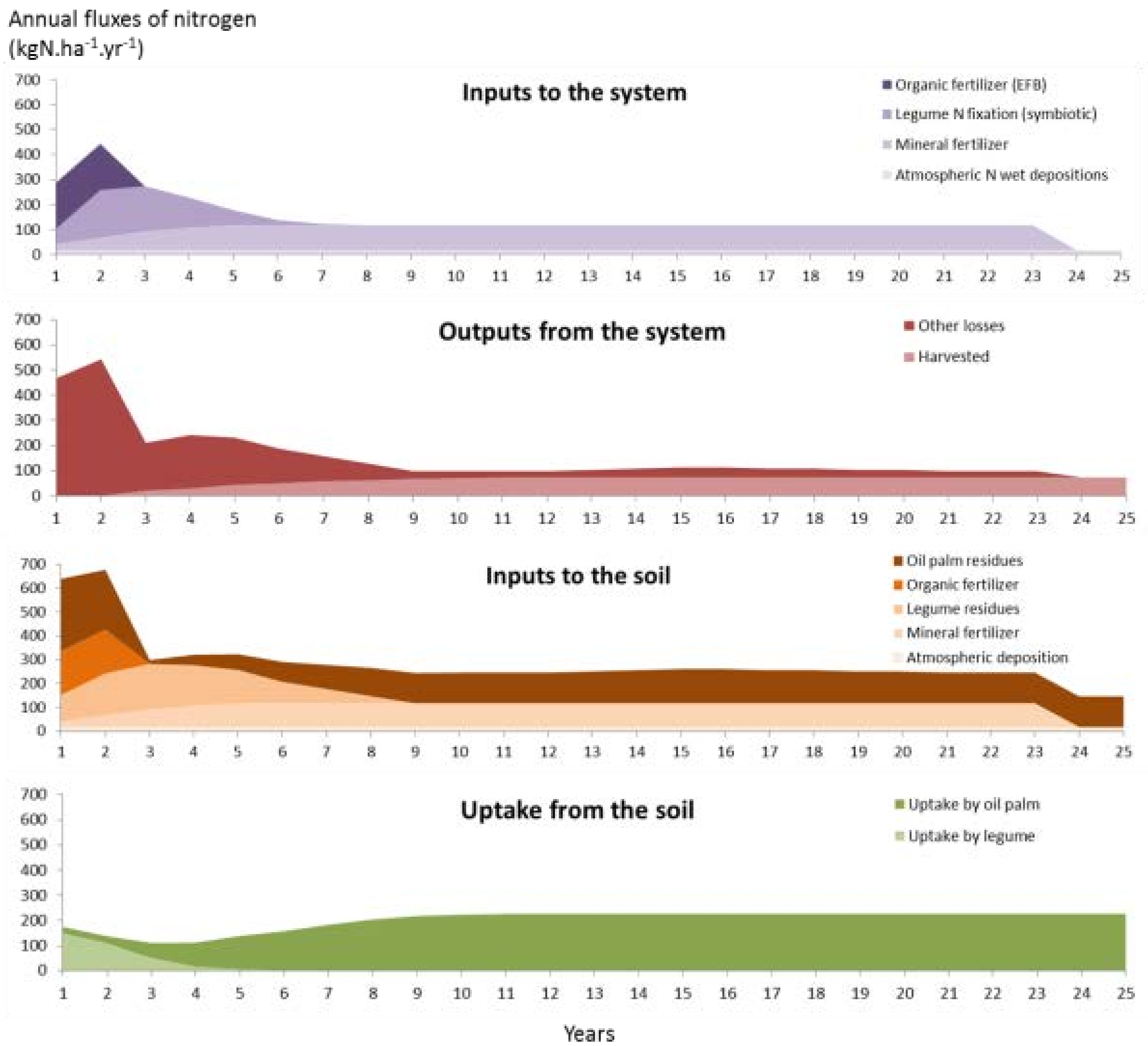

Figure 1.3. Summary of the temporal patterns of N fluxes in the oil palm plantation.

N fluxes vary over the crop cycle, and N budget must take into account this temporal variability to be precise. Annual fluxes are estimated based on mean values from Table 1.1 and assuming a yield of 25 t of fresh fruit bunches ha^{-1} yr^{-1} after 10 years, applications of 100 kg N ha^{-1} yr^{-1} of mineral N fertiliser (75 % ammonium sulphate, 25 %urea), and of 184 kg N ha^{-1} yr^{-1} of empty fruit bunches spread the first 2 years. The losses are estimated assuming that the nitrogen which entered the system is either exported through harvest or lost (no change in the N content of the soil over the whole cycle).

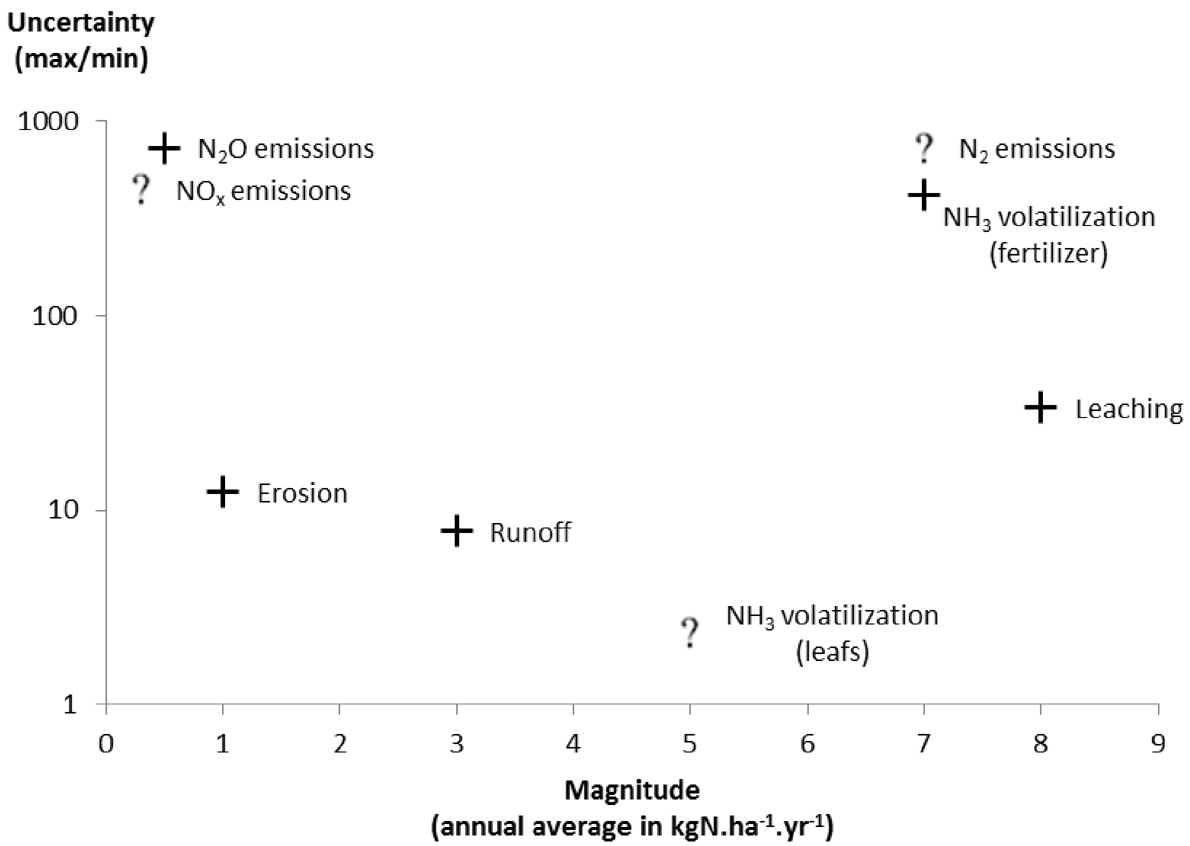

Figure 1.4. Uncertainty and magnitude of the N losses.

NH_3 volatilisation from fertiliser and leaching have high magnitude and high uncertainty. N_2O emissions have low magnitude but high variability. Uncertainties are calculated as the max/min ratio (logarithmic scale), and magnitudes are annual averages in kg N ha^{-1} yr^{-1} estimated assuming an application of 100 kg N ha^{-1} yr^{-1} of mineral N fertiliser (see Tables 1.1, 1.2, and 1.3 for sources). When no quantified estimates were available, approximations of uncertainty and magnitudes were done and are represented with a question mark. Uncertainty and magnitude of NO_x and N_2 were considered to be comparable to N_2O, except for the magnitude of N_2 which must be higher. Uncertainty and magnitude of NH_3 volatilisation from leaves were considered to be comparable to NH_3 volatilisation from annual crops (Andersen et al., 2001).

1.4.2. Critical conditions for N losses

From the literature analysis, we deduced the main conditions that may lead to large N losses. In terms of timing, the immature phase appears to be critical. In terms of spatial heterogeneity, critical conditions occur mostly in areas with low or no soil cover and in areas where high amounts of organic and mineral fertilisers are applied (Table 1.4).

During the immature phase, critical concomitant conditions may generate intense short-term losses. Disturbance of vegetation, litter, and soil during felling of old palms, sowing of legumes, and planting of new palms have important impacts on soil physical properties. This may produce a peak of losses through runoff, erosion, and N_2O/NO_x emissions, as measurements suggested. However, some studies reported less leaching in oil palm under legume cover compared with other vegetation covers (Agamuthu and Broughton 1985). This would support the idea that rather than enhancing N losses, growing legume cover might act as a regulator of the N content of the soil, immobilising N when it is in sufficient supply in the soil and fixing N when it is lacking in the soil. Indeed, some studies showed that N fixation by legumes was significantly reduced when NO_3^- concentration in the soil was high (Pipai, 2014). As N losses during the immature phase are quite intense, their overall impact on the global plantation budget may be significant despite the short duration of the immature phase compared to the whole crop cycle.

Localization of critical conditions in particular parts of the plantations may generate large losses in small areas, which may become significant over the whole cycle. During the mature phase, inputs of mineral and organic fertilisers and palm residues are not applied evenly across the plantations. The high amounts of carbon and N they contain are applied over small areas, which may enhance the N cycling and might therefore generate hotspots of N losses in these areas. Large losses may occur in areas with little or no cover due to a lack of surface protection, e.g., in weeded circle and harvest pathway, as measurements showed. Moreover, the soil compaction of these areas may enhance N_2O/NO_x emissions (Ball et al., 2008; Bessou et al., 2010). The combination of low surface cover with low root activity under the harvest pathway (Nelson et al., 2006) may favour losses through leaching in this area. But more research is needed to confirm it.

Table 1.4. Spatio-temporal likelihood of significant N losses identified from the literature.

Risks of losses due to critical conditions occurring in a same period or in a same area are represented in dark grey (high risk), light grey (medium risk), and white (low risk); potential risks of losses for which data is lacking are marked with question mark, and important factors influencing the risks are given. BNF biological nitrogen fixation

	At replanting	Immature (1 to 3 years)	Mature (4 to 25 years)		
			Circle	Pathway	Windrows
NH_3 volatilisation	No fertiliser application	Lower rate of fertiliser	Higher rate of fertiliser	No fertiliser application (if manual)	If fertiliser is spread on windrows
Leaching	High inputs (trunks) / no uptake	High inputs (fertilisation, BNF) / low oil palm / high BNF uptake	? High inputs, high stemflow / high root density	Compacted soil, no fertiliser application (if manual)	? High N content, high throughfall, high porosity / high root density
Runoff, erosion	No cover	Important soil cover	No cover, high stemflow, compacted soil	No cover, compacted soil, high throughfall	Important soil cover, high porosity / high throughfall
N_2O, NO_x, N_2 emissions	? High organic matter content, N content (trunks)	High inputs (fertilisation, BNF) / low uptake	? High stemflow, high compaction, high N content / high uptake	? High compaction, high throughfall	? High water content, high organic matter content, high N content

1.5. Discussion and key research needs

Determination of N losses and their impacts is complex, as reactive N undergoes and is influenced by many biological transformations and is widely dispersed by hydrologic and atmospheric transport (Galloway et al., 2003). These difficulties are acute in the case of perennial cropping systems given the long crop cycle and spatial and temporal patterns. Interactions in time and space additional to those discussed in this paper are also likely. For example, Agamuthu and Broughton (1985) suggested that the presence of legume cover during the immature phase could stimulate the rooting of palms through competition and hence reduce leaching during the mature phase. Schroth et al. (2000) noted that fertiliser placement may influence the roots' lateral distribution. Thus, broadcast fertiliser application at young age may favour a more extensive lateral root development and therefore a more efficient uptake in the inter-tree space during the mature phase (Foster and Dolmat, 1986). Finally, Dubos and Flori (2014) recently reported that the response time of the soil-plant system to practices may be of several years.

We reviewed all studies on experiments and N flux analysis in oil palm plantations that could be found in the literature. Despite our effort to gather information from multiple sources, we suppose that more data may be available in company research reports or in national publications of producing countries that were not accessible through the English language search engines examined here (Web of Knowledge, Science Direct, Agricola) nor through the authors' network.

Finally, we explored common current management practices mostly in industrial plantations. More variability surely exists across a wider range of plantation types, especially in smallholder fields (40 % in Indonesia; >90 % in Thailand in Rival and Levang, 2014). For instance, less widespread practices exist, such as various compost processes and fertiliser applications. Moreover, there has been recently an increasing interest in diverting empty fruit bunches and palm oil mill effluent residues toward bioenergy chains (Wiloso et al., 2015). In this context, a comprehensive understanding on the efficiency of organic fertilisers, beyond a simple nutrient-based mineral equivalency, is crucial in order to avoid unexpected perverse effects such as fertility loss or increased N losses.

This review highlighted the extent of the knowledge gap and key research needs in the case of oil palm. In particular, it emphasized the need for comprehensive datasets on N dynamics taking into account the spatial and temporal heterogeneity due to the long-term perennial cycle and the varying agricultural practices. Attention should be paid notably to quantify biological N fixation, immobilisation, and mineralisation during the immature phase and after fertiliser applications. Internal fluxes are of great importance in the system and can lead to critical losses. NO_3^- leaching, notably during the immature phase, needs deeper investigations. In parallel, a great effort should be put in measuring gaseous N losses to reduce their uncertainty. Regarding the influence of practices on N fluxes, further research is needed to decipher and quantify short- and long-term effects of land preparation, planting, and fertiliser management. Notably, the role of organic fertilisers should be further investigated considering both N fluxes during treatment, e.g., emissions during composting and after field application. A network of experimental trials with long term monitoring in various pedo-climatic and technical contexts would be needed in order to appraise the multidimensional variability of those fluxes.

The more knowledge on the various fluxes that accumulates, the more precise and accurate N budget approaches and fertiliser management tools become. Quantifying N fluxes also aims at identifying potential environmental impacts. Greater knowledge on N losses based on field measurements could serve as a basis to build up new emission factors for environmental impact assessment. Indeed, current emission factors, such as those from the IPCC guidelines, rely on datasets in which tropical crops and perennial crops are underestimated (Bouwman et al., 2002b). In the view of sustainability assessment, consolidated results on N cycling and related potential environmental impacts should be useful to build-up agro-ecological indicators for management or certification schemes, such as RSPO, the Roundtable on Sustainable Palm Oil, and to improve impact assessments such as Life Cycle Assessments.

1.6. Conclusions

Oil palm plantations have three main peculiarities affecting N dynamics in a way that differs from other cropping systems: the long duration of the growing cycle, the marked spatial heterogeneity, and the large internal fluxes and pools of N. Several studies have measured or estimated most of the various fluxes, but data is still lacking for some of them. In particular, the role of legumes during the immature phase, the complex dynamics of N in soils, and the impact of spatial heterogeneity of N losses are poorly understood. We concluded that the most uncertain N fluxes are N losses. Thus, more research into N losses is needed to better understand their dynamics in order to reduce losses to the environment and hence increase the economic and agro-ecological efficiency of management practices. Finally, we identified three main cases in which critical conditions may occur and enhance Nr losses: the immature phase, when palms are still young and legume cover is vigorous, during the mature phase in areas with sparse or no soil cover and during the mature phase where high amounts of organic and mineral fertilisers are applied. This review will serve as a baseline to analyse the suitability of existing models to assess N dynamics and losses in oil palm plantations and to guide further research in the field.

Acknowledgments

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We conducted a literature review of all the existing knowledge about N fluxes and losses in plantations. This first step was important to estimate the main N fluxes, N losses, identify their drivers, and point out the research gaps. Models are also important and complementary to field data, as measurements can be prohibitively difficult and costly, especially for the monitoring of several N loss pathways over the long growth cycle of oil palm. In a second step, we hence undertook a research about the state-of-the art of N losses modelling in oil palm plantations.

2. Quantifying nitrogen losses in oil palm plantation: models and challenges

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Contribution of co-authors:

Contribution types*	Contributors	Description
Conceptualisation	Lénaïc Pardon, Cécile Bessou, Paul Nelson	Goals, scope and main structure of the chapter
Methodology	Cécile Bessou, Nathalie Saint-Geours, Ni'Matul Khasanah	Mentoring for bibliographic research, scientific writing, sensitivity analysis methodology, and WANULCAS model use
Programming	Lénaïc Pardon	Programming some of the models in Excel, handling the process-based models, programming the Morris' sensitivity analysis in R software
Validation	Cécile Bessou, Nathalie Saint-Geours, Paul Nelson, Benoît Gabrielle	Validation of the scientific quality
Formal analysis	Lénaïc Pardon	Performing the Morris' sensitivity analysis
Investigation, data collection	Lénaïc Pardon	Bibliographic research of existing models
Resources	CIRAD (Montpellier, France)	Office, computational resources
Writing - Initial draft	Lénaïc Pardon, Cécile Bessou	Text, figures, tables
Writing – Review and editing	Co-authors: Lénaïc Pardon, Cécile Bessou, Nathalie Saint-Geours, Benoît Gabrielle, Ni'matul Khasanah, Jean-Pierre Caliman, and Paul. Nelson Journal reviewers: Noordwijk M., Corley H.	Critical review, comments, re-phrasing, complementary references
Visualisation	Lénaïc Pardon, Paul Nelson, Nathalie Saint-Geours	Conception or proposal of new figures
Supervision	Cécile Bessou, Paul Nelson, Benoît Gabrielle	Oversight and leadership responsibility for the research activity planning and execution

* Contributions typology is from Allen et al. (2014)

Abstract

Oil palm is the most rapidly expanding tropical perennial crop. Its cultivation raises environmental concerns, notably related to the use of nitrogen (N) fertilisers and the associated pollution and greenhouse gas emissions. While numerous and diverse models exist to estimate N losses from agriculture, very few are currently available for tropical perennial crops. Moreover, there is a lack of critical analysis of their performance in the specific context of tropical perennial cropping systems. We assessed the capacity of 11 models and 29 sub-models to estimate N losses in a typical oil palm plantation over a 25-year growth cycle, through leaching and runoff, and emissions of NH_3, N_2, N_2O, and NO_x. Estimates of total N losses were very variable, ranging from 21 to 139 kg N ha^{-1} yr^{-1}. On average, 31 % of the losses occurred during the first 3 years of the cycle. Nitrate leaching accounted for about 80 % of the losses. A comprehensive Morris sensitivity analysis showed the most influential variables to be soil clay content, rooting depth, and oil palm N uptake. We also compared model estimates with published field measurements. Many challenges remain in modelling processes related to the peculiarities of perennial tropical crop systems such as oil palm more accurately.

2.1. Introduction

Oil palm is the most rapidly expanding tropical perennial crop. The area of land under oil palm, currently amounting to approximately 19 M ha, has been rising at 660 000 ha yr^{-1} over the 2005–2014 period (FAOSTAT, 2014), and this trend is likely to continue until 2050 (Corley, 2009). This increase raises significant environmental concerns. Beside issues related to land use changes and the oxidation of peat soils when establishing plantations, the cultivation of oil palm can generate adverse environmental impacts, in particular through the use of nitrogen (N) fertilisers. The latter are associated with pollution risks for ground and surface waters, and emissions of greenhouse gases (Choo et al., 2011; Comte et al., 2012; Corley and Tinker, 2015). As a result, an accurate estimation of N losses from palm plantations is critical to a reliable assessment of their environmental impacts. Models appear necessary in this process because comprehensive direct measurements of N losses are too difficult and resource intensive to be generalised.

While a number of models exist to estimate N losses from agricultural fields, they mostly pertain to temperate climate conditions and annual crops. N losses under perennial tropical crops are expected to follow specific dynamics, given, for instance, the higher ranges of temperature and rainfall experienced in these climatic zones, and the high amount of crop residues recycled over the growth cycle. However, few models are available for tropical crops, and even fewer for perennial tropical crops (Cannavo et al., 2008). Such models, in particular mechanistic ones, were primarily developed for research purposes, in order to simulate crop growth as affected by biogeochemical processes, and to gain insight into the underlying processes. Nowadays, models are also widely used to estimate the emission of pollutants for the purpose of environmental assessment, aiming either at more accurate estimates of mean emissions, or at evaluation of the impact of certain management practices on emissions. Different types of models are used, ranging from highly complex process-based models to more simple operational models such as empirical regressions. Despite some consensus and recommendations regarding best practices for the modelling of field emissions, notably within the framework of life cycle assessment (e.g. ILCD, 2011; IPCC, 2006), there has not been any comprehensive review and comparison of potentially useful models for environmental assessment. Moreover, various publications pinpointed the need for models that are better adapted to tropical crops in the estimation of field emissions (Basset-Mens et al., 2010; Bessou et al., 2013a; Cerutti et al., 2014; Richards et al., 2016). To improve field emissions modelling in oil palm plantations, we need to determine the potential applicability and pitfalls of state-of-the art models regarding N cycling and losses in these systems.

Most environmental impact assessment methods, such as life cycle assessment, consider perennial systems to behave similarly to annual ones. Following this assumption, the inventory data on the farming system are generally based on one productive year only, corresponding to the time the study was carried out or the year for which data were available (Bessou et al., 2013a; Cerutti et al., 2014). However, models of annual cropping systems do not account for differences in N cycling that occur during the growth cycle of perennial crops such as oil palm. Some key parameters in these dynamics, such as the length of the crop cycle, the immature and mature stages, and inter-annual yield variations, are thus not accounted for. This also applies to other long-term eco-physiological processes, such as the delay between inflorescence meristem initiation and fruit bunch harvest. To improve the reliability and representativeness of the environmental impacts of oil palm, we thus need to better account for the spatio-temporal variability of both the agricultural practices and the eco-physiological responses of the plant stand throughout the perennial crop cycle (Bessou et al., 2013a). Since most of these impacts hinge on N management and losses, modelling the N budget of palm plantations is a key area for improvement and is the focus of this work.

Here, we assess the capacity of existing models to estimate N losses in oil palm plantations, while accounting for the peculiarities of oil palm plantations related to the N dynamics over the course of the growth cycle. We start with a review of models that could be used for oil palm, and we detail how they were selected, calibrated, and run with relevant input data for a particular case study. Outputs from the models were subsequently compared to each other and to previously reported field measurements. Key model parameters were identified using a Morris sensitivity analysis (Morris, 1991). Finally, we discuss the relevance of existing models and the remaining challenges to adequately predict N fluxes in oil palm plantations.

2.2. Material and methods

2.2.1. Model selection and description

Among existing models, we first selected those that appeared most comprehensive and relevant. We then also selected partial models, in order to cover the diversity of current modelling approaches as much as possible, and to explore potential complementarities between them. By "partial models" we mean models that simulate only one or a few N losses.

The selection criteria were (i) the possibility of estimating most of the N losses of the palm system; (ii) the applicability to the peculiarities of the oil palm system; and additionally, for partial models, (iii) those most widely used in environmental assessments, e.g. EMEP (2013). In total, we selected 11 comprehensive plus 5 partial models.

We compared models at two levels. At the first level the aim was to compare the 11 comprehensive models, to obtain an overview of their abilities to estimate the various N fluxes constituting the complete N budget of the plantations. The second level involved the partial models and aimed at better understanding the factors governing the variability of each type of N loss. Most of the 11 comprehensive models were actually a compilation of sub-models. We hence included these sub-models in the second-level comparison, in addition to the 5 partial models originally selected. In total, 29 partial models, hereafter referred to as sub-models, were compared at this second level.

2.2.2. Description of comprehensive models

Following the typology defined by Passioura (1996), three of the comprehensive models were classified as mechanistic, dynamic models (WANULCAS from Noordwijk et al., 2004; SNOOP from de Barros, 2012; APSIM from Huth et al., 2014). The others were simpler static models mainly based on empirical relationships (Mosier et al., 1998; NUTMON from Roy et al., 2005; IPCC, 2006, from Eggleston et al., 2006; Banabas, 2007; Brockmann et al., 2014; Meier et al., 2014; Schmidt, 2007; Ecoinvent V3 from Nemecek et al., 2014). Other mechanistic models commonly used in crop modelling, such as DNDC (Li, 2007) and Century (Parton, 1996), were not adapted for oil palm modelling and could not be used within our model comparison without proper preliminary research and validation work, which fell beyond the scope of this work.

The mechanistic models were built or adapted explicitly for oil palm. The other models were developed or are mainly used for environmental assessment. Among the latter, some were explicitly built for oil palm or proposed parameters adaptable to oil palm (Banabas, Schmidt, Ecoinvent V3), some involved parameters potentially adaptable to perennial crops (NUTMON, Brockmann, Meier-2014), while others were designed to be used in a wide range of situations, without specific geographical or crop-related features (Mosier and IPCC-2006, which are often used in Life Cycle Inventories).

Most of the models distinguished between mineral and organic fertiliser inputs, some included symbiotic N fixation, and a few considered atmospheric deposition and non-symbiotic N fixation (Table 2.1). All models required parameters related to soil, climate, and oil palm physiology, except for two of them (Mosier and IPCC-2006), which only required N input rates. Management parameters were mainly related to fertiliser application, i.e. the amount and type applied, and the date of application. The splitting of application was considered in APSIM, SNOOP, and WANULCAS, and the placement of the fertiliser was only taken into account in WANULCAS.

All models considered the main internal fluxes of N, either modelling them or using them as input data. The most common fluxes were transfer from palms to soil, via the mineralisation of N, in the residues left by the palms of the previous cycle and pruned fronds, followed by oil palm uptake and root turnover. The least considered fluxes were cycling of N through the other oil palm residues such as male inflorescences and frond bases, and uptake and recycling by legumes (accounted for by only five models).

Finally, the main losses modelled were leaching (all models), N_2O emissions (10 models), and NH_3 volatilisation from fertilisers (9 models). NO_x emissions and runoff were taken into account by fewer models (7 and 8 models, respectively). Emissions of N_2, erosion, and NH_3 volatilisation from leaves were the least modelled losses. In some cases, several losses were modelled jointly and it was not possible to differentiate the contribution of each loss. For instance, erosion was always combined into the calculation of leaching and runoff, except for NUTMON, which used the mechanistic erosion sub-model LAPSUS (Schoorl et al., 2002). However, we could not run LAPSUS since it required precise local parameters to run its digital terrain model component that were not available.

2.2.3. Description of sub-models

Each of the 29 sub-models modelled N losses from the soil– plant system via one of the following three types of pathways: loss via leaching and runoff (8 sub-models); loss by emission of NH_3, commonly referred to as volatilisation (9 sub-models); and loss by emission of the gaseous products of nitrification and denitrification: N_2, N_2O, and NO_x (12 sub-models).

For the first pathway (leaching and runoff), eight sub-models were tested. Leaching concerned inorganic N losses (NO_3^-, NH_4^+, whereas runoff included inorganic and organic N losses without separating between the dissolved and particulate forms. Leaching was taken into account by all eight sub-models. Runoff was calculated jointly with leaching in two sub-models (Mosier and IPCC-2006), and separately in modules of APSIM, SNOOP, and WANULCAS. None of the eight models calculated erosion losses. The Mosier and IPCC-2006 sub-models calculated losses as a linear function of N inputs via mineral and organic fertiliser applications and crop and legume residues. Both used an emission factor of 30 % of N inputs in our test conditions. Smaling (1993), SQCB-NO3 (Faist-Emmenegger et al., 2009) and Willigen (2000) used regressions and calculated losses taking into account N inputs, soil such as soil N organic content and soil clay content, climate data such as annual rainfall, and some physiological parameters such as root depth and N uptake rates. The input variables used depended on the sub-models. APSIM, SNOOP, and WANULCAS used a soil N module coupled with a water budget module to calculate the losses through leaching and runoff. In these three cases, a cascading layered approach was used to model the soil, and N transformation rates and water flows were calculated for each layer on a daily time step. The other five sub-models used a yearly time step.

For the second pathway (the volatilisation of NH_3^-, nine sub-models were tested. They modelled NH_3 emissions from mineral and organic fertilisers, with three sub-models accounting for emissions from leaves. All sub-models calculated the emissions from mineral fertiliser, except for Agrammon Group (2009), and four sub-models calculated the emissions from organic fertiliser. For the emissions from leaves, Agrammon used a constant rate of 2 kg N ha^{-1} yr^{-1}, whereas EMEP (2013, 2009) calculated them jointly with emissions from mineral fertiliser. For emissions from organic and mineral fertilisers, the sub-models assumed linear relationships between fertiliser application rate and N losses. The emission factors were modulated depending on the fertiliser type. For mineral fertilisers, emission factors ranged from 0 to 15 % of N inputs for ammonium sulphate and 10 to 39 % of N inputs for urea. For organic fertilisers, emission factors ranged from 20 to 35 % of N inputs. For Mosier and IPCC-2006, emission factors differed only between mineral and organic fertilisers. In some sub-models, these factors were also modified by other parameters. For instance, the Bouwman et al. (2002c) model took into account soil pH, soil temperature, and cation exchange capacity, whereas in the Agrammon model emission factors were affected by factors specific to the type of animal manure considered (e.g. pig vs. cattle manure) and the application method. However, this was not relevant to empty fruit bunches, the main organic fertiliser used in oil palm plantations.

For the third pathway (gaseous losses of N_2 and N oxides), 12 sub-models were tested. N_2O emissions were estimated by eight sub-models. NO_x emissions were estimated by four sub-models. N_2 emissions were estimated by four sub-models but were calculated jointly with other gases, except for WANULCAS and APSIM. Mosier, IPCC-2006, EMEP-2013, Crutzen et al. (2008), and Nemecek et al. (2007) sub-models calculated losses as a linear function of N inputs, using fixed emission factors for N_2O, from 1 to 4 % of N inputs, or NO_x with 2.6 % of N inputs in EMEP-2013. Meier et al. (2012) also used a linear relationship, but with an emission factor that could be modified. However, its correction factors were applicable to annual crops under temperate climate and not here, e.g. impact of tillage. Bouwman et al. (2002a), Shcherbak et al. (2014), and SimDen (Vinther and Hansen, 2004) sub-models used non-linear relationships between N inputs and N losses. The Bouwman-2002a model took into account various parameters for the calculation, mainly of drainage, soil water content, and C organic content. Shcherbak and SimDen took into account only N inputs and baseline emissions. APSIM and WANULCAS calculated the losses by combining a soil N module and a water budget module, plus a carbon module for APSIM.

2.2.4. Model runs and sensitivity analysis

2.2.4.1. Model calibration and input data

Oil palm plantations are usually established for a growth cycle of approximately 25 years. Palms are planted as seedlings and the plantation is considered immature until about 5 years of age, when the palm canopy closes and the plantation is considered mature. Harvesting of fresh fruit bunches starts after about 2–3 years. The models were run over the whole growth cycle, including changes in management inputs and output yields between immature and mature phases. We considered replanting after a previous oil palm growth cycle. Potential impacts of land use change on initial conditions were hence not considered. However, when possible, the initial decomposing biomass due to felling of previous palms was included in the models.

In order to compare the models, we kept calibration parameters and input variables consistent across models as much as possible. However, all models did not need the same type of parameters and input data. In particular, for some static models, input variables were initially fixed and could be considered as calibrated parameters based on expert knowledge. For instance, NUTMON and Ecoinvent V3 needed the oil palm uptake rate as an input value, but Schmidt and APSIM used their own calculations for uptake.

We considered a 1 ha plantation located in the Sumatra region of Riau, Indonesia. For climate during this period, the dataset contained daily rain, 2407 mm yr^{-1} on average, as well as temperature and solar radiation. As the dataset was only 16 years long, from 1998 to 2013, we had to repeat an average year to complete the last 9 years of the simulation. The soil was a typical Ultisol, with four layers (0–5, 5–15, 15–30, and 30–100 cm). The main characteristics, averaged over the upper 30 cm, were bulk density (1.4 t m^{-3}), drainage (good), clay content (31 %), initial organic C content (1.65 %, i.e. 0.0165 g g^{-1}), initial organic N content (5.5 t ha^{-1}), pH (4.5), and rate of soil organic N mineralisation (1.6 % per year) (Corley and Tinker, 2015; Khasanah et al., 2015; Roy et al., 2005; USDA, 1999).

Regarding management input variables, we used a set of values representing a standard average industrial plantation (Pardon et al., 2016a). These values were consistent and based on a comprehensive review of available measurements. For oil palm the main peculiarities were the yield (25 t of fresh fruit bunches ha^{-1} yr^{-1} after 10 years, i.e. 73 kg N ha^{-1} yr^{-1}), the uptake (222 kg N ha^{-1} yr^{-1} after 10 years), and the depth where most of the active roots are found (set at 1 m). For the management of the field, the input variables were the slope (0 %), planting density (135 palms ha^{-1}), presence of a legume cover sown at the beginning of the cycle (e.g. Pueraria phaseoloides or Mucuna bracteata), and presence of the biomass of felled palms from the previous growth cycle (550 kg N ha^{-1}, corresponding to the above- and below-ground biomass of felled palms). For fertiliser, the application of mineral fertiliser increased from 25 kg N ha^{-1} yr^{-1} the first year up to 100 kg N ha^{-1} yr^{-1} after the fifth year. It was assumed to be 25 % of urea and 75 % of ammonium sulphate. Organic fertiliser, i.e. empty fruit bunches, was applied around the palms for the first 2 years at a typically used rate of 184 kg N ha^{-1} yr^{-1}. This amount, over 2 years, corresponds to the number of empty fruit bunches generated from 1 ha over 25 years, assuming a yield of 25 t of fresh fruit bunches ha^{-1} yr^{-1}. Atmospheric deposition of N through rain was set at 18 kg N ha^{-1} yr^{-1}. Biological N fixation by the legume cover was set at 635 kg N ha^{-1} fixed over the first 7 years, and released to the soil during the same period. The release of N through the decomposition of the organic residues from palms was set at an annual average of 108 kg N ha^{-1} yr^{-1} going to the soil. These residues correspond to fronds and some inflorescences that are regularly pruned, naturally falling frond bases, and dead roots.

For model comparison, we calculated the annual estimated losses, considering the relative contributions of leaching, runoff, and erosion; NH_3 volatilisation; and N_2, N_2O, and NO_x emissions. Besides the inter-model comparison, we also compared the simulated losses with previously reviewed measurements from the literature (Pardon et al., 2016a). Most of the models are static ones and do not account for variations in processes during the crop cycle. To model the whole cycle, we ran these models on a yearly basis accounting for annual changes in some input variables from the scenario, such as fertiliser application rates, biological N fixation, crop N uptake, N exported in fresh fruit bunches, temperature, and rainfall. One model (SNOOP) simulates specific years of the crop cycle one by one, using a daily time step. For this model, the calculation was repeated 25 times, taking into account the year-to-year changes. The other models were built to simulate the whole growth cycle with a daily time step, as for WANULCAS and APSIM, or with a yearly time step, as for Banabas and Schmidt.

For the sub-model comparisons, we compared the three groups of sub-models separately: (1) leaching, runoff, erosion; (2) NH_3 volatilisation; (3) N_2, N_2O, and NO_x emissions. For these comparisons, we used the same input data and the same calibration as for the previous one.

We compared the magnitude of the losses estimated by the various sub-models, and when possible, we also identified the contribution of the various N input sources to the losses estimated, i.e. the influence of mineral and organic fertiliser inputs, biological N fixation, plant residues, and atmospheric depositions.

2.2.4.2. Sensitivity analysis

Sensitivity analysis investigates how the uncertainty of a model output can be apportioned to different sources of uncertainty in the model inputs (Saltelli et al., 2008). Sensitivity analysis aims at ranking sources of uncertainty according to their influence on the model outputs, which helps to identify inputs that should be better scrutinised in order to reduce the uncertainty in model outputs.

We conducted a Morris sensitivity analysis (Morris, 1991) for the three groups of sub-models in order to identify the input variables that have the most effect on the magnitude of the losses. We used RStudio software to code and run the models (R Development Core Team, 2010), and the “morris” function from the “sensitivity” package version 1.11.1. Process-based models were not included in the sensitivity analysis as the source code of SNOOP was not accessible and APSIM and WANULCAS were not directly programmable without adapting the model structure to run the sensitivity analysis, which fell beyond the scope of this study.

Each model used n input variables. For each input variable X_i ($i \in [1;n]$), we defined a nominal, minimum, and maximum value. For climate, soil, oil palm characteristics, and N input fluxes, the ranges were determined based on literature references. For emission factors and other parameters, some ranges were directly provided by some sub-models (e.g., IPCC-2006). Other parameters were varied within a -90 to +90 % range relative to their nominal values. The ranges and references are listed in Table A.1., in Appendix 2. For the analysis, each range was normalised between 0 and 1 and then split into five levels by the morris function.

The Morris sensitivity analysis technique belongs to the class of “one-at-a-time” sampling designs. For each model, we carried out 400*$(n+1)$ runs, with each set of $n+1$ runs called a “trajectory”. For each trajectory, an initial model run was carried out in which each input variable was randomly set to one of the five possible levels. For the second run, one variable X_1 was changed to another random level differing from the initial one, and the difference in output between the first and second runs was recorded. That difference, divided by the normalised change in input level, is called an “elementary effect” of variable X_1. For the third run, another variable X_2 was changed, keeping all other input variable values the same as in the second run. The elementary effect of X_2 was recorded, and so on, until the $(n+1)th$ run. Each trajectory was initiated using a new random set of input variable values, and each trajectory generated one elementary effect value for each X_1.

Then, following Morris’s method, we calculated two sensitivity indices for each variable X_1: the mean of absolute values of the 400 elementary effects μ_i^*, being the mean influence on the output when the input varies in its minimum/ maximum range, and their standard deviation σ_i. The higher the μ_i^* is, the more influential the variable X_i. The higher the σ_i is, the more important the interaction between the variable Xi and the other input variables in the model, or the influence of X_i is non-linear. The mean of the absolute values of the elementary effect μ_i^* was used rather than the mean of the actual values σ_i because the effect could be positive or negative.

Table 2.1. Main input/output variables and processes modelled in the 11 comprehensive models.

			WANULCAS (van Noordwijk et al., 2004)	SNOOP (de Barros, 2012)	Schmidt (2007)	APSIM (Huth et al., 2014)	Banabas (2007)	NUTMON (Roy, 2005)	Ecoinvent V3 (Nemecek et al., 2012)	Meier et al. (2014)	Brockmann et al. (2014)	Mosier (1998)	IPCC (2006)
Environmental and crop factors		Soil and climate											
		Crop (e.g. type, root depth)											
Non N cycling processes		Carbon cycle											
		Plant growth											
		Water cycle											
N Inputs	Mineral fertiliser	Amount											
		Type (e.g. urea)											
		Application date											
		Splitting											
		Placement											
	Organic fertiliser	Amount											
		Type (e.g. C/N)											
		Application date											
		Splitting											
		Placement											
		Legume N fixation											
		Atmospheric depositions											
		Non legume N fixation											
N internal fluxes	Residues decomposition	Previous palm -> Soil											
		Fronds -> Soil											
		Dead roots -> Soil											
		Male inflo, frond bases -> Soil											
		Legume residues -> Soil											
	Uptake	Soil -> Oil palm											
		Soil -> Legume											
		Mineralisation / Immobilisation											
		Nitrification / Denitrification											
		Ammonification											
N losses estimated		Leaching			a		b			d		f	h
		N2O emissions					b	c					
		NH3 from fertiliser					b	c			e	g	
		Runoff			a		b			d		f	h
		NOx emissions					b	c				g	
		N2 emissions					b						
		Erosion			a		b			d			
		NH3 from leaves					b				e		
			WANULCAS	SNOOP	Schmidt	APSIM	Banabas	NUTMON	Ecoinvent	Meier	Brockmann	Mosier	IPCC

Used as input variable

Calculated by the model

Neither used nor calculated

Losses with the same letter are calculated jointly

2.3. Results

2.3.1. Comparison of the 11 comprehensive models

Estimations of total losses of N were very variable, ranging from 21 to 39 kg N ha^{-1} yr^{-1} around an average of 77 kg N ha^{-1} yr^{-1} (Figure 2.1a). Annual estimates were 20–25 t of fresh fruit bunches ha^{-1} yr^{-1} for yield and 132–147 kg N ha^{-1} yr^{-1} of N inputs (mineral fertiliser, atmospheric deposition, biological N fixation, empty fruit bunches, and previous felled palms), with 2407 mm yr^{-1} of rainfall and 932–1545 mm yr^{-1} of evapotranspiration. Two main factors contributed to the variability of N losses: some pathways were not taken into account by some of the models (see Table 2.1); and estimates of leaching, runoff, and erosion, which greatly contributed to the total losses, were particularly variable across models.

According to the models, the leaching and runoff pathway was the most important of the three, with an average loss of 61 kg N ha^{-1} yr^{-1}, i.e. about 80 %of the losses, ranging from -12 to 135 kg N ha^{-1} yr^{-1}. A negative leaching loss was estimated with NUTMON after the sixth year, when oil palm N uptake exceeded 160 kg N ha^{-1} yr^{-1}. NH_3 volatilisation was the next most important pathway with 11 kg N ha^{-1} yr^{-1} on average, ranging from 5 to 13 kg N ha^{-1} yr^{-1}. Emissions of N_2, N_2O, and NO_x had the lowest magnitude, but considerable variability, with 6 kg N ha^{-1} yr^{-1} on average, ranging from 0 to 19 kg N ha^{-1} yr^{-1}.

According to the models, N losses varied substantially along the growth cycle. On average, 31 % of the losses occurred during the immature period, which represents 12 % of the cycle duration (Figure 2.1b). Most of the models simulated maximum losses near the beginning of the cycle. The magnitude of this peak was very variable, up to 738 kg N ha^{-1} yr^{-1} for Schmidt. Its timing in the cycle depended on the model, occurring for instance during the first, second, or fourth year for Ecoinvent V3, IPCC-2006, and APSIM, respectively (Figure 2.2: for clarity, only four examples are shown, to illustrate the variability of the results). This high loss of N toward the beginning of the growth cycle was due to the large amount of N entering the soil at this time, via the felled palms from the previous cycle, the spreading of empty fruit bunches, and biological N fixation. The high variability in the magnitude and timing of the peak was due to differences in modelling approaches, especially the inclusion or otherwise of various N inputs and internal fluxes.

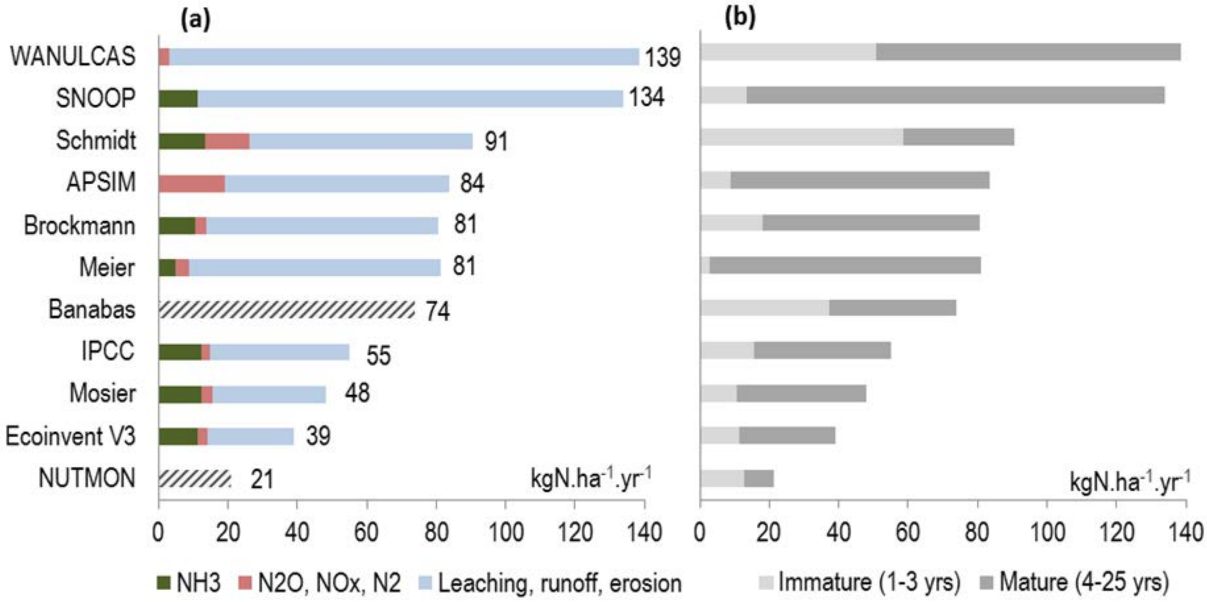

Figure 2.1. Estimates of N losses by 11 models.

(a) Distribution of the annual average losses between the three pathways: leaching and runoff; NH_3 volatilisation; N_2O, NO_x, N_2 emissions. Overall losses of N were very variable, with an average of 77 kg N ha^{-1} yr^{-1}, ranging from 21 to 139 kg N ha^{-1} yr^{-1}. The leaching and runoff pathway was the most important of the three, corresponding to about 80 % of the losses. The hatched bars represent calculations including several pathways at once: Banabas estimated the three pathways jointly, NUTMON estimated jointly all gaseous emissions and leaching losses were negative. SNOOP estimated N_2, N_2O, and NO_x emissions as null, and APSIM and WANULCAS did not model the NH_3 volatilisation. (b) Distribution of the annual average losses between the immature and the mature phases, corresponding to 1–3 years, and 4–25 years after planting; respectively. On average, 31 % of the losses occurred during the immature period, which represents 12 % of the cycle duration.

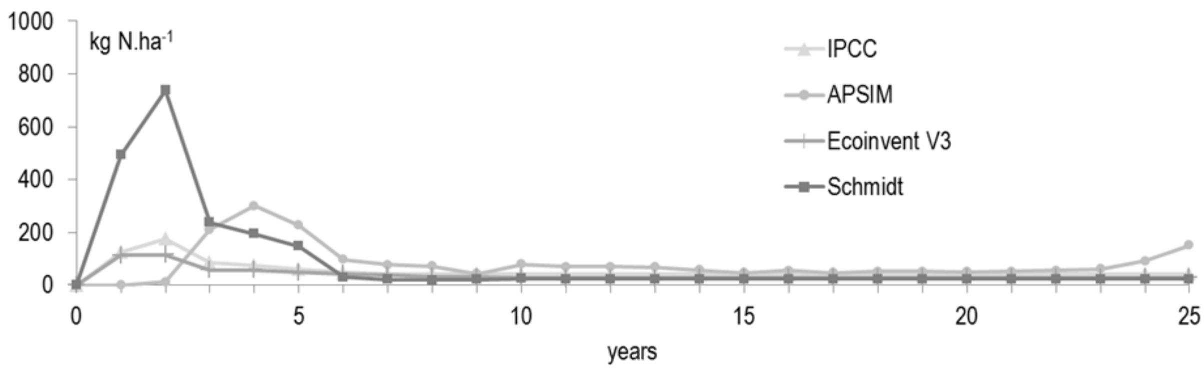

Figure 2.2. Temporal patterns of N losses along the growth cycle for four approaches selected to illustrate the variability of the results.

Most of the models simulated maximum losses near the beginning of the cycle. The timing of the peak depended on the model, occurring between the first and the fourth year. The magnitude of the peak was very variable, up to 738 kg N ha^{-1} yr^{-1} for Schmidt.

2.3.2. Comparison of the 29 sub-models

2.3.2.1. Losses through leaching and runoff

For this pathway, eight sub-models were tested (Figure 2.3), which were all sub-models integrated in the comprehensive models. There were no stand-alone models focusing on this pathway. Banabas, Schmidt, and Meier-2014 models were not included in this comparison because they did not use specific sub-models but calculated leaching, runoff, and erosion as the surplus of the N budget. The average loss estimate of the eight sub-models was 59 kg N ha^{-1} yr^{-1}, with a -12 to 135 kg N ha^{-1} yr^{-1} range.

All eight sub-models considered leaching. Five models considered runoff, but this flux was very low, i.e. < 0.06 kg N ha^{-1} yr^{-1}, due to the assumption of a zero field slope. None of these models considered erosion. Therefore, the fluxes calculated for this pathway could be considered as leaching losses, and their variability mainly hinged on the way leaching was modelled. In comparison, field measurements of this pathway type range from 3.5 to 55.8 kg N ha^{-1} yr^{-1} (Figure 2.4).

Without accounting for N inputs via empty fruit bunches application, atmospheric deposition, and biological N fixation, the average annual losses were estimated at 26 kg N ha^{-1} yr^{-1}. There was a substantial variation between sub-models, which spanned an overall range of -17 to 60 kg N ha^{-1} yr^{-1} (mean of six sub-models). When empty fruit bunches application was taken into account, the losses increased by an average of 3 kg N ha^{-1} yr^{-1} (mean of five sub-models). When biological N fixation was taken into account, the losses increased by an average of 18 kg N ha^{-1} yr^{-1} (mean of two sub-models).

In terms of temporal patterns (Figure 2.5), APSIM estimated peak losses through leaching and runoff of up to 251 kg N ha^{-1} in the fourth year, when biological N fixation was taken into account. The peak losses through leaching estimated by SQCB-NO3 more than doubled (up to 103 kg N ha^{-1}) when empty fruit bunches application was taken into account. This peak of losses through leaching at the beginning of the cycle has also been observed in field measurements (Pardon et al., 2016a).

In terms of spatial patterns, WANULCAS calculated that, of the 135 kg N ha^{-1} yr^{-1} lost through leaching, about 88 kg N ha^{-1} yr^{-1} came from the weeded circle surrounding the palm stem, where the mineral and organic fertilisers were applied; and about 31 kg N ha^{-1} yr^{-1} originated from the windrow where the trunks from the previous palms were left.

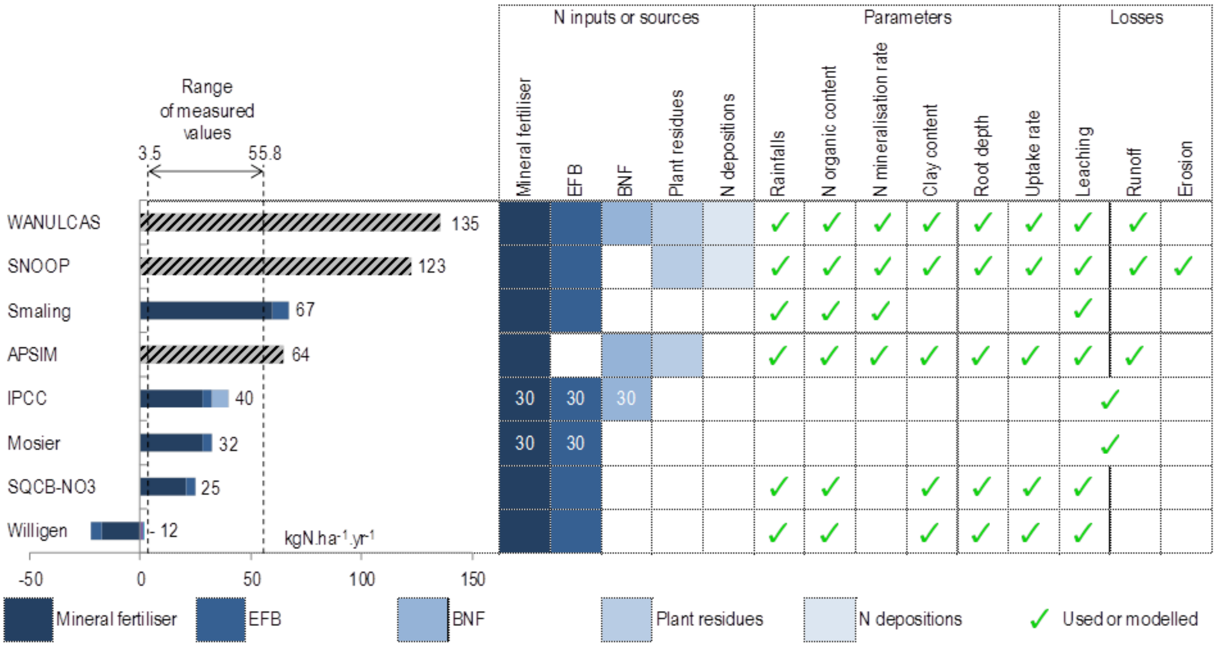

Figure 2.3. Comparison of annual average losses through leaching and runoff, estimated by eight sub-models.

The average loss estimate was 59 kg N ha^{-1} yr^{-1}. The results represented mostly losses through leaching due to low values for runoff losses (< 0.06 kg N ha^{-1} yr^{-1}). The hatched bars represent calculations which include several sources at once: in WANULCAS, SNOOP, and APSIM, all sources are considered in the same calculation. Measured values are from Pardon et al. (2016a). The Table shows the N inputs and parameters used by the sub-models, and emission factors for linear relationships. Emission factors are in %; e.g. in IPCC-2006, leaching and runoff are 30 % of mineral N applied. BNF: biological N fixation; EFB: empty fruit bunches, i.e. organic fertiliser.

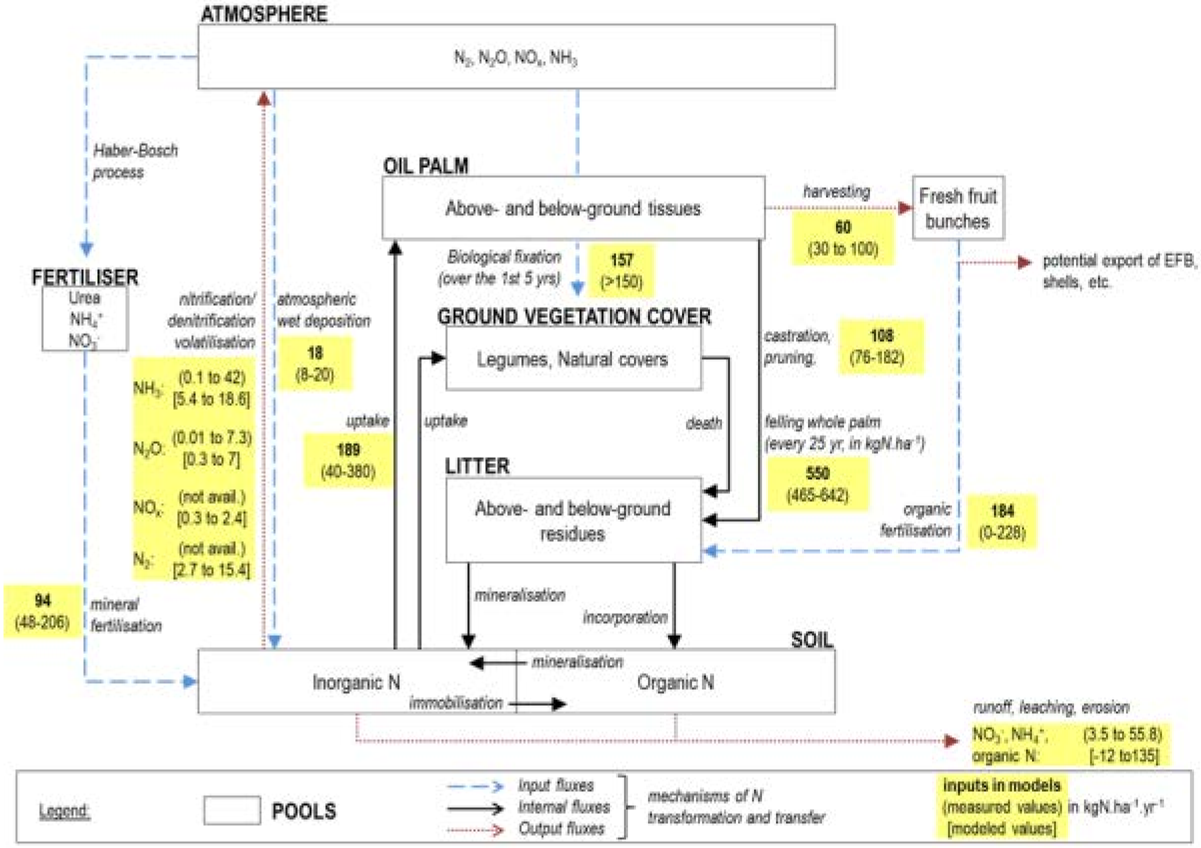

Figure 2.4. Comparison of measured and modelled N losses in oil palm plantations.

The range of modelled values for leaching and runoff was wider than the one of measured values of leaching, runoff, and erosion. Modelled NH_3 volatilisation seemed underestimated; however the maximum value of 42 kg N ha^{-1} yr^{-1} was measured for mineral fertiliser applications of solely urea, while the rate of urea in our scenario was of 25 % of mineral fertiliser. Modelled N_2O emissions were similar to field measurements, although the minimum value was not as low. The pools are represented by the rectangles, and the main fluxes are represented by the arrows. Flux values are ranges given in kg N ha^{-1} yr^{-1}. Measured values are from Pardon et al. (2016a). POME: palm oil mill effluent; EFB: empty fruit bunches.

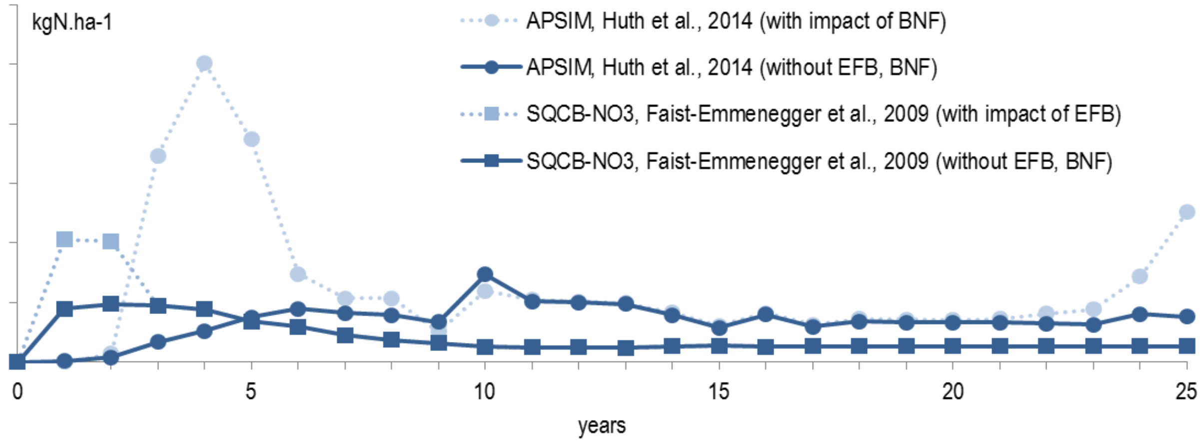

Figure 2.5. Influences of EFB and BNF on the temporal patterns of losses through leaching and runoff. The timing of the peak of losses depended on models, and its magnitude depended on which N inputs were accounted for. Two examples are represented: the influence of BNF in APSIM, and the influence of EFB in SQCB-NO3. BNF: biological N fixation; EFB: empty fruit bunches, i.e. organic fertiliser.

2.3.2.2. NH_3 volatilisation

For this pathway, nine sub-models were tested (Figure 2.6). In this comparison, two sub-models were partial models not used in the 11 comprehensive models (EMEP-2013 and Bouwman-2002c). Two sub-models were used by several comprehensive models: Asman (1992) was used by Ecoinvent V3 and Meier-2014, and Agrammon was used by Ecoinvent V3 and Brockmann. Modelled estimates averaged 10.0 kg N ha^{-1} yr^{-1}, with a range of 5.4–18.6 kg N ha^{-1} yr^{-1}.

Whenever possible, we differentiated the influence of mineral fertiliser, empty fruit bunches, and leaves on the emissions. The average emissions from mineral fertiliser were estimated at 9.2 kg N ha^{-1} yr^{-1} (mean of eight sub-models). The emission factors for urea and ammonium sulphate differed considerably between models, ranging from 10 to 39 % and 1.1 to 15 %, respectively. However, in several cases these differences compensated for each other when total emissions from mineral fertiliser were calculated. For instance, emissions calculated using the Schmidt and Asman models were close, with 8.4 and 9.1 kg N ha^{-1} yr^{-1}, respectively, whereas their emission factors were very different, being 30 and 2 % in Schmidt and 15 and 8 % in Asman, for urea and ammonium sulphate, respectively. The average emissions from empty fruit bunches were estimated at 3.7 kg N ha^{-1} yr^{-1} (mean of four sub-models). However, these estimates were done with emission factors more adapted to animal manure than to empty fruit bunches. The emissions from leaves were estimated separately only by Agrammon, with a constant rate set by definition in the model at 2 kg ha^{-1} yr^{-1}. For comparison, field measurements of losses as NH_3 range from 0.1 to 42 kg N ha^{-1} yr^{-1} (Figure 2.4).

In terms of temporal patterns, only the sub-models considering emissions from empty fruit bunches presented a peak which occurred over the first 2 years.

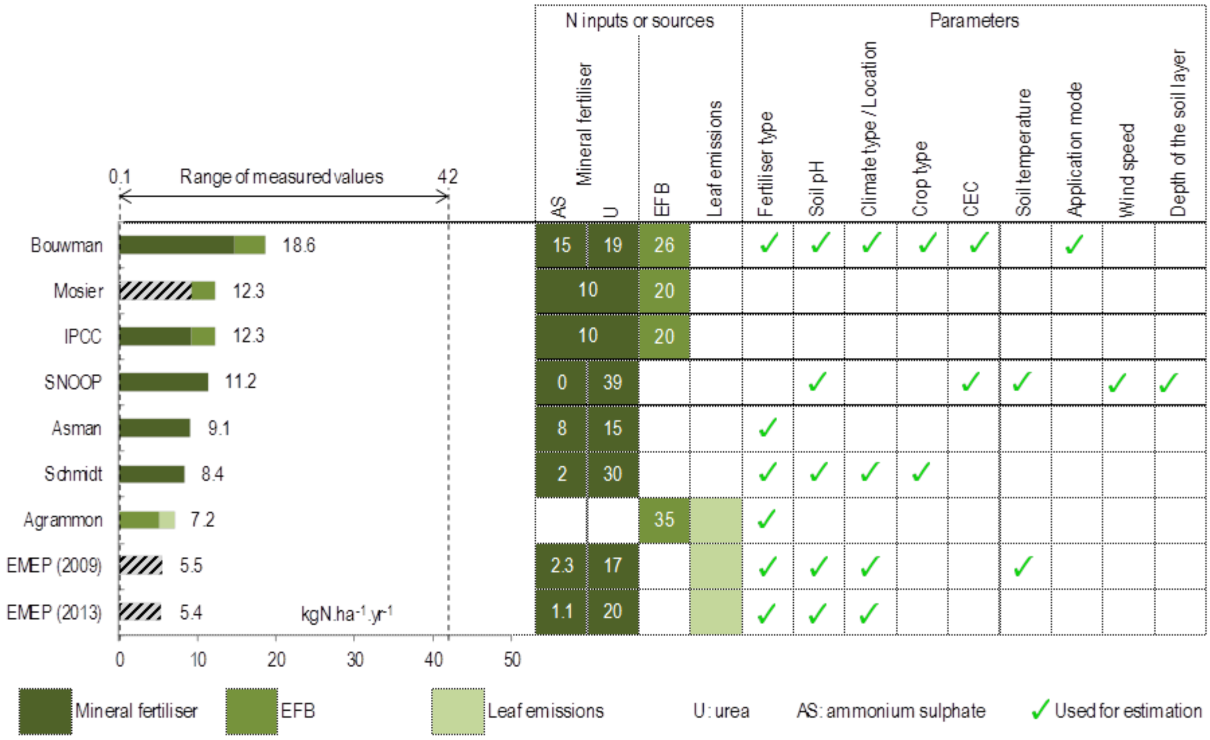

Figure 2.6. Comparison of annual average losses through NH_3 volatilisation, estimated by nine sub-models. The average emissions from mineral fertiliser were estimated at 9.2 kg N ha^{-1} yr^{-1}. The emission factors for urea and ammonium sulphate differed considerably between models, ranging from 10 to 39 % and 1.1 to 15 %, respectively. The hatched bars represent calculations that include several sources at once: in Mosier, NH_3 emissions from mineral fertiliser include NO_x emissions, and in EMEP-2009 and EMEP-2013, emissions from mineral fertiliser include those from leaves. Measured values are from Pardon et al. (2016a). The Table shows the N inputs and parameters used by the sub-models, and emission factors for linear relationships. Emission factors are in % of N inputs. EFB: empty fruit bunches, i.e. organic fertiliser.

2.3.2.3. N_2O, N_2, NO_x emissions

For this pathway, 12 sub-models were tested (Figure 2.7). Three of these sub-models were partial models not used in the 11 comprehensive models (Crutzen, EMEP-2013, and Shcherbak). Four sub-models were used in several comprehensive models: Nemecek-2007 was used in Ecoinvent V3 and Brockmann; and IPCC-2006 was used in Schmidt, Ecoinvent V3, Meier-2014 and Brockmann. The average estimate of combined N_2, N_2O, and NO_x emissions was 5.2 kg N ha^{-1} yr^{-1}, with a wide range from 0 to 19.1 kg N ha^{-1} yr^{-1}. This wide range could be explained partly because some sub-models estimated only N_2O or NO_x, while others calculated two or three of these gases jointly. Therefore, we did comparisons for N_2O and NO_x separately, in order to better understand the variability of the results. Emissions of N_2 were always calculated jointly with another gas, except for WANULCAS and APSIM. When possible, we also determined the influence of mineral fertiliser, empty fruit bunches, biological N fixation, plant residues, and soil inorganic N on emissions.

For N_2O, the average estimate of the outputs was 3.4 kg N ha^{-1} yr^{-1}, ranging from 0.3 to 7 kg N ha^{-1} yr^{-1} across eight sub-models (Figure 2.8). The average contributions were estimated at 2.0 kg N ha^{-1} yr^{-1} for mineral fertiliser (mean of six sub-models), 0.8 for empty fruit bunches (mean of four sub-models), 0.5 for biological N fixation (mean of three sub-models), 1.6 for plant residues (mean of three sub-models), and 1.6 for soil inorganic N (one sub-model). In this range of results, it was difficult to identify the most suitable models. For instance, the Bouwman-2002a model seemed relevant as it used a climate parameter for the subtropical context. Shcherbak's model seemed relevant for oil palm management as it calculated losses as a non-linear function of N inputs, which avoids overestimating emissions when mineral fertiliser inputs were less than 150 kg N ha^{-1} yr^{-1}. However, the results were very different, being the highest for the former, with 7 kg N ha^{-1} yr^{-1}, and one of the lowest for the latter, with 0.8 kg N ha^{-1} yr^{-1}. For NO_x, the average estimate of the outputs was 1.4 kg N ha^{-1} yr^{-1}, ranging from 0.3 to 2.4 kg N ha^{-1} yr^{-1} across four sub-models (Figure 2.9). In comparison, measurement-based estimates of the losses as N_2O range from 0.01 to 7.3 kg N ha^{-1} yr^{-1} (Figure 2.4).

In terms of temporal patterns (Figure 2.10), the sub-models that included mineral fertiliser inputs only did not show any peak of emissions over the crop cycle, e.g. in Bouwman et al. (2002a), whereas the ones taking into account at least one other N input, such as felled palms, empty fruit bunches, and biological N fixation, showed a peak during the immature period, e.g. in Crutzen and APSIM. In field measurements, higher levels of losses through N_2O have also been observed at the beginning of the cycle (Pardon et al., 2016a). With some sub-models the peak occurred during the first 3 years of the cycle, e.g. at 10 kg N ha^{-1} yr^{-1} in the second and third years in Crutzen, but in APSIM it occurred later, at 9 kg N ha^{-1} yr^{-1} in the fourth year.

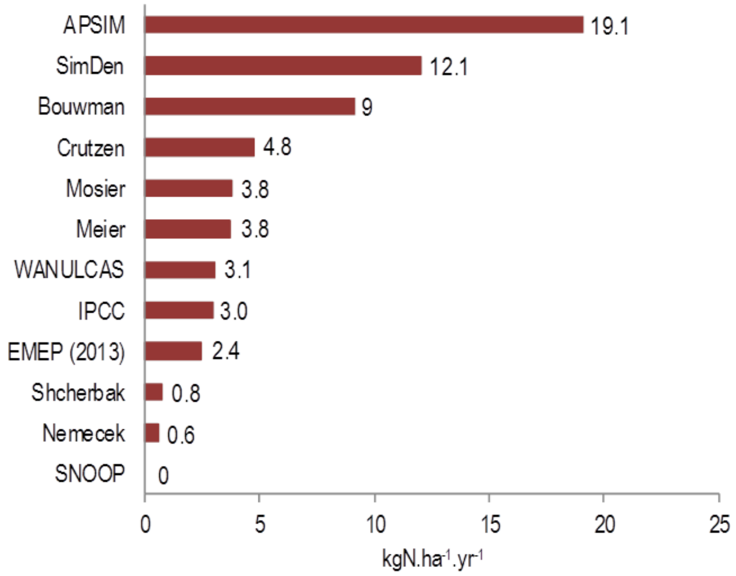

Figure 2.7. Comparison of annual average losses through N_2O, N_2, and NO_x emissions, estimated by 12 sub-models.

The average estimate of combined N_2, N_2O, and NO_x emissions was 5.2 kg N ha^{-1} yr^{-1}. The wide range of 0 to 19.1 kg N ha^{-1} yr^{-1} could be explained partly because some sub-models estimated only N_2O or NO_x, while others calculated two or three of these gases jointly.

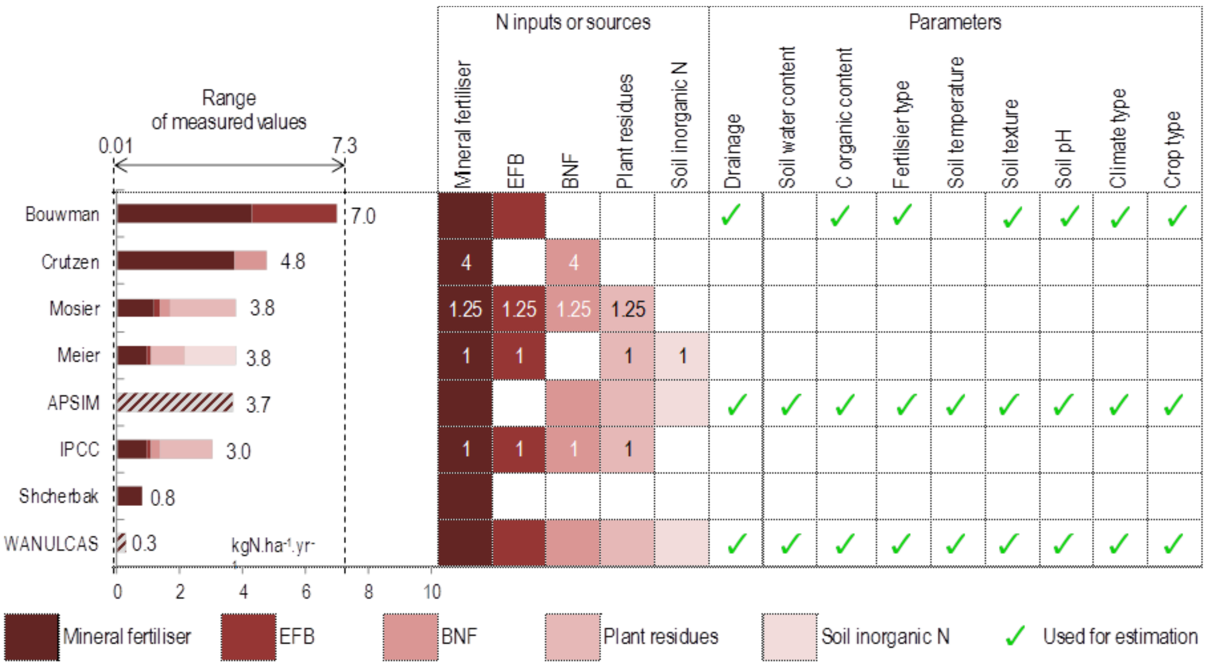

Figure 2.8. Comparison of annual average losses through N_2O emissions, estimated by eight sub-models.

The average estimate was 3.4 kg N ha^{-1} yr^{-1}, ranging from 0.3 to 7 kg N ha^{-1} yr^{-1}. For APSIM, all sources are considered in one calculation. Measured values are from Pardon et al. (2016a). The Table shows the N inputs and parameters used by the sub-models, and emission factors for linear relationships. Emission factors are in % of N inputs. BNF: biological N fixation; EFB: empty fruit bunches, i.e. organic fertiliser

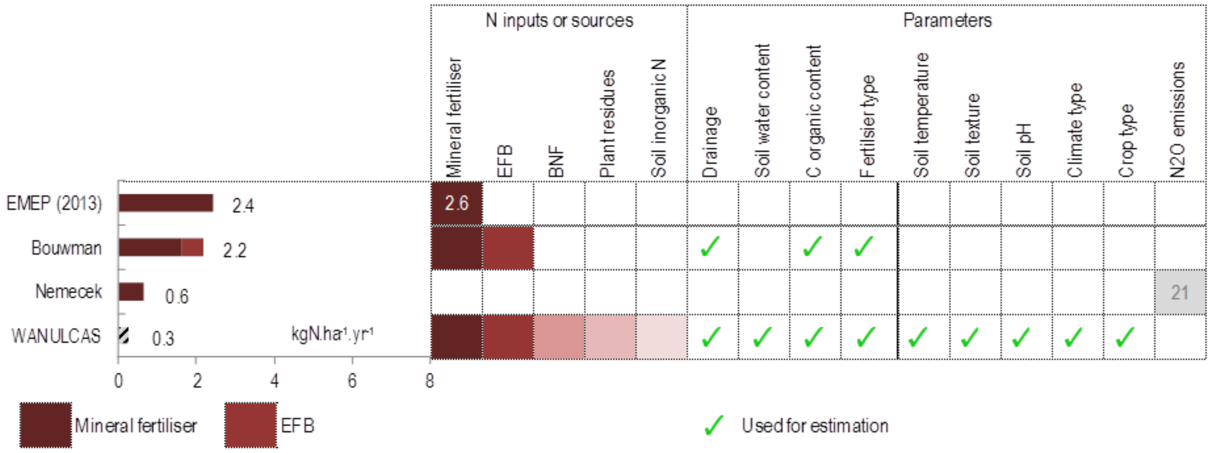

Figure 2.9. Comparison of annual average losses through NO_x emissions, estimated by four sub-models. The average estimate was 1.4 kg N ha^{-1} yr^{-1}, ranging from 0.3 to 2.4 kg N ha^{-1} yr^{-1}. For Nemecek-2007, all sources are considered in one calculation. The Table shows the N inputs and parameters used by the sub-models, and emission factors for linear relationships. Emission factors are in % of N inputs. EFB: empty fruit bunches, i.e. organic fertiliser.

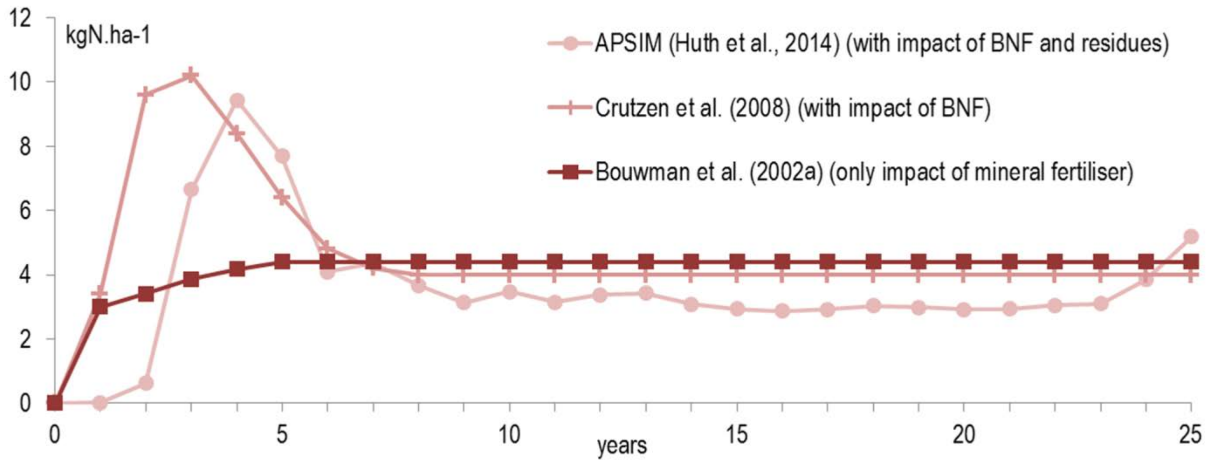

Figure 2.10. Influences of previous palm residues, EFB and BNF on the temporal patterns of losses through N_2O emissions.

The sub-models that included mineral fertiliser inputs only did not show any peak of emissions over the crop cycle, e.g. in Bouwman et al. (2002a), whereas the ones taking into account at least one other N input, such as palm residues or biological N fixation, showed a peak during the immature period. Three examples are represented: Bouwman 2002a (regression model, influence of mineral fertiliser), Crutzen 2008 (linear regression model, influence of mineral fertiliser and BNF), and APSIM (mechanistic model, with influence of BNF, and previous palm residues). BNF: biological N fixation.

2.3.3. Sensitivity analysis

For the leaching and runoff pathway, five out of eight sub-models were tested (Figure 2.11). None of these sub-models took erosion into account. We therefore did not test the influence of slope. On average for the five sub-models, the most influential input variables were clay content, rooting depth, oil palm N uptake, and the IPCC emission factor, resulting in values of $\mu^* > 200$ kg N ha^{-1} yr^{-1}. For clay content, rooting depth, and oil palm N uptake, there were also high non-linearities and/or interactions with other variables, with $\sigma > 250$ kg N ha^{-1} yr^{-1}. In the case of clay content, the variability was substantial. It was very influential for SQCBNO3 and Willigen, with $\mu^* > 395$ kg N ha^{-1} yr^{-1} and $\sigma > 1200$ kg N ha^{-1} yr^{-1}, but had no influence on Smaling, which was not sensitive to clay content when it was less than 35 % (μ^* and σ being zero). Nitrogen inputs, through mineral fertiliser application, empty fruit bunches application, and biological N fixation, and rainfall had lower mean influence and lower non-linearities and/or interaction indices, μ^* ranging from 64 to 110 kg N ha^{-1} yr^{-1} and σ ranging from 40 to 141 kg N ha^{-1} yr^{-1}. Other input variables related to soil characteristics, such as carbon content and bulk density, had lower mean influences with $\mu^* < 45$ kg N ha^{-1} yr^{-1}.

For NH_3 volatilisation, seven out of nine sub-models were tested (Figure 2.12). The influences of input variables were lower for this pathway than for leaching and runoff, with $\mu^* < 80$ and $\sigma < 35$ kg N ha^{-1} yr^{-1}. For the seven sub-models, the mean influences of variables related to organic fertiliser, i.e. emission factor and rate of application, were on average higher than for mineral fertiliser, i.e. emission factor, rate of application, and urea rate in fertiliser applied, with μ^* being 38–78 and 12–32 kg N ha^{-1} yr^{-1}, respectively. The interaction indices were also higher for organic fertilisers than for mineral fertilisers. Temperature and soil pH were less influential with $\mu^* < 2$ kg N ha^{-1} yr^{-1}.

For N_2, N_2O, and NO_x emissions, 7 out of 12 sub-models were tested (Figure 2.13). The influences of input variables were lower for this pathway type than for the other two, with $\mu^* < 44$ and $\mu^* < 19$ kg N ha^{-1} yr^{-1}. However, the mineral fertiliser rate had a very high mean influence compared to the other pathway types, being σ: 44 kg N ha^{-1} yr^{-1} because one sub-model was very sensitive to the fertiliser application rate, i.e. μ^*: 283 kg N ha^{-1} yr^{-1} for Shcherbak. Most of the N inputs had a lower mean influence on emissions than emission factors, except for biological N fixation.

Across the three pathways, i.e. 19 sub-models, the five most influential variables were related to leaching and runoff losses (Figure 2.14). These variables, which had μ^* greater than 100 kg N ha^{-1} yr^{-1}, were clay content, oil palm rooting depth, oil palm N uptake, and emission factors of IPCC-2006 and Mosier. Their interaction indices were also very high, except for the two emission factors. Mineral and organic fertiliser application rates and biological N fixation were the only input variables not specific to one pathway but used to simulate losses in all the three pathways. Soil pH, temperature, and other N inputs in soil, such as atmospheric N deposition, residues of legume, and oil palm, had lower influences on losses.

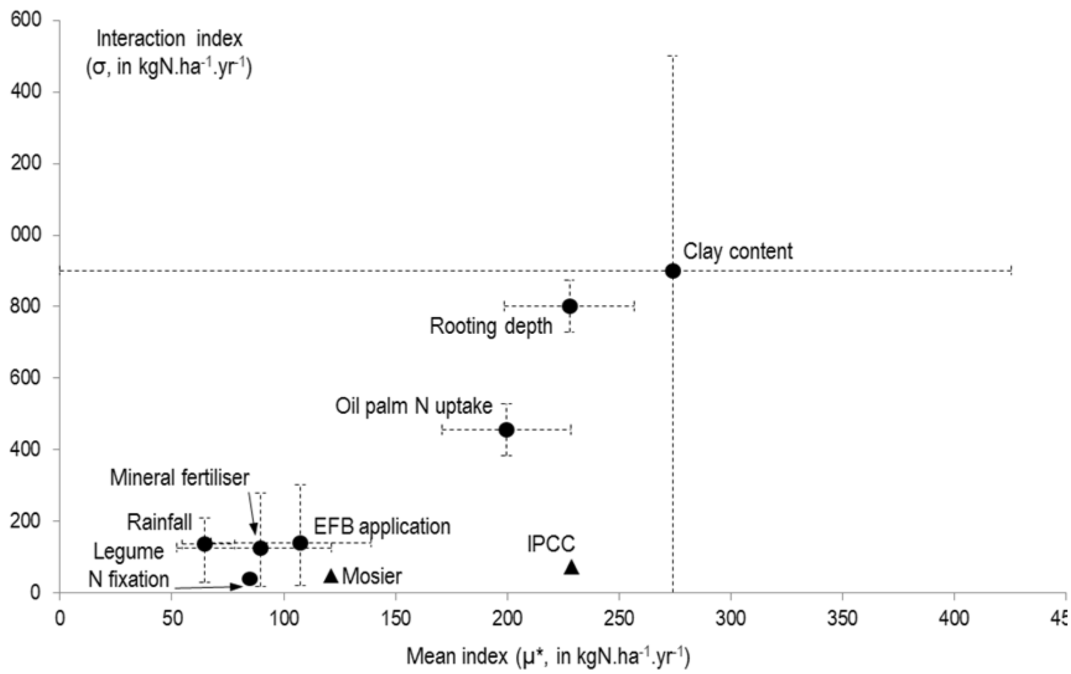

Figure 2.11. Morris's sensitivity indices for five sub-models calculating leaching and runoff losses.
Clay content, rooting depth, and oil palm N uptake had high interaction indices, and they had the most important mean indices with IPCC (2006) emission factor. Sub-models tested: IPCC-2006, Mosier, Smaling, Willigen, and SQCB-NO3. Indices lower than 50 kg N ha^{-1} yr^{-1} are not represented. Triangles: emission factors; circles: N inputs, oil palm and environment characteristics. EFB: empty fruit bunches, i.e. organic fertiliser.

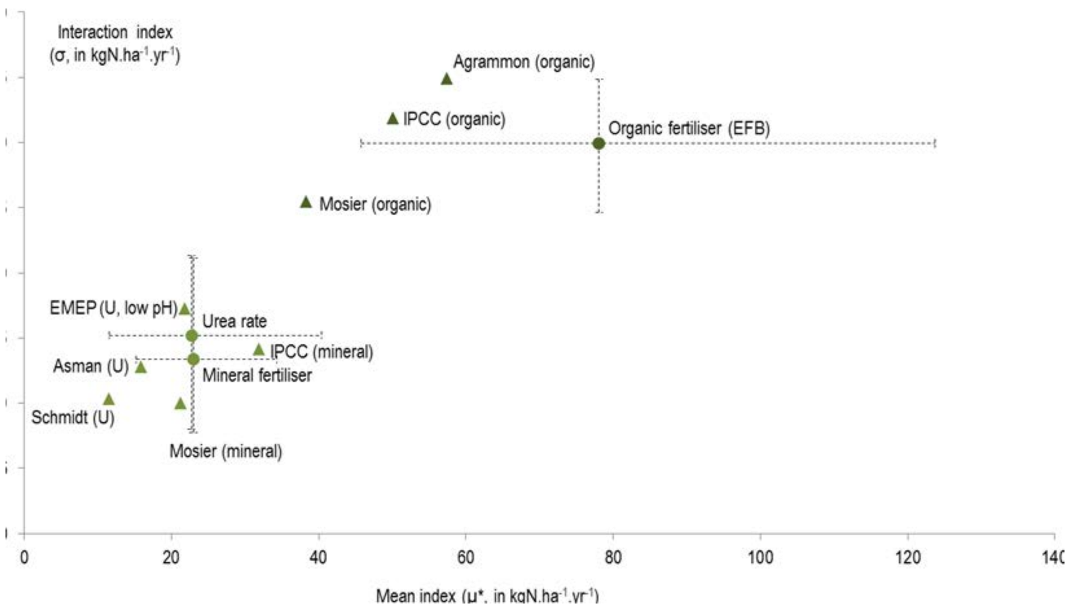

Figure 2.12. Morris's sensitivity indices for sub-models calculating NH_3 volatilisation.
The input variables related to organic inputs (dark green) had higher Morris indices than mineral inputs (clear green). Sub-models tested: IPCC-2006, Mosier, Asman, Schmidt, Agrammon, EMEP-2009 and EMEP-2013. Indices lower than 10 kg N ha^{-1} yr^{-1} are not represented. Triangles: emission factors; circles: N inputs. AS: ammonium sulphate; U: urea; EFB: empty fruit bunches, i.e. organic fertiliser.

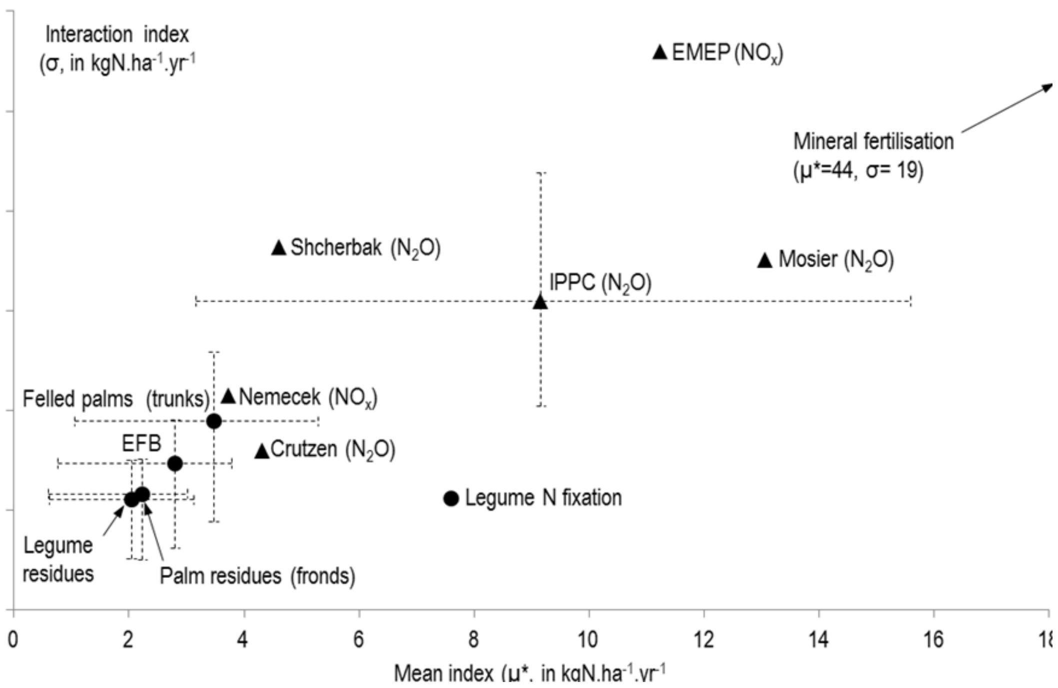

Figure 2.13. Morris's sensitivity indices for sub-models calculating N_2O, NO_x, and N_2 emissions.
Mineral fertiliser application had the highest indices (out of this graph). For other input variables, emission factors (triangles) had higher Morris indices than N inputs (circles). Sub-models tested: Mosier, IPCC-2006, Crutzen, Meier-2014, EMEP-2013, Nemecek-2012. Indices lower than 2 kg N ha^{-1} yr^{-1} are not represented. EFB: empty fruit bunches, i.e. organic fertiliser.

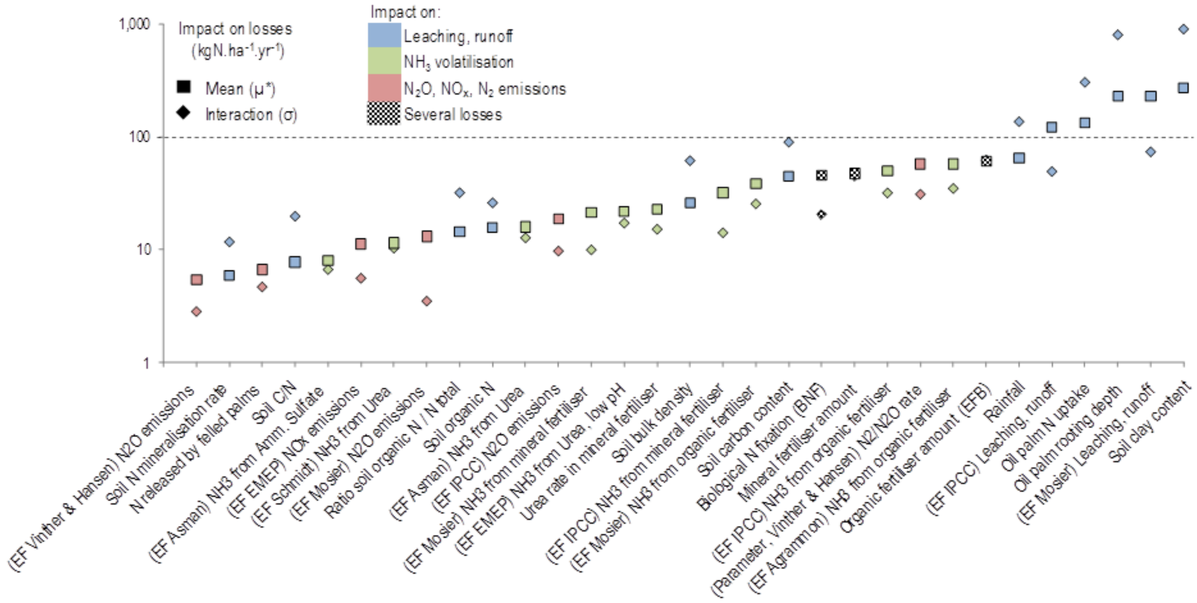

Figure 2.14. Average Morris indices for 31 variables of the 19 sub-models.

The five variables with the highest influence ($\mu*$ > 100 kg N ha-1 yr-1) were related with leaching and runoff losses (logarithmic scale). Variables were ranked by increasing mean sensitivity index ($\mu*$). The mean effect ($\mu*$ squares) was an estimation of the linear influence of the variable on losses. The interaction effect (σ, diamonds) was an estimation of non-linear and/or interaction effects(s) of the variable on losses. Variables with $\mu*$< 5 kg N ha-1 yr-1, i.e. 16 variables, are not represented. EF: emission factor; BNF: biological N fixation; EFB: empty fruit bunches, i.e. organic fertiliser.

2.4. Discussion

2.4.1. Relevance of model comparisons and flux estimates

The model comparison revealed large variations between models in the estimation of N losses from oil palm plantations. This variability was apparent a priori in the structures of the models, which were process-based or regression based, had a yearly or daily time-step, and were more or less comprehensive in terms of processes accounted for. We may assume that other models exist, which we could not access or calibrate, but those tested very likely provide a representative sample of modelling possibilities for simulating the N budget of oil palm plantations. Some models were clearly operated beyond their validity domains, especially regression based models for leaching. As this study did not aim to validate the robustness of the models, we did not filter out any of them as the overall set of model outputs helped highlight key fluxes and uncertainties. Further modelling work across contrasting plantation situations might be worthwhile to further test the validity of the models. In particular, nutrient, water, or disease stresses, or the impact of the previous land use, may critically influence the overall crop development and associated N budget.

The variability in model type or structure resulted in a large range of model outputs for the oil palm case simulated. There was an approximate 7-fold difference between the lowest and the highest overall N loss estimates. In order to investigate the plausibility of these estimates, we used a simple budget approach. Assuming that soil N content remained constant over the cycle, N inputs would equal N exported in fresh fruit bunches plus the increase in N stock in palms plus N lost. The assumption of constant soil N appears reasonable because soil N dynamics are closely related to soil C dynamics, and soil C stocks in plantations on mineral soil have been shown to be fairly constant over the cycle, especially when oil palm does not replace forest (Frazão et al., 2013; Khasanah et al., 2015; Smith et al., 2012). In our scenario based on measured values (Pardon et al., 2016a), average N inputs, N exports, and N stored in palms were 156, 60, and 22 kg N ha^{-1} yr^{-1}, respectively. Assuming a constant N stock over the cycle, these values imply N losses of 74 kg N ha^{-1} yr^{-1}.

Based on this plausible estimate of 74 kg N ha^{-1} yr^{-1}, it was possible to identify three groups among comprehensive models: models which likely underestimated losses (IPCC-2006, Mosier, Ecoinvent V3, NUTMON), models which likely overestimated losses (SNOOP, WANULCAS), and models simulating a plausible amount of loss (Banabas, Meier-2014, Brockmann, APSIM, Schmidt).

Underestimates may be due to simulated leaching losses being too low. This was particularly clear for SQCB-NO3 and NUTMON, which used regressions not adapted to the high N uptake rates of oil palm, resulting in negative leaching losses in some instances. However, IPCC-2006, Mosier, and SQCB-NO3 estimated leaching losses within the of 3.5–55.8 kg N ha^{-1} yr^{-1} range of measured losses when considering leaching, runoff, and erosion combined (Figure 2.4). All models seemed to underestimate NH_3 volatilisation compared with measured values (Figure 2.4). However, this was due to the fact that the higher measured value of 42 kg N ha^{-1} yr^{-1} was for mineral fertiliser applications of solely urea, whereas the rate of urea in our scenario was 25 % of mineral fertiliser. For the IPCC-2006, Mosier, and SQCBNO3 models, the underestimation may also be explained by the fact that none of them were complete in terms of N budgets. They accounted neither for all gaseous emissions, such as emissions of N_2, nor for all inputs, such as atmospheric deposition.

Overestimates of losses were primarily related to leaching losses, which were very high for both WANULCAS and SNOOP. This could result from interactions developing between modules in process-based models. For instance, the zoning of the palm plantation might have interacted with N inputs in WANULCAS, as the mineral N input from fertiliser was applied close to the palm trunks where water infiltration is likely to be higher due to stemflow. Another potentially important interaction involves N immobilisation and mineralisation in soil. Indeed, in WANULCAS, the mineralisation of residues and empty fruit bunches caused high losses through leaching in the first years of the crop cycle, while in APSIM, the immobilisation of N dominated the dynamics over several years and leaching losses were delayed and reduced to a large extent. However, more work is necessary to better understand how the structure of the models can lead to overestimate leaching.

Lastly, the models that came up with a plausible estimate of overall N losses, i.e. close to 74 kg N ha^{-1} yr^{-1}, showed large differences in single N flux sizes. APSIM estimated a plausible overall loss of 84 kg N ha^{-1} yr^{-1}, but its prediction of leaching seemed too large compared to measured values. This was very probably because some other fluxes were not taken into account, such as NH_3 volatilisation and N input through empty fruit bunches. Similarly, Meier-2014 and Brockmann output plausible overall loss estimates, but large leaching losses, while neither N_2 emissions nor N input through biological N fixation were taken into account. Schmidt and Banabas estimates seemed plausible and they accounted for most of the fluxes. Modelled N_2O emissions were similar to field measurements, although the minimum modelled emissions were still higher than the minimum losses measured in the field. Therefore, our results call for caution with regard to the choice of a single model to simulate N losses in oil palm. In absence of further empirical studies available to test these models, we would recommend using several models to predict N losses.

Some notable patterns differentiated process-based vs. regression-based models, and more comprehensive vs. less comprehensive models. The process-based models tended to predict higher overall losses and appeared to overestimate leaching losses. The less comprehensive models either seemed to underestimate overall losses, or tended to overestimate leaching losses, which counterbalanced missing fluxes in the N budget. Regarding leaching losses, the process based models produced similar estimates to those that deduced these losses from the total balance.

Process-based models have the advantage of being able to simulate the impact of management practices, such as the timing, splitting, and placement of fertilisers. They also take into account other processes related to the N cycle, such as carbon cycling, plant growth, and water cycling. However such models need more data, e.g. related to soil characteristics. Furthermore, the interactions between modules may generate unexpected behaviours, e.g. for simulating leaching, and they are generally not easily handled by non-experts. On the other hand, simple models, such as IPCC-2006 and Mosier, have the potential to provide plausible results if some N fluxes were supplemented, without requiring a lot of data. However they cannot take into account peculiarities of oil palm or the effects of management practices. One way forward is the development of simple models, such as agroecological indicators based on the Indigo© concept (Girardin et al., 1999). These indicators are designed to be easy to use, while incorporating some specificities of crop systems such as management practices.

2.4.2. Challenges for modelling the N budget in oil palm plantations

We identified two important challenges for better modelling the N cycle in oil palm plantations: (1) to model most of the N inputs and losses while accounting for the whole cycle, and (2) to model particular processes more accurately by accounting for the peculiarities of the oil palm system (Table 2.2).

Given the changes in N dynamics, management practices, and N losses through the growth cycle of oil palm, it is important for models to be built in a way that accounts for this whole cycle. In particular, the immature phase is an important period to consider, as about a third of the N losses occurred during this phase according to the models. Measurements in the field have also shown losses to peak during this phase (Pardon et al., 2016a), which involves large inputs of N from the felled palms, the spreading of empty fruit bunches, and biological N fixation. This results in complex N dynamics on the understorey crop, litter, and soil components of the ecosystem. Regarding N inputs, it seems important to also account for biological N fixation and atmospheric deposition since their contributions to the N budget were not negligible, besides fertiliser applications. Internal fluxes, such as the decomposition of felled palms and residues of oil palm and groundcover, are among the largest fluxes in the oil palm system, and their influence on N dynamics is substantial (Pardon et al., 2016a). In the case of a new planting, the impacts of land use change and land clearing might also need to be further investigated to better quantify the input fluxes due to decomposition as well as the influence of transitional imbalance state of the agroecosystem on N loss pathways.

For N losses, further model development is also needed to close the N budget. First, it would be worthwhile to model erosion without requiring detailed input data, while accounting for changes in erosion risk through the crop cycle and the effects of erosion control practices on N dynamics. Erosion was not modelled independently of other losses in most of the reviewed models. Further, NH_3 emissions from leaves could easily be included. Finally, despite the difficulties of understanding and simulating the complexity of processes driving N_2O emissions (Butterbach-Bahl et al., 2013), N_2O, NO_x, and N_2 should be modelled in a more comprehensive and systematic way. In particular, N_2O emissions, and thus presumably NO_x and N_2 emissions, have high spatial and temporal variability (Ishizuka et al., 2005). Parameters related to fertiliser application are therefore not the only drivers of these emissions, as surmised in the simple models. Since the time resolution of N_2O measurements in the field influences the cumulative emissions recorded for this gas significantly (Bouwman et al., 2002a), it is paramount to model those N losses accounting for the changes in driving parameters over the whole crop cycle.

Finally, losses should not be calculated jointly if the objective is to assess the environmental impacts of the plantation and to identify those practices most likely to reduce N losses and impacts. Indeed, different N fluxes may lead to different N pollution risks. N losses through erosion, runoff, or leaching do not end up in the same environmental compartments, e.g. surface water vs. groundwater. They hence do not contribute in the same way to potential environmental impacts such as eutrophication. For the purpose of environmental assessment, models should hence be as comprehensive and detailed as possible. Regarding these criteria, the Schmidt model appeared the most comprehensive and detailed one, as it distinguishes between six N fluxes. However, this model could be improved by separately modelling losses through erosion, runoff, and leaching, i.e. calculating a total of eight N fluxes.

The second challenge is to improve the modelling of some of the key N cycling processes, while accounting for the peculiarities of the oil palm system. Regarding internal fluxes, a better representation of the interaction between legumes and soil N dynamics is an important challenge, as the actual role of legumes during the immature period is complex and not fully understood yet. Indeed, legumes have the capacity to regulate their N provision, by fostering N fixation or N uptake, depending on soil nitrate content (Giller and Fairhurst, 2003; Pipai, 2014). They may contribute to the reduction of N losses through immobilisation or to their increase through N fixation and release.

Reducing the uncertainty in the modelling of leaching is an important challenge, as about 80 % of the total losses came from leaching, according to the models, and results were very variable across models. Models should be better adapted to the oil palm systems, as some regression models clearly appeared out of their validity domain. Further research on leaching prediction should focus on the effects of soil clay content, oil palm rooting depth and oil palm N uptake, since they emerged as the most influential variables according to the sensitivity analysis. The -90 to +90 % relative variation range used in the latter for the parameters that were not given a specific range may appear as a rather extreme set of values, but it made it possible to encompass a wide range of conditions. The sub-models included in the sensitivity analysis were regression models that did not explicitly simulate N cycling processes, resulting in a lack of influence of some parameters that may affect leaching in practice and in process-based models. Therefore, it could be interesting to perform complementary sensitivity analyses focused on process-based models, such as APSIM.

In order to take into account the influence of management practices on internal fluxes and losses, it would be necessary to use a daily step approach, to account for the timing or splitting of N fertiliser applications. Modelling approaches that incorporate spatial heterogeneity, as in WANULCAS, should be favoured, to assess the effect of fertiliser or empty fruit bunch placements. For gaseous losses, emission factors could be adapted to the oil palm system, as all of them, i.e. for NH_3 or N_2O/NO_x fluxes, were based on data from temperate areas on mineral soils, including mostly animal manure as reference for organic fertilisers. On a general note, more field measurements and model development are needed to account for the peculiarities of palm plantation management on peat soils. They involve substantial and potentially widespread areas, notably in Indonesia (Austin et al., 2015). Those plantations require specific management, including complex drainage systems, and may entail severe pollution risks, notably leaching, which are not yet properly accounted for in current models, e.g. IPCC-2006.

Table 2.2. Synthesis of the challenges identified in modelling the N cycle in oil palm plantations. BNF: biological N fixation.

Challenges	Recommendations for modellers	Data available and lacking
To better understand and model the N cycle during the immature period	- To better model the magnitude and the timing of the peak of emissions - To better understand and model the dynamics of N release from the residues, and the dynamics of legume N fixation, uptake, and release	- Measurements of kinetics are available for residue decomposition (Pardon et al., 2016a) - Knowledge is lacking concerning fluxes of N between legumes and soil, and actual losses over this period (Pardon et al., 2016a)
To better model the main losses through leaching, runoff, NH_3 volatilisation, and N_2O emissions	Leaching and runoff: - To favour a modelling approach using soil layers to obtain more precise estimates - To favour a daily step approach to model the influence of timing and splitting of fertiliser application - To focus on the most influential variables: soil clay content, oil palm rooting depth and oil palm N uptake NH_3 volatilisation: - To select emission factors more relevant to tropical conditions and perennial crops	N_2O emissions: data is still lacking for tropical conditions (Pardon et al, 2016a) to allow evaluation of the models
To model most of the N fluxes in order to complete the N cycle	- For input fluxes: include atmospheric N deposition and BNF - For internal fluxes: include felled palms from the previous cycle, and all the palm residues (fronds, inflorescences, roots) - For losses: to model erosion without requiring too much data, to consider NH_3 emissions from leaves, to model NO_x and N_2 even with simple models already available	- Measurements of quantities and kinetics of decomposition are already available for internal fluxes (Pardon et al., 2016a). - Measurements under oil palm are lacking for NO_x and N_2 (Pardon et al, 2016a)
To favour ways of modelling adapted to oil palm specificities and to the objectives of the modelling	- To favour models accounting for the whole cycle - To favour a daily step approach and to integrate the spatial heterogeneity, in order to account better for the influence of fertiliser management - To favour low data requirement models so they can be run easily - To estimate separately the losses via each pathway to calculate its impact and to identify potential mitigation practices	

2.4.3. Implications for management

The main levers that managers can use to reduce N losses involve the level of inputs, including fertiliser management, but also the handling of the immature phase. To manage fertiliser inputs, managers need to know the economic response, which is the main driver of practices, and the environmental response, to type, rate, timing, and placement. They may decide on the optimum fertiliser management practices based on these two dimensions. Models that include both N losses and fresh fruit bunch production in relation to management scenarios can provide the information needed to evaluate both responses.

The model comparison showed the importance of the immature phase with respect to N losses, and suggested field research lines and modelling approaches to improve our understanding of loss processes and their estimation.

There are also direct implications of our results for crop management during this phase. Light, water, and N are not fully used by the young palms, as their canopies and root systems do not cover the available ground in the field. Thus, in the current systems, the combination of high input rates with suboptimal resource capture capacity of the growing oil palms in the immature period results in high losses and negative environmental impacts. There are two possible approaches for reducing those. One is to reduce the inputs: for instance, it might be better to plant a non-legume cover crop and to manage N supply to the palms only with fertilisers. An alternative approach would be to grow another crop during this phase, which would use the surplus N and either export it in product or take it up in biomass so that it would decompose later. For instance, for fast-growing trees like balsa, trunks could be harvested after 5 years and exported, whilst leaving some branches, leaves, and roots to decompose on the soil.

There are also re-planting systems that make it possible to combine old and young palm trees in the same plantation block. The advantage can be both economic and agroecological as the immature phase actually becomes productive thanks to the remaining old palm trees and the nutrient cycling potentially more competitive. However, there is still limited data available to quantify and model the potential competition and adapt fertiliser management. Moreover, potential reduction in N losses should not come at the cost of increased use of herbicides, which may be used to kill the old palm trees without damaging the newly planted ones.

From the environmental point of view, it is also important to consider fertiliser management and N losses within a wider system and value chain. First, fertilisers encompass residues from the mill, whose environmental costs and benefits to the plantation should be considered from a whole life cycle perspective. This would include the production of waste, transport, or avoided impact through the substitution of synthetic fertilisers, etc. This can be done using life cycle assessments. Second, the carbon balance, i.e. the balance of carbon sequestration and release, is closely coupled to the N balance. Thus, models that include both cycles are warranted to fully evaluate the environmental impacts of oil palm production.

2.5. Conclusions

N losses are a major concern when assessing the environmental impacts of oil palm cultivation, and management practice targeted at reducing N losses and costs is critical to this industry. Modelling N losses is crucial because it is the only feasible way to predict the type and magnitude of losses, and thus to assess how improved management practices might reduce losses. Our study showed that there were considerable differences between existing models, in terms of model structure, comprehensiveness, and outputs. The models that generate N loss estimates closest to reality were the most comprehensive ones, and also took into account the main oil palm peculiarities, irrespective of their calculation time step. However, in order to be useful for managers, a precise modelling of the impact of management practices on all forms of N losses seems to require the use of a daily time step or the modelling of spatial heterogeneity within palm plantations. The main challenges are to better understand and model losses through leaching, and to account for most of the N inputs and outputs. Leaching is the main loss pathway and is likely to be high during the young phase when inputs are high due to decomposition of felled palms and N fixation by legumes. Field data are still needed to better understand temporal and spatial variability of other losses as well, such as N_2, N_2O, and NO_x emissions, in the context of oil palm investigations. These improvements could allow managers to evaluate the economic and environmental impacts of changes in management, such as, for instance, modifying fertiliser inputs or the plant cover type during the immature phase.

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We compared 11 existing models which may be used to predict N losses in plantations. We identified their ability of capturing oil palm peculiarities, their limits, and the main uncertainties in modelling. In order to analyse more deeply the drivers of N losses in process-based models, and to gather supplementary potentially useful to develop an agri-environmental indicator, we undertook an in-depth sensitivity analysis of one of the models compared. We chose APSIM-Oil palm process-based model which had been validated for production in oil palm.

3. Yield and nitrogen losses in oil palm plantations: main drivers and management trade-offs determined using simulation

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Contribution of co-authors:

Contribution types*	Contributors	Description
Conceptualisation	Lénaïc Pardon, Neil Huth, Paul Nelson, Cécile Bessou	Goals, scope, choice of the method for sensitivity analysis
Methodology	Neil Huth, Paul Nelson	Mentoring for R programming, APSIM handling, analysis method, and scientific writing
Programming	Lénaïc Pardon, Neil Huth	Programming the Morris' sensitivity analysis in R software (Lénaïc Pardon), and handling APSIM runs (Neil Huth)
Validation	Neil Huth, Paul Nelson, Cécile Bessou	Validation of the scientific quality
Formal analysis	Lénaïc Pardon, Neil Huth	Performing the Morris' sensitivity analysis, analysing and synthesising the results
Investigation, data collection	Murom Banabas	Data collection for the fertiliser trials
Resources	CSIRO (Toowoomba) and JCU (Cairns) in Australia	Office, computational resources
Writing - Initial draft	Lénaïc Pardon	Text, figures, tables
Writing – Review and editing	Co-authors: Lénaïc Pardon, Neil Huth, Paul Nelson, Murom Banabas, Benoît Gabrielle and Cécile Bessou Anonymous journal reviewers	Critical review, comments, re-phrasing, complementary references
Visualisation	Lénaïc Pardon, Paul Nelson, Neil Huth	Conception or proposal of new figures
Supervision	Neil Huth, Paul Nelson, Cécile Bessou, Benoît Gabrielle	Oversight and leadership responsibility for the research activity planning and execution

* Contributions typology is from Allen et al. (2014)

Abstract

Oil palm cultivation has environmental impacts, including those associated with nitrogen (N) losses. Improving management practices to optimise yield and N losses is critical. In order to identify the key management and site parameters driving yield and N losses, over a 25-year cycle, we undertook a Morris's sensitivity analysis of the Agricultural Production Systems sIMulator oil palm model (APSIM-Oil palm), using 3 sites in Papua New Guinea. We selected 12 parameters and 3 outputs: yield, nitrous oxide (N_2O) emissions and N leaching. The influence of the 12 parameters on the outputs depended on site characteristics, age of the palms, and climate. The most influential parameters for losses were N mineral fertiliser rate, drainage and fraction of legume in groundcover vegetation. The simulations suggested that APSIM-Oil palm is a useful tool for assessing management options for optimising yield and environmental outcomes in different environments. The results can also guide future measurements needed to improve N loss estimates, and further development of models and risk indicators.

3.1. Introduction

Oil palm is an important crop for global production of vegetable oil and the economies of tropical countries. The area of land under oil palm cultivation, currently approximately 19 M ha, has been rising at 660 000 ha^{-1} yr^{-1} over the 2005–2014 period (FAOSTAT, 2014) and is likely to continue rising until 2050 (Corley, 2009). This expansion raises environmental concerns, not only regarding land-use change and its consequences, but also concerning potential impacts of losses of nitrogen (N) from fields during cultivation. Addition of N via fertilisers and biological fixation (by legume cover crops) is a common practice to help achieve the yield potential of the crop (Corley and Tinker, 2015; Giller and Fairhurst, 2003). However, this addition is associated with potential risks of N losses into the hydrosphere and atmosphere, and subsequent environmental impacts such as terrestrial acidification, fresh water eutrophication, or climate change. For instance, a life cycle assessment study estimated that the addition of N fertiliser was responsible for 48.7 % of the greenhouse gases emitted during the cultivation period to produce 1 t of oil palm fruit bunches (Choo et al., 2011).

Reducing N losses requires identification of their drivers throughout the oil palm growing cycle, which spans about 25 years. A recent literature review showed that N losses remain the most uncertain and least documented of N fluxes in oil palm systems (Pardon et al., 2016a). The largest and most environmentally significant losses are N leaching and N_2O emissions, both of which are influenced by environmental conditions and management practices (Pardon et al., 2016a). At the global scale, the main climatic driver for both N leaching and N_2O emissions is known to be rainfall. Regarding soil properties, N leaching losses are driven largely by soil N content and texture (Mulla and Strock, 2008) and N_2O emissions are driven mainly by soil texture, content of water, N and organic C, pH and temperature (Stehfest and Bouwman, 2006). However, the main drivers of N losses in oil palm systems are likely to differ from those applying to annual crops under temperate climates. First, tropical soils often have an acidic pH, and their temperature variability is often lower than in temperate areas. Furthermore, water-related factors are usually important in tropical contexts, due to higher rainfall. Second, the substantial amounts of N and C entering the soil in oil palm systems may have a particular impact on N losses (Pardon et al., 2016a). Third, the legume cover usually established under young palms may influence N dynamics and losses (Pardon et al., 2016a).

Modelling is an essential tool for estimating losses and identifying key drivers, since direct measurements and experimentation are prohibitively difficult and costly, especially over the long growing cycle of oil palm. N management inevitably involves trade-offs between achieving high yields and minimising environmental impacts, and models that simultaneously simulate yield and N losses allow such trade-offs to be examined. Several models are available for estimating N losses in oil palm, but they give widely divergent estimates of losses due to their diverse structures and assumptions (Pardon et al., 2016b). There exist other models such as OPRODSIM (Henson, 2005), PALMSIM (Hoffmann et al., 2014) or ECOPALM (Combres et al., 2013) that were calibrated to simulate the growth of oil palm and its potential fruit yield, but those do not estimate emissions to the environment. Two models simulate the impact of management practices, such as organic matter application and legume cover establishment, on both yield and N losses in oil palm systems (Pardon et al., 2016b): APSIM-Oil palm (Huth et al., 2014) and WANULCAS (Noordwijk et al., 2004). APSIM- Oil palm has published validation and test data sets for yield response to N fertiliser, at several sites in Papua New Guinea, and so was chosen for this study. This model was developed using the Agricultural Production Systems sIMulator (APSIM). APSIM is a freely available and widely used open-source program incorporating modules for cycling of water, C and N that have been tested in a large variety of settings around the globe (Holzworth et al., 2014).

In this paper, we present a sensitivity analysis of the APSIM-Oil palm model, performed using a novel combination of state-of-the-art software systems. This analysis aimed at identifying the key management and site parameters driving yield and N losses estimated by this model, in order to highlight improvement tracks for both model development and practices in the field.

We chose three sites in Papua New Guinea on mineral soils, where the APSIM-Oil palm model had already been validated against field data and for which we had available soil and weather data. We simulated an oil palm growth cycle of 20 years, following the standard management practices in industrial oil palm plantations. We tested the influence of twelve parameters on yield and N losses, using the Morris's sensitivity analysis method (Morris, 1991). This is a widely used and robust method that is particularly relevant in contexts of high computational costs (Campolongo et al., 2007; Saltelli and Annoni, 2010), as is the case with a complex model such as APSIM-Oil palm, and the number of parameters chosen for this study. We estimated N fertiliser rates for each site to optimise trade-offs between yield and N losses. We finally outlined the implications of the results for modelling, measurements and management.

3.2. Material & methods

3.2.1. Study sites and datasets

We chose three sites in Papua New Guinea (Figure 3.1), where APSIM-Oil Palm had already been validated against field data for production (Huth et al., 2014). These sites are presented in this paper by their plantation names, being Sangara (8.73°S, 148.20°E), Sagarai (10.42°S, 150.04°E) and Hargy (5.29°S, 151.07°E). Measurements of N losses and data regarding management practices were available for some of these sites (Banabas et al., 2008; Pipai, 2014), as well as fertiliser trials from the Papua New Guinea Oil Palm Research Association (PNGOPRA) trial database. The soil profiles and long term weather data were the ones used for validation (Huth et al., 2014). The weather data at a daily time step, i.e. rainfall, solar radiation and temperature, lasted from 1986 to 2014 for Sangara, 1990–2008 for Sagarai, and 1990–2008 for Hargy.

Key characteristics	Units	Sangara	Sagarai	Hargy
Soil texture	-	Sandy Clay Loam	Clay	Loam
Soil organic C	(%)	2.1	4.1	5.3
Soil pH	-	6.0	5.6	6.0
Rainfall	(mm yr^{-1})	2400	2400	4350
N fertiliser response in trials	FFB yield (tonnes ha^{-1})			

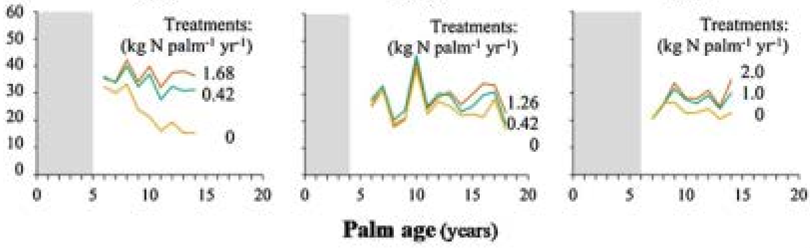

Figure 3.1. Key characteristics of the sites used for oil palm modelling.

In the graphs, grey shaded areas indicate the period before N fertiliser rate treatments were imposed. FFB: fresh fruit bunches.

This set of three sites presented the advantage of spanning different conditions in terms of soil properties and climate, which may affect N losses differently. At Sangara, the soil is a sandy clay loam developed in moderately weathered volcanic ash deposits ('Higaturu family', Bleeker, 1987), with a C content of 2.1 % and pH of 6.0 (in the 0–10 cm layer), and average annual rainfall of about 2400 mm yr^{-1}. At Sagarai, the soil is a deep clay formed in recent alluvial deposits ('Tomanou family', Bleeker, 1988), with a C content of 4.1 % and pH of 5.6 (0–10 cm), and rainfall of about 2400 mm yr^{-1} with a higher inter- monthly variability than in Sangara, i.e. an alternation of dry periods followed by short intense rainfalls. At Hargy, the soil is a loam formed in volcanic ash soil ('Kau series', Hartley et al., 1967), with a C content of 5.3 % and pH of 6.0 (0–10 cm), and rainfall of about 4350 mm yr^{-1}.

The genetic material was Dami commercial dura x pisifera for all trials. The field trials revealed differences in the response of oil palm to N fertiliser across sites, and this pattern was also predicted by APSIM-Oil palm (Huth et al., 2014). The model had a good capacity to simulate palm production, while accounting for site peculiarities such as the background of the soil in terms of N supply (Huth et al., 2014). The contrast between sites in terms of response to N fertiliser was particularly interesting for our study to investigate how the baseline N supply of soil may affect the sensitivity of estimated yield and N losses to the tested parameters.

At the three sites, several rates of N fertiliser were applied in two to three doses per year, and compared to a control treatment without N application (Huth et al., 2014). Other nutrients are also important for oil palm growth and production. P, K, Mg and B amendments were applied for all treatments, and were hence not limiting. At Sangara, there was a marked response of yield to N fertiliser rate, with a decrease in yield over time for the treatment without N fertiliser. The yield response to N fertiliser is a complex process in oil palm depending on many factors (Chew and Pushparajah, 1995; Dubos et al., 2016). However, we can assume that this marked response might be due to a baseline low fertility of the soil in terms of N supply, as suggested by the relatively low organic matter content at Sangara. At Sagarai there was no clear response of yield to N fertiliser rate, probably because of a sufficient N supply from the soil, as suggested by its higher organic matter content. The limiting factor at this site was likely to be the water supply, and water stress may explain the variability of the yield from year to year. At Hargy, there was no clear response of yield to N fertiliser rate, and the yield was less variable than at the two other sites. This was likely due to the higher organic matter content and the higher and more constant rainfall. The limiting factor at this site was likely to be solar radiation, given the very high rainfall.

3.2.2. Inputs, outputs and parameters

We used the APSIM-Oil palm model Next Generation, version 2016.02.10.604. Although oil palm plantations are usually established for a growth cycle of approximately 25 years, we simulated a cycle of 20 years, as we were restricted by the length of the climate records available. We simulated replanting after a previous oil palm growth cycle. Hence, potential impacts of land use change on initial conditions were not considered. On the other hand, the initial input of decomposing biomass due to felling of previous palms was taken into account.

Management practices vary between plantations, with respect to choice of planting material, rate and placement of mineral and organic fertilisers, weeding practices, etc. But some practices have relatively low variability, such as planting density, duration of the growth cycle, and sowing of a legume cover. For the modelling, we used management practices that are standard across industrial oil palm plantations globally (Corley and Tinker, 2015) and in Papua New Guinea. Palms were planted as seedlings at a density of 135 palms ha^{-1}. A legume cover, fixing N from the atmosphere, was sown at the beginning of the cycle. Harvesting of fresh fruit bunches started 3 years after planting.

Fertiliser and empty fruit bunches from the palm oil mill were applied in the plantation. As the influence of the rates of fertiliser and empty fruit bunches were part of the sensitivity analysis, the rates of application differed from one simulation to another. For mineral fertiliser, the application of ammonium nitrate was split in three doses per year. The annual rates were set using simple scaling (0–1) specified for each simulation, and applied to the upper range value:

28, 61, 121, 181 and 212 kg N ha^{-1} yr^{-1}, for age 1–5 years, respectively. After the 5^{th} year, annual rates were then constant. For empty fruit bunches, the application was done at the beginning of each year, starting after the 5^{th} year. A constant annual rate was determined for each simulation (see Table 3.1 for ranges).

Table 3.1. Ranges of parameter values used to perform the sensitivity analysis.
See text for sources. DM: dry matter, EFB: empty fruit bunches

Common parameter ranges				
Management				
N fertiliser rate	(kg N ha^{-1} yr^{-1})	0-212		
Initial groundcover	(% of surface)	20-60		
Legume fraction	(% of cover)	0-100		
Initial residue mass	(tDM ha^{-1})	70-104		
EFB application rate	(tDM ha^{-1} yr^{-1})	0-12		
Soil water dynamics				
Maximum root depth	(m)	1-5		
Drainage coefficient	-	0.4-0.8		
C&N cycling				
Residue C/N ratio	-	Frond 39-47, Trunk 145-174		
EFB C/N ratio	-	45-60		
Site-specific ranges		Sangara	Sagarai	Hargy
Soil water dynamics				
Runoff coefficient	-	60-75	70-85	60-75
Water lower limit*	(m m^{-1})	0.36-0.40	0.41-0.45	0.28-0.32
C&N cycling				
Soil organic C*	(%)	1.7-2.5	3.3-4.9	4.2-6.4

* First layer as example

APSIM-Oil palm simulates the biological fixation of N by legumes and N processes in soil. Atmospheric N deposition is not accounted for in APSIM-Oil palm. The biological fixation of N is modelled considering that a fraction of the groundcover vegetation is a legume. For this legume fraction, a constant rate of 44 % of the N content of the biomass was set to come from N fixation (Pipai, 2014), the rest being taken up from the soil. In terms of N dynamics in soil, APSIM-Oil palm uses a soil N module coupled with a water budget module with a cascading layered approach (Probert et al., 1998). C and N transformation rates and N transportation are hence calculated for each layer, on a daily time step, depending on water contents and flows. APSIM-Oil palm also models N_2O losses and N leaching. N_2O emissions are calculated as the sum of N_2O emissions from nitrification and denitrification processes (Thorburn et al., 2010). For each layer, nitrification is calculated depending on soil moisture, temperature and pH, and denitrification is calculated depending on soil moisture, temperature and organic C. N_2O emissions during nitrification are calculated as a fixed proportion of N nitrified, and N_2O emissions during denitrification are calculated using the N_2/N_2O ratio predicted by the model of Del Grosso et al. (2000). N leaching is calculated as the amount of nitrate that reaches the bottom of the lowest soil layer, after which N is no longer available for plant uptake. Drainage of water from one layer to the next is modelled using a drainage coefficient, which is the proportion of soil water above the field capacity that drains in 1 day N losses through NH_3 volatilisation, erosion, and runoff are not simulated in this version of APSIM-Oil palm. Therefore, we chose N_2O emissions and N leaching as outputs to test the sensitivity of N losses, in addition to the annual yield, as it is one of the main drivers of management decisions.

After initial tests to identify the best trade-off between the computational cost and the number of parameters to test, we selected twelve parameters (Table 3.1) likely to be important for N losses according to previous measurements and modelling studies on oil palm systems (Pardon et al., 2016a, 2016b). First, we chose management parameters related to important N and C inputs to the soil, and legume cover establishment, as we assumed that these practices would be influential. Five parameters were related to management practices: rate of mineral N fertiliser applied, initial proportion of the area covered by ground- cover vegetation, legume fraction in this cover, rate of initial residues from previous palms, and rate of empty fruit bunches applied. Second, we prioritised the soil parameters to test. We chose water-related soil parameters, as we assumed that they would be influential, based on previous measurements and modelling studies (Pardon et al., 2016a, 2016b). Four parameters related to soil water dynamics were tested: runoff coefficient (i.e. runoff as a function of total daily rainfall), drainage coefficient, lower limit of extractable soil water (affecting the plant available water content) and maximum root depth of palms. Third, as N dynamics are closely linked with C dynamics, and given the high C and N inputs in soil in oil palm system, we also chose three other parameters related to C and N cycling: soil organic C content, initial residue C/N, and empty fruit bunch C/N.

Ranges for each parameter were chosen to be realistic for each site, but wide enough to explore as much as possible the parameter space (Table 3.1). For management practices, the ranges were identical across the three sites. They were consistent with measured ranges found in the literature for oil palm in different contexts (Pardon et al., 2016a; Pipai, 2014). The range for mineral fertiliser annual rate after the 5th year was 0–212 kg N ha^{-1} yr^{-1}, which encompassed the whole range of values from 56 to 206 kg N ha^{-1} yr^{-1} mentioned in the literature for mature palms (Carcasses, 2004, unpublished data; FAO, 2004; Foster, 2003; Hansen, 2007; Wicke et al., 2008). The zero rate tested the extreme case, where no fertiliser was applied all along the simulation. The range for annual rate of empty fruit bunch application after the 5th year was 0–12 t of dry matter ha^{-1}, i.e. 0–30 t of fresh matter ha^{-1} per annum. In plantations, higher annual rates of up to 60 t of fresh matter ha^{-1} can occur (Redshaw, 2003), but such high rates are generally applied once every two years. For initial groundcover, we used the range of 20–60 % measured by Pipai (2014) in Papua New Guinea. For legume fraction in groundcover, we used a range of 0–100 %, to consider all the actual possibilities of management practices, from the sowing of a non-legume groundcover, to the sowing of a vigorous legume groundcover covering most of the area after 1 or 2 years. And for initial residue mass from previous palms, only one complete estimate of 85 t of dry matter ha^{-1} was available in the literature to our knowledge (Khalid et al., 1999a, 1999b). In the absence of other measurements, we applied a factor of ± 20 % to determine the range of 70–104 t of dry matter ha^{-1}.

For soil water dynamics parameters, the ranges for the runoff coefficient (Ponce and Hawkins, 1996) were based on measurements done at the three sites (Banabas et al., 2008). The range for the drainage coefficient was the same for the three sites and across all the soil layers. It was representative of the range of this parameter for different soil types used within the standard APSIM test data sets (Holzworth et al., 2011) and soils databases (Dalgleish and Foale, 1998). Within the model, the overall plant available water capacity of a soil profile is determined by the upper and lower limits of plant available soil water within each soil layer. However, a single parameter range is required for the sake of this analysis. The measurement error for the upper and lower limits of plant available soil water content is commonly 0.02 m m^{-1} (Dalgleish and Foale, 1998). A constant parameter range of 0.04 m m^{-1} was therefore applied to the lower limit of plant available soil water for each layer at each site to provide a method for a single, combined parameter adjustment for use by the Morris approach. The range for the maximum root depth, from 1 to 5 m, was based on measurements for oil palm in various contexts, including Papua New Guinea (Jourdan and Rey, 1997; Schroth et al., 2000; Sommer et al., 2000; Ng et al., 2003; Nelson et al., 2006).

Finally, for C and N cycling parameters, the ranges for soil organic C were based on actual measured values at Sangara and Sagarai and in a nearby planting for Hargy (unpublished PNGOPRA reports). The ranges were ± 20 % of the average measured values, which represented about twice the value of standard deviation for these measurements. The ranges were applied to the uppermost two layers only, as C content varies less in deeper layers. Ranges of C/N for empty fruit bunches and initial residues were taken from the literature and were also consistent with measured values at the sites. For empty fruit bunches, we determined a C/N range of 45–60 (Rosenani and Hoe 1996; In Moradi 2014; Gurmit et al., 1999, In Corley and Tinker 2003). For initial residues, we determined C/N ranges of 39–47 for fronds and of 145–174 for trunks, after measurements by Moradi et al. (2014).

3.2.3. Morris sensitivity analysis

We performed a sensitivity analysis to provide a parameter prioritisation (Saltelli et al., 2004) for N losses (Figure 3.2). This type of analysis is a means of ranking model parameters in terms of their effects on the variability in a model output. Although variance-based sensitivity indices are considered best practice to carry out comprehensive sensitivity analyses, they are hard to apply in the case of models with high computational costs (Saltelli and Annoni, 2010). In such a situation, as is the case with APSIM, the method described by Morris (1991) is a good choice, as it shares the positive qualities of the variance-based techniques, while requiring less computational resources (Campolongo et al., 2007). We applied this method, using the "morris" function from the "sensitivity" package (version 1.11.1) available in the R statistical software (R Development Core Team, 2010). This version of the function includes a space-filling optimisation of the experimental design (Campolongo et al., 2007).

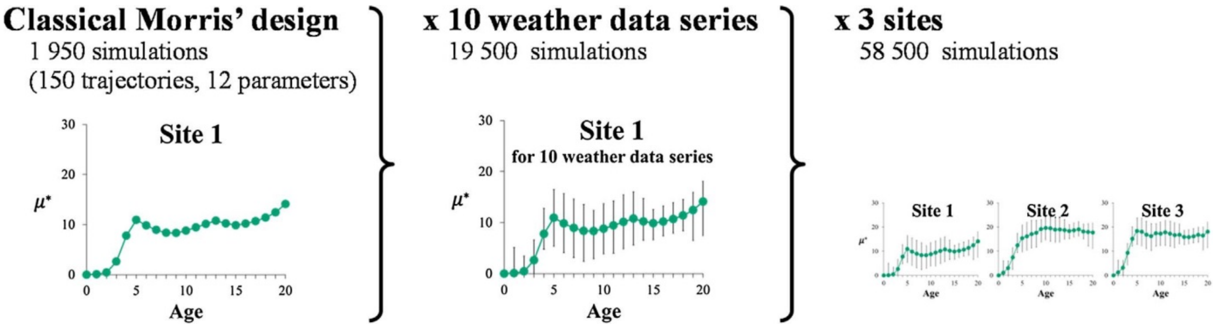

Figure 3.2. Structure of the sensitivity analysis.
58 500 simulations of 20 years were completed, which corresponds to 1 170 000 annual yield and N loss outputs.

The Morris sensitivity method belongs to the class of "One-at-a- time" sampling designs as it varies one factor at a time independently of the others, recording at each time the effect of this variation on the output. In this method, each dimension of the given parameter space is divided into a given number of levels and an initial level for each is chosen at random. Each parameter is adjusted by one level in turn and the resultant change in output is called the "elementary effect" of the parameter being changed. This space-filling approach (Campolongo et al., 2007) differs from the original Morris (1991) technique in that it creates a parameter trajectory that more efficiently explores the parameter space. The process is repeated a suitable number of times to capture the variability in elementary effect across the entire parameter space. Ranges for each parameter are normalised to allow for a comparison of elementary effects between parameters of differing magnitude.

Following Morris's method, two sensitivity indices were calculated for each of the 12 parameters: the mean of absolute values (μ^*) and the standard deviation (σ) of the elementary effects. The relative value of μ^* can be used to rank the importance of each parameter; the higher μ^* is, the more influential is the parameter. The σ value of a parameter indicates the interaction level between parameters or may indicate non-linearity in the response. In this analysis, each parameter range was split into 20 levels. After initial tests to identify the best trade-off between computational costs and adequacy of sampling, 150 parameter trajectories were used to explore the parameter space.

In total, for each site, we performed 1 950 simulations of a 20-year growth cycle, i.e. (1 + 12)*150. The effect of climate variability was examined by reproducing these 1 950 simulations for 10 different planting years, so that parameter sensitivity at any given plantation age up to 20 years was evaluated against 10 different annual climatic conditions for that site. In order to run simulations of 20 years, with 10 different planting years, 30-year climate records were needed. However, the climate records available were of 18 years for Sangara and Sagarai, and 28 years for Hargy. Therefore, we reproduced the 12 first years at the end of the records for Sangara and Sagarai, and the 2 first years for Hargy record.

Finally we calculated, for each age of the palms, the mean, minimum and maximum values of the 10 μ^* values corresponding to the 10 planting years.

3.3. Results

3.3.1. Outputs of the simulations

Simulated yields, N leaching and N_2O emissions are summarised on Figure 3.3. Overall, the mean values appeared realistic compared to field data recently reviewed for oil palm (Pardon et al., 2016a). Extreme values were reached for some particular combinations of parameter values, which confirmed that we covered sufficiently wide parameter ranges. For instance, some very low yields were modelled in Sagarai and Hargy, and even zero yields in Sangara. This occurred very rarely, when low N inputs were combined with high C inputs, i.e. no fertiliser, and/or no legume N fixation, combined with high amount of initial residue and/or high rate of empty fruit bunches. In these extreme situations, the soil N was immobilised by residue decomposition, leading to an accumulation of N in organic matter and to a dearth of N available for palm growth.

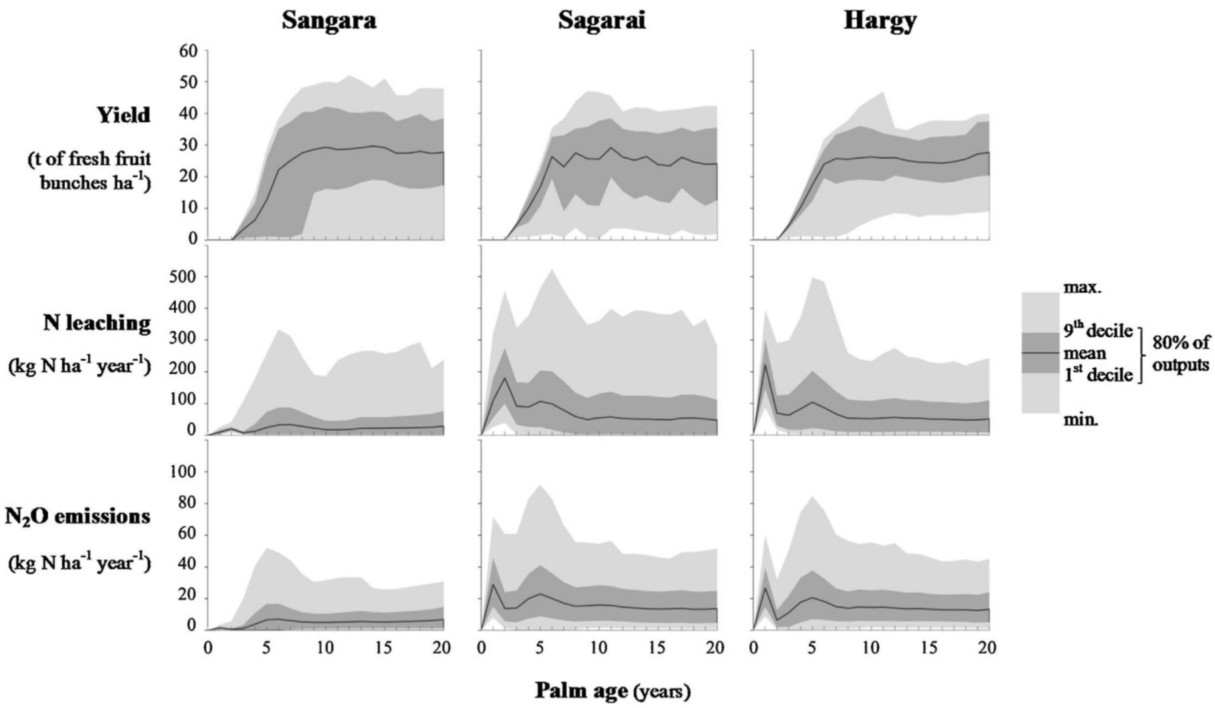

Figure 3.3. Simulated yield and N losses, showing mean, minimum, maximum, 1st decile and 9th decile values for the 19 500 simulations at each site.

The annual variability is not related to inter-annual climate variability, as simulations using the ten weather data sets are averaged in the figure.

Annual mean yields were 22, 21 and 21 t of fresh fruit bunches ha^{-1} yr^{-1}, at Sangara, Sagarai and Hargy; respectively (Figure 3.3). The results were more variable in Sangara and Sagarai than Hargy, which was consistent with the observed yields from the fertiliser trials. Mean simulated N leaching loss was 22, 72 and 69 kg N ha^{-1} yr^{-1}, at Sangara, Sagarai and Hargy; respectively. These simulated values were comparable to the range of 0–72 kg N ha^{-1} yr^{-1} reported in field measurements in oil palm (Pardon et al., 2016a; assuming a loss of 1–34 % of 0–212 kg of N applied). However, the losses of 72 and 69 kg N ha^{-1} yr^{-1} were close to the upper limit of reported measurements. Mean simulated N_2O emissions were always lower than N leaching, with 5, 16 and 15 kg N ha^{-1} yr^{-1}, at Sangara, Sagarai and Hargy; respectively. The estimate in Sangara was also realistic compared to the range of 0.01–7.3 kg N ha^{-1} yr^{-1} reported in field measurements in oil palm (Pardon et al., 2016a), while those in Sagarai and Hargy were higher. The high mean losses modelled in Sagarai and Hargy compared to Sangara were correlated with the differences in N response between the sites, and also consistent with the soil and climate conditions of the sites. In Sagarai, the excess N might have leached quicker than in Sangara because of more frequent intense short rain events, while denitrification was enhanced by the higher C content of soil. In Hargy, the excess N might have also leached quicker than in

Sangara because of much higher rainfall, while denitrification was enhanced due to moisture and soil C content even higher than in Sagarai.

There was a similar temporal pattern of N losses across all sites (Figure 3.3). A first peak of losses occurred over the 1^{st}-2^{nd} years, a second peak occurred over the 4^{th}–7^{th} years, and the emissions levelled off after the 8^{th}-10th years. The peaks of N leaching occurred 1 year after the peak of N_2O emissions, except at Hargy, where they were synchronous. The first peak happened when soil mineral N was accumulating over the first months after planting, due to the mineralisation of initial residues from the previous oil palm crop, whereas the uptake by groundcover vegetation was not yet at its maximum and uptake by palms was low (Figure 3.4). This excess soil mineral N might have been leached or denitrified. The second peak occurred when mineral fertiliser rates progressively increased, while the N fixed and stored in the groundcover vegetation was released by mineralisation, and uptake by palms was not yet at its maximum (Figure 3.4). For both peaks, the higher losses modelled in Sagarai and Hargy compared to Sangara might be due to the higher baseline N supply of soil, which would have accelerated the mineralisation of residues in Sagarai and Hargy. The slower mineralisation in Sangara would have reduced the amount of mineral N released and available for losses.

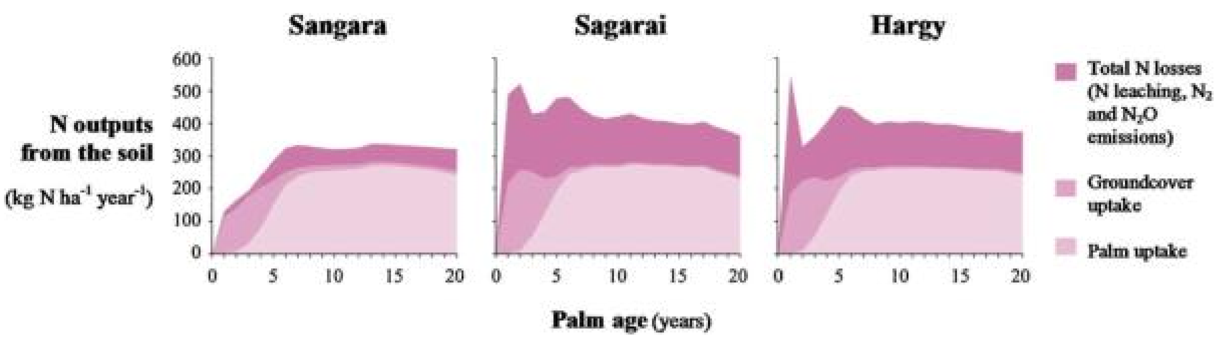

Figure 3.4. Mean values of N outputs from the soil over all simulations.

The annual variability is not related to inter-annual climate variability, as the ten weather data are averaged in the figure. The total N loss is higher than in Figure 3.3, because here N_2 emissions from denitrification are also taken into account.

3.3.2. Influential parameters

The influence of the twelve parameters on the outputs differed depending on site characteristics, age of the palms, and climate.

First, the relative influence of parameters on yield, and their interactions and/or non-linearities, were highly dependent on site characteristics (Figure 3.5). In Sangara, the yield was driven mostly by N fertiliser rate, and also by groundcover vegetation and its legume fraction. These three parameters showed higher interactions and/or non-linearities than in other sites, probably due to competition between groundcover vegetation and palms in a context of relatively low baseline N supply. In Sagarai, yield was driven mostly by two soil water dynamics parameters, being maximum root depth and water lower limit. Both of them showed higher interactions and/or non-linearities than other parameters. In Hargy, yield was driven mostly by N fertiliser rate, maximum root depth and drainage coefficient, but with an overall sensitivity, interaction and/or non-linearity lower than at the two other sites. These results confirmed that the most critical factors influencing yield were N supply-related ones in Sangara and water stress-related ones in Sagarai. For N losses, on the contrary, the ranking of the parameters was similar between sites (Figure 3.5). However, the influence of drainage was higher in Sagarai and Hargy, where inter- annual variability of climate and annual rainfall were higher. The influence of maximum root depth on N leaching was also higher in Hargy, where annual rainfall was higher. N fertiliser rate and drainage coefficient showed higher interactions and/or non-linearities than other parameters, especially in Sagarai and Hargy.

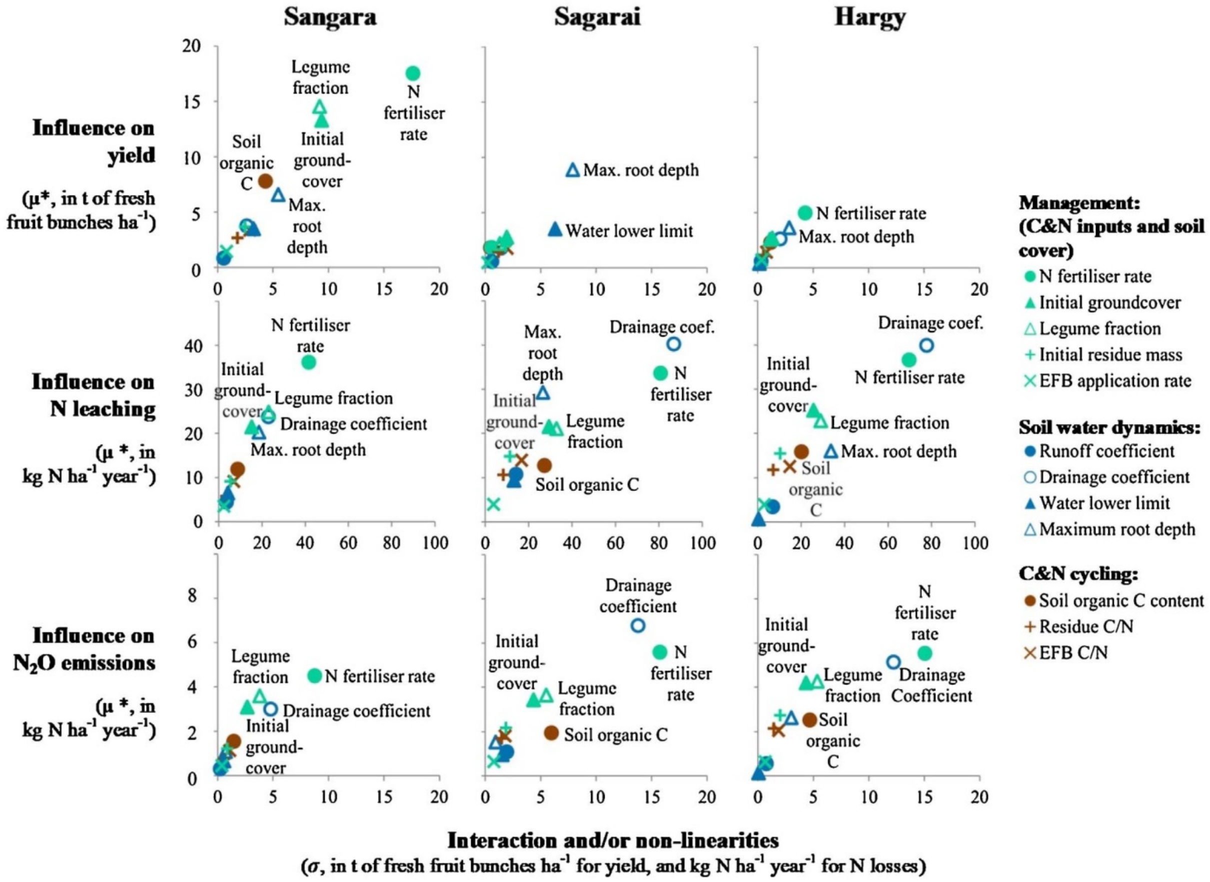

Figure 3.5. Effect of site characteristics on the influence and interactions/non-linearities of the parameters listed on the right of the graphs, on yield and N losses of oil palm plantations.

The values are annual averages over a 20-year-cycle. μ* is the mean of absolute values of the elementary effects of a given parameter. The higher μ* is, the more influential is the parameter. σ is the standard deviation of the elementary effects, which indicates nonlinear effects and the amount of interaction between parameters. The higher σ is, the more important is the interaction between the parameter and the other parameters tested, or the influence of the parameter is nonlinear. EFB: empty fruit bunches.

Second, for the three outputs, the influence of the parameters changed with the age of the palms, as shown in Figure 3.6. For instance, in Sangara, soil organic C content had a large influence on yield between the 5th-8th years but then decreased, whereas the maximum root depth became more and more influential with time. For N losses, the ranking of the parameters was also very different between the development stages of the palms. The first peak of N losses was driven by the drainage coefficient and, to a lesser extent in Sagarai and Hargy, by groundcover vegetation rate and soil organic C. The second peak was driven mostly by legume fraction and N mineral fertiliser rate and, in the case of Sagarai and Hargy, drainage coefficient. After about 10 years of age, N losses were driven by N mineral fertiliser rate and drainage coefficient, and also maximum root depth in the case of N leaching. Third, the influence of the parameters depended on climate (Figure 3.6).For instance, in Sangara, the influence of N mineral fertiliser rate on yield differed substantially according to climate, indicated by the large minimum-maximum error bars in the Figure. For N losses, climate variability had a higher impact in Sagarai than in the two other sites, as shown by the wider error bars. This was consistent with the fact that inter-annual climate variability is larger at Sagarai. The impact of climate was especially clear with respect to the influence of N mineral fertiliser rate and drainage coefficient on N leaching.

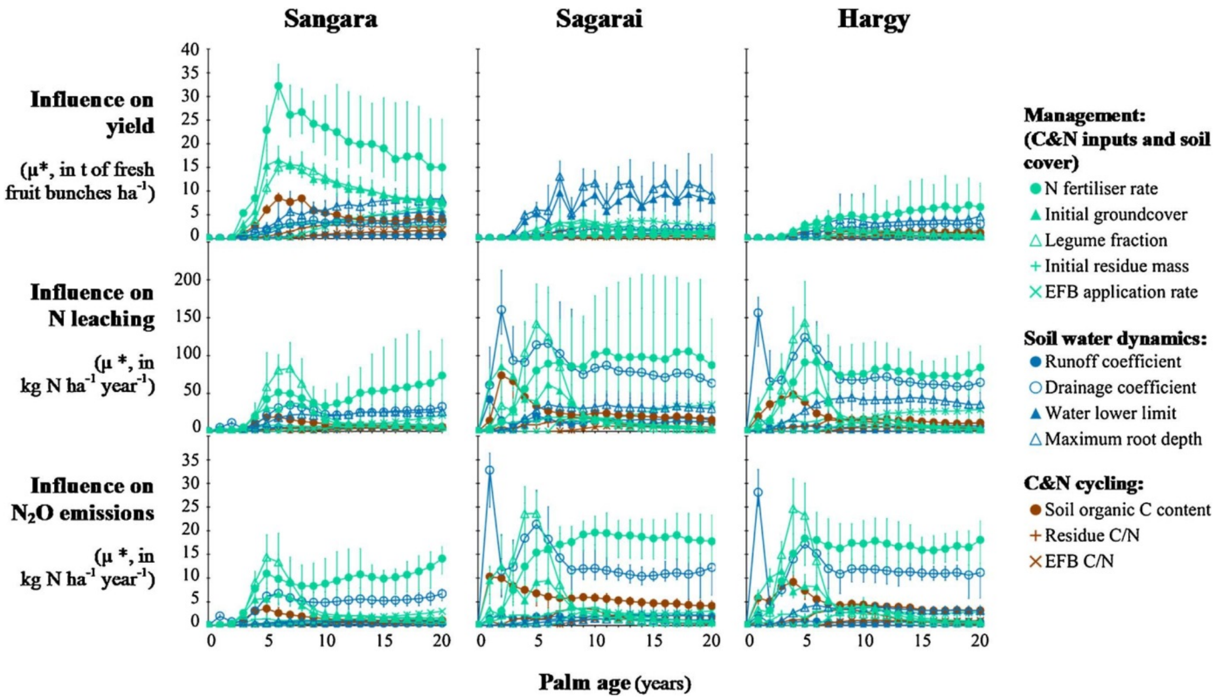

Figure 3.6. Effect of the age of palms and climate on the influence of the parameters listed on the right of the graphs, on yield and N losses of oil palm plantations.

μ* is the mean influence of the parameter on the chosen output. The higher μ* is, the more influential is the parameter. The error bars represent the minimum and maximum values among the 10 planting year scenarios, and hence illustrate the effect of climate on the magnitude of μ*. The annual variability of means is not related to inter-annual climate variability, as simulations using the ten weather data sets are averaged in the figure. The average influence of a parameter on an output is not directly calculated from the average value of the output, but from the comparison of individual simulations. Therefore, it is possible that the average influence of the parameter on the output exceed the average value of this output, as is the case for instance for yield in Sangara. However, this average influence cannot be higher than the maximum value of the output. EFB: empty fruit bunches.

3.3.3. Trade-off between yield and N losses

Unsurprisingly, across all sites, the management factor with most influence on N losses was N fertiliser rate. However, our simulations, as well as the fertiliser trials, indicated little or no response of yield to fertiliser rate at Sagarai and Hargy when other nutrients were non- limiting.

Thus, the model simulations suggested that mean optimal rate to achieve high yield while minimising N losses might be about 70–80, 0, and 30–40 kg N ha^{-1} yr^{-1} in Sangara, Sagarai, and Hargy; respectively (Figure 3.7). These mean optimal rates were estimated for one growth cycle, targeting an achievement of 90 % of the maximum yield reached in the simulations. At these rates, the mean annual yields would reach 25, 20, and 20 t of fresh fruit bunches ha^{-1} yr^{-1}, whereas the N losses would be below 20, 50, and 60 kg N ha^{-1} yr^{-1}, at the same sites; respectively.

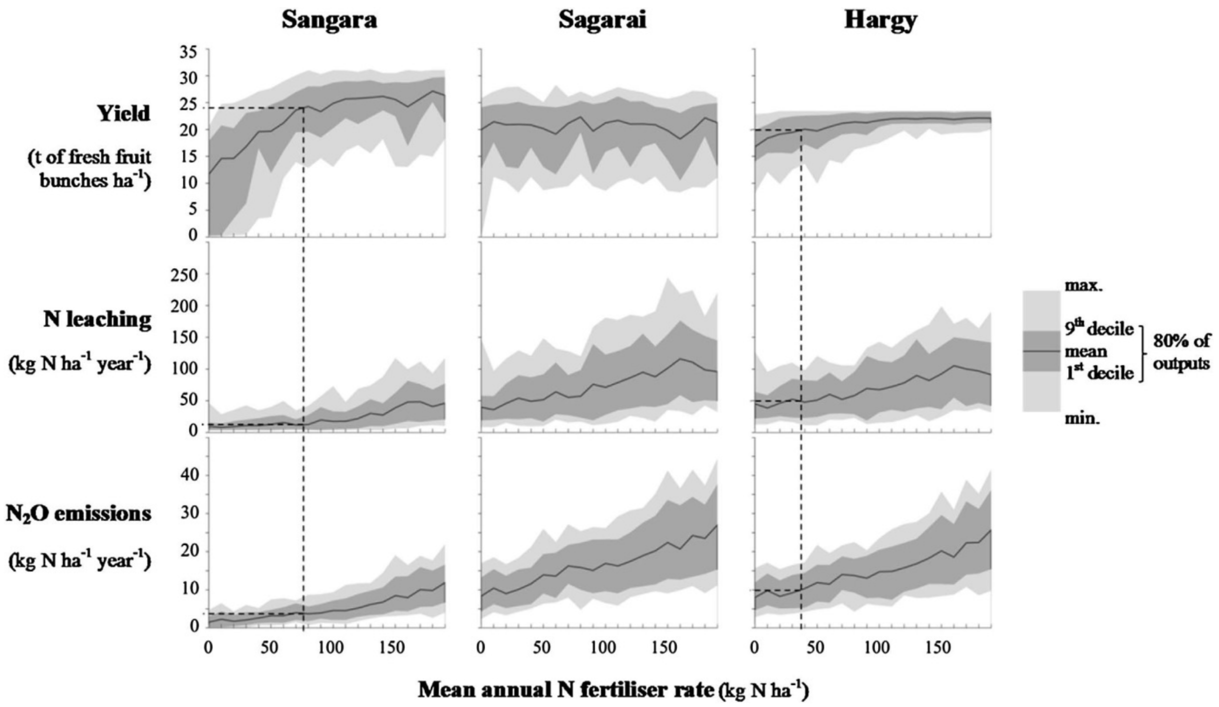

Figure 3.7. Response of yield and N losses to N mineral fertiliser rate and optimal rates of fertiliser. The values are annual averages over a 20-year-cycle. Dotted lines represent optimal rates of N mineral fertiliser to achieve high yield, i.e. 90 % of the maximum yield reached in the simulations, while limiting N losses. At Sagarai, the optimal rate would be 0 kg N ha^{-1} yr^{-1} according to the results.

3.4. Discussion

3.4.1. Relevance of the simulation built-up and outputs

Environmental conditions studied here spanned a wide range of conditions, which are shared with other oil palm producing areas. Climate records of 30 years are usually considered long enough to characterise the climate of a given location, which was the case at Hargy. The records were significantly shorter at Sangara and Sagarai, but still long enough to capture multi-year oscillations such as El Nino/ La Nina events, which are known to affect oil palm production. The results are not transferable to situations where a marked annual dry season may impact the production and N dynamics severely, because none of the studied sites had a severe dry season. However, the annual rainfall range of 2400–4300 mm, with the particular case of an inter-monthly variability in Sagarai, corresponds to the climate conditions occurring in the major oil palm growing areas.

The conditions tested spanned several mineral soil types also found in Indonesia and Malaysia, formed on alluvial and volcanic ash deposits. The main soil texture groups of the FAO (2001) classification are covered in this study: fine (Sagarai), medium (Sangara) and coarse (Hargy). Finally, the range of soil organic C content across the three sites, from 1.7 to 6.4 %, spanned most of the values found in major oil palm cultivated areas, except for some poor soils depleted in organic C (Khasanah et al., 2015). However, these results are not transferable to peatlands or possibly to highly acidic soils.

The range of management practices studied here spanned most of the situations found in major oil palm producing areas. In some particular cases, our results may not be transferable, as is the case for very poor soils, where high rates of up to 60 t of fresh empty fruit bunches may be applied per ha (Redshaw, 2003), or in areas where nutrient deficiencies other than N have not been corrected. However, in general, our ranges for fertiliser rates, organic matter application amounts, and groundcover management practices covered the values published in the literature (Pardon at al., 2016a; Pipai, 2014).

The results of our study indicated that N inputs were particularly influential, as expected, although their effects were variable across sites and tested outputs. N fertiliser rate was a particularly important parameter for yield and N losses in Sangara, where there was a clear response to N fertiliser, but it did not influence much the yields in the two other sites. Such contrasted yield responses to fertilisers in oil palm were also reported in the literature. For example, fertiliser trials in Indonesia have frequently shown positive responses of yield to N fertiliser (Foster and Parabowo, 2003; Tampubolon et al., 1990), whereas other trials elsewhere have shown little or no response (Chew and Pushparajah, 1995; Dubos et al., 2016). Therefore, our three sites spanned different conditions, and results may be transferable for other situations, where N is limiting or not. However, caution is needed, as different factors may limit the yield, such as other nutrients, water supply or solar radiation, however their effects on N dynamics and losses may differ between the cases.

Modelled N losses peaked over the first years of the crop cycle (Figure 3.3), which was consistent with measurements in oil palm plantations (Pardon et al., 2016a). Most measurements of N leaching were done in Malaysia, and measurements of N_2O emissions were done in Indonesia and Papua New Guinea (Pardon et al., 2016a). At Sangara, the simulated N losses were comparable to the range of measured values. At Sagarai and Hargy, the simulated N losses were close to the upper limit reported for N leaching, and above this limit for N_2O emissions. This suggests that high soil C content and/or high rainfall may generate particularly high emissions, which is not surprising. However, given that very few measurements of N losses under oil palm are currently available, especially for N_2O emissions, this comparison must be considered with caution. These high modelled values may also be overestimated by the APSIM-Oil palm model, resulting from the high soil organic C contents of Sagarai and Hargy, as discussed in the following section.

3.4.2. Study limitations

There was a large variation in the magnitude and ranking of parameter influence among the three sites. We could expect that a similar modelling exercise covering even more diverse environments may produce further contrasted results and help to explore further relevant influences. The influence of other parameters, such as placement, timing and splitting of N fertiliser, would be worth studying to explore other management implications.

For oil palm, only the WANULCAS model (Noordwijk et al., 2004) simulates practices related to spatial heterogeneity, such as placement of fertiliser. Spatial interactions between N inputs and other parameters (e.g. stemflow, throughfall, root distribution and organic matter inputs) could have a significant impact on N losses estimates. WANULCAS predicted higher N leaching rates than other models in a comparison using standard conditions (Pardon et al., 2016b). A probable reason for this high estimate was that, in the WANULCAS simulation, N fertiliser was applied close to the trunks, where water infiltration might be higher due to the stemflow.

Regarding N leaching, the influence of maximum root depth might be underestimated, because the N is considered as lost in APSIM-Oil palm when it reaches the bottom of the deepest layer, regardless of the maximum root depth which can be shallower. The marked influence of the drainage coefficient on N losses, as highlighted in this modelling work, may provide an explanation of why clay content has been shown to be important across a broad range of models (Pardon et al., 2016b).

For N_2O emissions, the results seemed to be overestimated in Sagarai and Hargy, compared with field measurements reported for oil palm (Pardon et al., 2016a). This could result from the fact that APSIM-Oil palm does not model the potential reduction of N_2O produced in a deep layer to N_2 in a shallower layer, before its release in the atmosphere. In sites with high C content in deeper soil layers, such as in Hargy, a significant proportion of the high simulated N_2O emissions might be reduced before reaching the soil surface.

The study of other N loss pathways, such as NH_3 volatilisation, runoff and erosion, would give a more comprehensive view of the drivers of N losses. However, to our knowledge, no process-based model is currently available for oil palm to simulate NH_3 volatilisation and erosion along the whole growth cycle, together with the other N loss pathways.

Finally, as APSIM-Oil palm has been validated for production at the three sites studied here, our assessment of the influence of the parameters on yield should be robust. For N losses, although N_2O emissions might be overestimated, mean modelled values appeared realistic compared to field data (Pardon et al., 2016a). Hence, the influence of parameters on N losses is also likely to be reliable. Caution is required regarding the effect of legume management on N losses. In APSIM-Oil palm, a constant 44 % of the N content of the legume biomass is set to come from atmospheric fixation, which is consistent with average measured values reported for standard practices (Pipai, 2014). Yet, in the field, legumes can regulate their N provision, by fostering N fixation or N uptake from soil, depending on soil N mineral content (Giller and Fairhurst, 2003). Given the economic and environmental importance of biological fixation, we discuss in the following section potential legume management practices to reduce N losses.

3.4.3. Implications for managers, experimentalists, and modellers

Previous crop residues provide a large N input to the soil, but yield and N losses were not very sensitive to the magnitude of this input. This low influence could be due to the immobilisation in the soil of N from residue mineralisation, preventing its uptake and/or emissions to air or groundwater. A strategy for reducing N losses could be to export those residues as feedstock in bioenergy chains (Paltseva et al., 2016). The decomposing initial residues constitute a breeding site for rhinoceros beetles, *Oryctes rhinoceros,* which is an important oil palm pest in Southeast Asia (Gillbanks, 2003). Exporting the residues may hence limit the effects of this pest. However, such a practice would also involve significant costs and labour, as the quantity of residue is about 70–80 t ha^{-1} of dry matter (Khalid et al., 1999a). Such a proposition would also need to be carefully evaluated, depending on soil fertility, in order to avoid long-term depletion of C and N soil stocks and decrease in soil quality.

Empty fruit bunch application rate and C/N had a low influence on yield and N losses. This result seems to strengthen the common practice of preferentially using empty fruit bunches for enriching the low-carbon soils of the plantations, rather than for N management. As for initial residues, an alternative practice could be to use empty fruit bunches as bioenergy feedstock, or for composting, which is an expanding practice. Such practices reduce the amount of matter to bring back to the field, but they also involve costs and labour for the treatment of empty fruit bunches.

Mineral N fertiliser rate and legume fraction had significant influence on N losses, but low influence on yield, in Sagarai and Hargy. For N fertiliser, in such conditions where N input is not the limiting factor, lower rates may help to reduce N losses, whilst not significantly affecting yields. Lower fertiliser rates would also have the advantage of reducing costs of fertiliser application. Conclusions regarding the legume fraction may not be robust given the assumption in APSIM-Oil palm, that legume N fixation rate is a constant 44 %. Using a variable rate of legume N fixation, depending on the soil N mineral content, would be more realistic. Such type of N fixation modelling already exists, for instance in the AFISOL crop model for pea (Vocanson, 2006) or EPIC crop model for soybean (Bouniols et al., 1991).

Assuming a variable fixation rate, practices could be adapted in order to make the best use of the catch/fixation and release capabilities of the cover. For instance, a denser or earlier sowing of the legume might help to catch the excess N accumulating in soil from the mineralisation of initial residues. This would help to mitigate the first peak of losses. This denser or earlier sowing of the legume could also enhance other important services of the groundcover in young plantations, such as regulating weed growth; preventing runoff and erosion; and reducing the impact of *Oryctes* beetle infestation, by increasing the speed of residue decomposition, and reducing the access to breeding sites (Giller and Fairhurst, 2003). Then, mineral N fertiliser rates might be adjusted more precisely to the legume growth. From 1–3 years of age, the fertiliser rates could remain the same as for standard practices, as N release by the legume groundcover is still low, and palm roots do not yet fully occupy the field. But at about 4–5 years of age, in sites with no response of yield to N fertiliser, N fertiliser rates could be reduced to enhance atmospheric N fixation. And at about 6–8 years of age, N fertiliser rates could be reduced to adjust more precisely N inputs to the N released by legume decomposition. This would help to mitigate the second peak of losses.

However, these potential management practices for legume ground- cover need further investigation. More field measurements specific to oil palm plantations are needed, such as the response of N fixation rate to initial residue amount, the response of N fixation rate to soil N mineral content, and the dynamics of legume N release to the soil. This knowledge would allow to improve APSIM-Oil palm, and to test scenarios involving legume fraction, N fertiliser rates and initial residues, in order to identify best practices.

The drainage coefficient was identified as an influential parameter for both N_2O emission and N leaching. This parameter is important for tipping bucket-type models as the one used in APSIM-Oil palm to simulate soil water contents. Defining soil drainage with a higher accuracy could hence reduce uncertainty in modelling. Alternatively, given the importance of water movement for N losses, it may be worthwhile using a Richards' equation-based model instead of a tipping bucket approach. Richards' equation-based models require more data regarding the soil water characteristic, but methods exist to simply estimate the necessary parameters (Huth et al., 2012). Furthermore, the large interaction between climate and influence of parameters emphasises the need for realistic long-term weather datasets for modelling studies in perennial crops, as is the case for modelling crop rotations (e.g. Verburg et al., 2007).

This modelling work also pointed out several gaps in the available data on N losses and their drivers. In particular, there are little data for palms under 10 years old. Yet, N losses are likely to be higher under young palms than older ones, according to this analysis and previous measurements (Ishizuka et al., 2005 for N_2O; Foong et al., 1983 and Foong, 1993 for N leaching). There have been few studies onto the drivers of N losses in young plantations, and this study suggests they would differ from those in mature plantations. Legume cover fraction, drainage and soil organic C seem to be important parameters to measure, when measuring N_2O and N leaching under young palms. Furthermore, as the inter-annual and shorter time scale variability of climate can modify the magnitude and the ranking of parameter influences from year to year, it is essential to have accurate long-term climate records. Datasets containing both N_2O emission and N leaching measurements would also be very useful for model validation.

Finally, this study highlighted the most influential management parameters that must be considered to reach optimal trade-offs between yields and N losses. The site-specificity of these trade-off assessments indicates the value of the model for assessing site-specific economic-environmental trade-offs. Just as the economic optimum rate of fertiliser must be assessed in site-specific trials, so should N losses be predicted on a site-specific basis. Yields can be monitored quite readily and there are clear economic incentives to investigate responses to management factors. However, N loss responses are prohibitively expensive to measure and do not provide direct benefits. A model combining accurate estimates of the two may therefore give managers a cost-effective tool for assessing management scenarios to strike the best compromise in the economic-environmental trade-offs. It is important that the starting conditions for each modelled crop cycle are well defined as critical factors such as soil properties, previous crop biomass and legume cover change with time. Identifying and quantifying trade-offs to guide management is crucial for optimising economic and environmental outcomes, as human interference in the nitrogen cycle has been identified as one of the three most pressing environmental problems facing humanity (Rockström et al., 2009).

3.5. Conclusions

We undertook a Morris's sensitivity analysis of APSIM-Oil palm for three sites in Papua New Guinea. The parameters having most influence on N losses were N fertiliser rate, drainage and fraction of legume in the vegetation groundcover. We showed that the influence of parameters depended on site, age of the palms, and climate. N fertiliser was not a driver of yield at all sites. For young palms, legume fraction and soil organic C content were important drivers, while after 10 years of age the most important drivers were N fertiliser rate and drainage. Climate particularly affected the influences of N fertiliser rate and drainage on N leaching, at sites where rainfall was variable. We highlighted that measurements of N losses are needed for young palms, as N losses are likely to be higher under young palms and the drivers are likely to differ from those in mature plantations. As shown at the three study sites, optimal ranges of fertiliser N rate to achieve efficient trade-offs between yield and N losses may differ substantially between sites. Models may hence be useful to quantify these trade-offs and point to changes in management that are likely to be beneficial. Coupling model outputs with life cycle assessment, that allows for assessing potential environmental trade-off along the supply chain, may be also needed to assess the best practices when accounting for potential impacts beyond the plantation edge, notably when comparing management alternative for recycling or exporting field residues (Chiew and Shimada, 2013; Wiloso et al., 2015).

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We identified the key drivers of N losses and yield in APSIM-Oil palm process-based model. The Morris' sensitivity analysis also provided 58 500 complete simulations of oil palm growth in various environmental and management conditions. We hence used all the information identified in the previous chapters, together with expert knowledge, to build IN-Palm, an agri-environmental indicator for N losses in oil palm plantations.

4. IN-Palm: an agri-environmental indicator to assess potential nitrogen losses in oil palm plantations

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Contribution types*	Contributors	Description
Conceptualisation	Cécile Bessou, Lénaïc Pardon, Christian Bockstaller, Paul Nelson, Jean-Pierre Caliman, Jacques Ranger	Goals, scope, methodological choices, and conception of the nitrogen leaching trial (Jacques Ranger)
Methodology	Cécile Bessou, Christian Bockstaller, Raphaël Marichal, Paul Nelson	Mentoring for scientific writing and agri-environmental indicator development methodology
Software	Lénaïc Pardon, Rémi Carcasses	Programming of IN-Palm in Excel (Lénaïc Pardon) and preliminary version of IN-Palm (Rémi Carcasses)
Validation	Jean-Pierre Caliman, Christian Bockstaller, Jean-Paul Laclau, Cécile Bessou	Validation of the scientific and operational relevance of the methodological choices, analyses and software
Formal analysis	Lénaïc Pardon, Ribka Sionita, Raphaël Marichal, Cécile Bessou	Analysis of the data from the nitrogen leaching trial
Investigation, data collection	Ribka Sionita, Lénaïc Pardon, Raphaël Marichal, Cécile Bessou	Data collection for the nitrogen leaching and runoff-erosion trials (Ribka Sionita), interviews and field observation for management practices (Lénaïc Pardon, Raphaël Marichal, Cécile Bessou)
Resources	SMART-Research Institute (Sumatra, Indonesia) and CIRAD (Montpellier, France)	Field work, office, computational resources, accommodation, travels
Data Curation	Ribka Sionita, Lénaïc Pardon	Data checked by Ribka Sionita, with help from Lénaïc Pardon
Writing - Initial draft	Lénaïc Pardon	Text, figures, tables
Writing – Review and editing	Co-authors: Lénaïc Pardon, Christian Bockstaller, Raphaël Marichal, Ribka Sionita, Paul Nelson, Benoît Gabrielle, Jean-Paul Laclau, Pujianto, Jean-Pierre Caliman and Cécile Bessou	Critical review, comments, re-phrasing, complementary references
Oral or informal contribution	Experts: Murom Banabas, Victor Baron, Bernard Dubos, Neil Huth, Christophe Jourdan, Emmanuelle	Advice and comments about the relevance of IN-Palm

	Lamade, Jean Ollivier, Hsiao-Hang Tao, Alif Saifudin, Eti Testiati, Putri Aulia Wahyuningsih and Rudy Harto Widodo	
Visualisation	Lénaïc Pardon	Conception of figures
Supervision	Cécile Bessou, Paul Nelson, Benoît Gabrielle	Oversight and leadership responsibility for the research activity planning and execution

* Contributions typology is from Allen et al. (2014)

Abstract

Oil palm is currently cultivated on about 19 M ha and palm oil represents more than one third of the global vegetable oil market. Addition of nitrogen via legume cover and fertilisers is a common practice in industrial oil palm plantations. A part of this nitrogen is prone to be transferred to the environment and can contribute significantly to environmental impacts. To improve the sustainability of palm oil production, it is crucial to determine which management practices minimise N losses. Continuous field measurements would be prohibitively costly as a monitoring tool, and in the case of oil palm, available models do not account for all the potential nitrogen inputs and losses or management practices. In this context, we decided to develop IN-Palm, a model to help managers and scientists to estimate nitrogen losses to the environment and identify best management practices. The main challenge was to build such a model in a context of knowledge scarcity. Given these objectives and constraints, we developed an agri-environmental indicator, using the INDIGO® method and fuzzy decision trees. We performed a validation of the nitrogen leaching module of IN-Palm against field data from Sumatra, Indonesia. We also used IN-Palm to test theoretical management changes in residue and fertiliser management. IN-Palm is implemented in an Excel file and uses 21 readily available input variables to compute 17 modules. It estimates annual emissions and scores for each nitrogen loss pathway and provides recommendations to reduce nitrogen losses. IN-Palm predictions of nitrogen leaching were acceptable according to several statistics calculated, with a tendency to underestimate nitrogen leaching. IN-Palm was efficient to help testing management changes in a given context while accounting for climate uncertainty. Finally, a complementary test of IN-Palm by the end-users will be performed in a plantation in Sumatra.

4.1. Introduction

Oil palm is an important crop for global production of vegetable oil and for the economies of many tropical countries. The area of land under oil palm is currently about 19 M ha (FAOSTAT, 2014) and palm oil represents more than one third of the global vegetable oil market (Rival and Levang, 2014). Oil palm is very productive and addition of nitrogen (N) via legume cover and fertilisers is a common practice to maintain productivity and avoid depleting soil resources. Rates of N fertiliser application can amount to 100 to 200 kg N ha yr^{-1} under adult palms, and application of fertilisers accounts for a large share of the production costs, ranging between 46 % and 85 % of field costs (Pardon et al., 2016a). A part of fertiliser-derived N is prone to be transferred to the environment and can contribute significantly to environmental impacts, such as eutrophication, acidification and climate change (Choo et al., 2011; Schmidt, 2010). Moreover, N flows are important to minimise, as they were identified as one of the anthropogenic perturbations already exceeding the planetary boundaries beyond which the Earth system may be irreversibly altered (Steffen et al., 2015). Different forms of N compounds are particularly important, notably ammonia (NH_3), nitrous oxide (N_2O), which is a potent greenhouse gas, and nitrate (NO_3^-), whose high concentrations are well known to affect water quality and aquatic ecosystems functioning.

To improve the sustainability of palm oil production systems, it is crucial to determine which management practices minimise N losses. Because N losses involve numerous compounds and impact pathways and are temporally variable, field measurements would be prohibitively costly as a continuous monitoring tool. On the other hand, models can be useful to estimate potential losses based on current knowledge. However, in the case of oil palm plantations, there is insufficient knowledge to appraise all loss mechanisms. Available models do not account for all the potential N inputs and losses or management practices, such as residue and cover crop management. This leads to high uncertainty in N loss estimations (Pardon et al., 2016b). In this context, we decided to develop a model specific to oil palm that estimates all potential N losses to the environment, as influenced by management practices, throughout the whole crop cycle.

Given our objectives and constraints, we decided to develop an indicator derived from the nitrogen indicator of the INDIGO® method for developing agri-environmental indicators (Bockstaller et al., 1997; Bockstaller and Girardin, 2008). Such indicators are more suitable than process-based models for use in conditions with knowledge scarcity, as they use a limited number of input variables, while harnessing readily accessible data from a range of sources, such as measured or modelled, qualitative or quantitative, empirical or expert knowledge (Girardin et al., 1999). In their typology of indicators, Bockstaller et al. (2015) described such indicator as predictive effect-indicator based on an operational model, differing from causal indicators using one or simple combination of input variables and measured effect indicators. This kind of indicators also has the advantage of being sensitive to practices and allowing ex-ante assessments in form of simulation. Thus, even if estimates made by indicators are less precise than the ones made by the best process-based models, they may be sufficient to assess environmental risks and to support decisions based on site-specific practice levers.

This paper describes our development of an agri-environmental indicator, IN-Palm, designed to enable managers of oil palm plantations to answer the question: “what practices can I implement in this field, this year, to reduce N losses, given the environmental conditions, characteristics of the field, and long-term consequences of previous practices?”. IN-Palm was derived from the INDIGO® indicator for N risk assessment in vineyards (Thiollet-Scholtus and Bockstaller, 2015). A preliminary adaptation of the INDIGO® N indicator to oil palm had been done by Carcasses (2004), but it had not been validated, and it estimated only three types of N loss, i.e. N leaching, NH_3 volatilization and N_2O emissions, and only for oil palm plantations older than 7 years. In order to improve the extent and relevance of the risk assessment, we now account for all the loss pathways throughout the complete crop cycle. In order to address the lack of knowledge and to include all the available and relevant data, we used a decision tree modelling approach (Breiman, 1984) to design most of the indicator modules, combined with fuzzy logic (Zadeh, 2008) to obtain a more realistic and sensitive output space. Fuzzy decision tree modelling approach has already been used for agri-environmental modelling (e.g. van der Werf and Zimmer, 1998, for the pesticide indicator of the INDIGO® method; see Papadopoulos et al., 2011, for a detailed example of the method applied to N balance in agriculture). Here, we present the design, calibration and validation of IN-Palm. We end by discussing the results of scenario testing aimed at assessing the sensitivity of the indicator to management practices, and hence its usefulness as a decision-making tool for field management.

4.2. Materials and methods

4.2.1. INDIGO® method and fuzzy decision tree modelling approach

The development of INDIGO® agri-environmental indicators started in the 90’s (Bockstaller et al., 1997; Girardin and Bockstaller, 1997) and has resulted in a set of agri-environmental indicators (Bockstaller et al., 2009, 2008). The original concept was to build operational models that would be efficient to improve agricultural management practices, despite the lack of knowledge to model all soil-plant-atmosphere transfer mechanisms involved in agroecosystems.

INDIGO® indicators are generally structured as a set of risk (R) modules, each yielding an output, e.g. the R-N_2O module estimates the risk linked to nitrous oxide emissions. As indicators must be readily understandable by non-experts, it was proposed that the outputs be expressed not in physical units but in dimensionless scores on a scale of 0 to 10, calculated with respect to reference values. The reference values represent minimum values of the indicator output for which the agroecosystem is considered to be sustainable (Bockstaller et al., 1997).

To develop IN-Palm, we followed the five-step methodology proposed by Girardin et al. (1999): (1) identification of the objectives and end-users, (2) construction of the indicator, (3) selection of reference values, (4) sensitivity analysis, and (5) validation of the indicator, i.e. demonstration that the indicator satisfies the target objectives. The objective of IN-Palm is to serve as a decision-support tool for oil palm plantation managers to help them minimise risks of N loss to the environment.

We also introduced a new modelling approach for most of the modules: decision tree modelling. Decision tree modelling (Breiman, 1984) is particularly suitable here, as it enables quantitative outputs to be obtained without simulating the actual processes that are not fully understood, but by instead integrating expert knowledge as rules. One of the limits of standard decision trees, though, is that their output space is discontinuous. Indeed, the model may react abruptly to a small variation of input, i.e. with a threshold effect between limit of classes (Bockstaller et al., in revision), while the actual system may react more smoothly. Or it may not react, due to a too-coarse class structure, while the actual system does react. In order to obtain a more realistic output space, the modeller needs to increase the number of rules, which requires more knowledge and quickly increases the complexity of the model (Craheix et al., 2015). Application of fuzzy logic (Zadeh, 2008) to decision trees is a very efficient method in such a context, as continuous outputs can be obtained from exactly the same tree structure, without requiring more knowledge (Olaru and Wehenkel, 2003). Another advantage of the method is that this process of aggregation is transparent and reproducible.

To build and compute our fuzzy decision tree modules we used the same method as van der Werf and Zimmer (1998). First, for each module, the choice of the input variables, the structure of the tree, the conclusions of the rules, and the threshold values between classes were defined by expert judgment, using all available knowledge. Second, for each input factor, we defined two classes: Favourable and Unfavourable. More classes for each factor would require more knowledge to justify the threshold values, whereas preliminary tests, using the Fispro software (Guillaume and Charnomordic, 2010), showed that precision in outputs was not significantly improved. Third, we used a cosine function for all membership functions, because this produces a smoother and more realistic transition between the two classes than a linear function, without requiring more parameters (van der Werf and Zimmer, 1998). Fourth, to deduce the outputs of each module, we used Sugeno's inference method (Sugeno, 1985).

4.2.2. Modelled processes

Recent studies have identified important peculiarities of N dynamics and losses in oil palm plantations. First, published measurements show that N dynamics and N losses vary over the cycle, with highest losses reported under young plantations (Pardon et al., 2016a).

Second, a legume understorey, e.g. *Pueraria phaseoloides* or *Mucuna bracteata*, is generally sown at the beginning of the growth cycle, and the N fixed by the legume was identified as one of the largest N fluxes (Pardon et al., 2016a). The amount of legume understorey was also reported to be one of the most influential parameters on N losses before 7 years of age in a sensitivity analysis of APSIM-Oil palm simulation model (Pardon et al., 2017). Moreover, in a range of models compared, N fixation was always modelled with constant fixation rates (Pardon et al., 2016b), while in the field, legumes usually have the capacity to regulate their N provision, by fostering N fixation or N uptake from soil, depending on soil mineral N content (Giller and Fairhurst, 2003).

Third, internal N fluxes within the agroecosystem, such as N released during decomposition of palm residues, were identified among the largest N fluxes (Pardon et al., 2016a). Moreover, the modelling, or not, of the kinetics of residue N release to the soil had a significant impact on the magnitude and timing of the first peak of losses simulated by several models (Pardon et al., 2016b).

Fourth, N losses were reported to have a high variability, depending, among others, on management practices and spatial variability (Pardon et al., 2016a). For instance, the amount of understorey vegetation, or the placement of residues on the ground, may affect runoff and erosion.

We designed IN-Palm in order to account for peculiarities of the oil pam system and obtain a complete estimate of N losses: (1) modelling of all loss pathways at all crop ages ; (2) modelling the contribution of the legume understorey in one specific module, with N fixation rate depending on mineral N available in soil; (3) modelling the kinetics of litter decomposition and N release in soil with two intermediate modules; and (4) accounting for the spatial effect of management practices, with an intermediate module estimating the fraction of soil covered.

4.2.3. Data used for design, calibration, reference values and validation

Different sources of data were combined for four different purposes: (1) to design the structure of the indicator, (2) to calibrate modules, (3) to define reference values for losses, and (4) to validate the R-Leaching module and test scenarios. For each of these purposes, one or several sources of data were used (Figure 4.1).

For design of the structure, calibration of the modules, and definition of reference values, we mainly used three sources of data: measurements of N fluxes and losses in oil palm plantations synthesised in a literature review (Pardon et al., 2016a); qualitative and quantitative data from a range of models used for estimating N losses in oil palm and assessed in a model comparison (Pardon et al., 2016b); and expert knowledge from a panel of experts.

For design of the structure and module calibrations, we also used existing models. We used two regression models, one for estimating NH_3 volatilization from organic fertiliser (Bouwman et al., 2002c) and the other for NO_x emissions (Bouwman et al., 2002a). To calibrate the N_2O emission modules we used the factors and classes defined in (Stehfest and Bouwman, 2006). Finally, we used a dataset of 58,500 simulations (Pardon et al., 2017), from the APSIM-Oil palm process-based model (Huth et al., 2014), for the calibration of the Palm N Uptake module and estimation of evapotranspiration in the Soil Water Budget module.

For validation of the R-Leaching module and the scenario testing, we used three measurement datasets from an oil palm plantation in Sumatra, Indonesia. The first dataset was from a 2-year-long trial investigating the response of N losses, via runoff and erosion, to slope and soil cover management under adult oil palms (Sionita et al., 2014). The results of this trial were available in an aggregated format, and we used them for the calibration of the R-Runoff-Erosion module. The second dataset, described in more detail below, was from an 8-year-long trial in which N concentrations in soil solution were measured. We used this dataset for the validation of the R-Leaching module. The third dataset was a 16-year-long rainfall record and soil characteristics, already used in a model comparison (Pardon et al., 2016b). We used this dataset to perform scenario testing of IN-Palm.

The trial in which N concentrations in soil solution were measured was conducted between 2008 and 2015 in a mature oil palm field. Nitrate and ammonium concentrations were measured in soil solution at three depths (0.3, 1 and 3 m) under palms planted in 1993 on flat land with a sandy loam soil texture, less than 2% soil organic carbon (C) content, and average rainfall of 2,363 mm yr^{-1}. The plot was managed following standard industrial management practices, and urea was applied manually twice per year in weeded circles of about 2 m around the palms. A total of 48 tension lysimeters (porous ceramic cups) were installed in 2005 and the data began to be stable in 2008, under 15-year-old palms. Sixteen ceramic cups were located at each of the three depths to sample representatively the spatial variability of organic matter and fertiliser inputs within the plantation. For each ceramic cup, a suction of 80 kPa was applied twice a day and a composite sample was analised weekly to determine nitrate and ammonium concentrations. A total of 6465 samples were analised from 2008 to 2015. Weather data was recorded in an open area located 100 m from the experimental plot: rainfall and N concentration of rain were recorded daily; solar radiation, air temperature, air humidity and wind speed were recorded semi-hourly by a Davis automatic weather station. Urea application date and rate, as well as production of fresh fruit bunches, were also recorded.

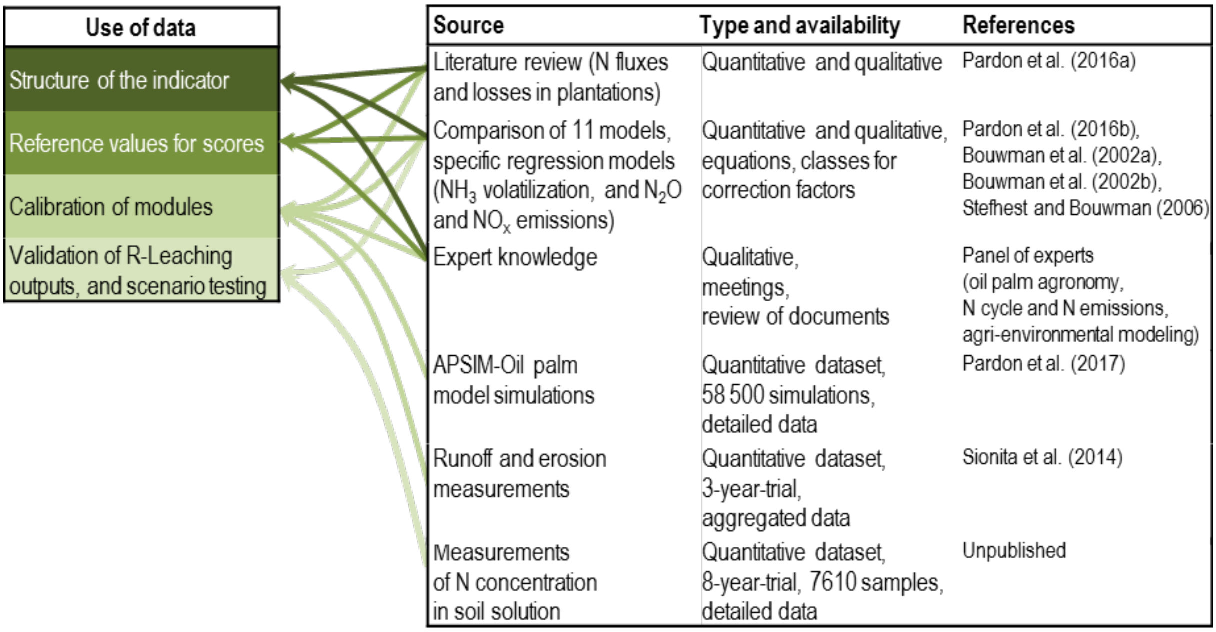


Figure 4.1. Sources of data used in IN-Palm development and validation.

Data from the literature, existing models, measurement datasets and expert knowledge, were used for the design of the structure, score calculations, module calibrations, validation of R-Leaching module and scenario testing.

4.2.4. Validation of the R-leaching module

In order to assess the capacity of the indicator to reach the objectives, we validated the R-Leaching module. Three validation steps were proposed by Bockstaller and Girardin (2003): validation of the structure of the indicator by a panel of experts, validation of the soundness of indicator outputs, and validation of the utility by end-users. In this study, we performed the two first steps.

Structure of the indicator was validated by a panel of experts, who are either co-authors of this paper or acknowledged. Experts' fields of expertise were oil palm agronomy, N cycle and N emissions, and agri-environmental modelling. They evaluated the scientific validity of the indicator structure, the modelling approaches chosen, and the input variables and parameters selected. This evaluation was conducted several times during the development of the indicator.

Validity of outputs was evaluated for the R-Leaching module, comparing modelled values to values calculated from field measurements. From the soil solution N concentration dataset, we calculated weekly mean N concentrations measured in the soil solutions collected from ceramic cups at 3 m depth. The N measured at 3 m depth was considered lost for palms, as most of the fine roots from palms are generally assumed to be located above 1.5 m depth (Corley and Tinker, 2015). The number of samples per week at 3 m depth was very variable, ranging from 0 to 11 depending on many factors, such as soil moisture or technical difficulties to maintain the vacuum in tension lysimeters. In order to perform a robust validation, we ignored the least certain periods, when less than 3 samples were recorded per week. This led to a series of 24 complete months, all within the 2008-2011 period, among 96 months in total in the 2008-2015 period. However, we checked that the concentrations of mineral N measured at other dates were in the same range as in the time series of 24 months selected for the validation of the R-Leaching module.

We calculated deep drainage using the water balance equation:

$$Drainage = W_{initial} - W_{final} + Rain - Intercepted\ water - Runoff\ water - Evapotranspiration$$

(adapted from Corley and Tinker, 2003), where W is the plant available water in soil. Calculations were done at a daily timestep, for a soil depth of 1.5 m, assumed to include nearly all the fine roots of palms (Corley and Tinker, 2015). A too-deep soil thickness would have led to an overestimation of evapotranspiration, and hence an underestimation of drainage. Initial soil water was assumed to be at plant available water capacity, i.e. 150 mm m^{-1} (Moody and Cong, 2008, p. 48). Water intercepted by fronds, and eventually evaporated, was assumed to be 11% of rainfall (Banabas et al., 2008; Kee et al., 2000). Runoff water was estimated as a percentage of rainfall, using the equation from Sionita et al. (2014) relevant for this site's conditions. Evapotranspiration was estimated using the Penman-Monteith equation (Allen et al., 1998, equation 6, p. 24). Drainage was hence equal to the amount of water in excess of plant available water capacity, after computation of all other inputs and outputs. Daily input values necessary for calculations were rainfall, solar radiation, air temperature, air humidity and wind speed. Finally, we obtained daily values of N leaching by multiplying drainage by the average

N concentration at 3 m depth. We cumulated these daily values in monthly values, to compare them to the monthly outputs of the R-Leaching module.

To compare modelled and measured N leaching values we used a set of four model efficiency statistics: (1) the coefficient of determination of the linear regression between modelled and observed values, (2) the Root Mean Square Error to Standard Deviation Ratio, (3) the Nashe-Sutcliffe efficiency, and (4) the Mean Error (Moriasi et al., 2007). Moreover, we completed these performance indicators with the method of the probability area, using a likelihood matrix, which is particularly relevant for models yielding risk assessment, such as scores of losses (Bockstaller and Girardin, 2003; also implemented in Pervanchon et al., 2005; Aveline et al., 2009).

4.2.5. Scenario testing

We also tested theoretical management scenarios, in order to check the sensitivity of the indicator to input variables, and its behaviour in different management conditions. This gave an idea of the indicator's utility for the end-users in terms of sensitivity of simulated N losses to changes in management. The same soil characteristics and climate records were used as those in the model comparison performed by Pardon et al. (2016b). We chose three scenarios: (1) standard management practices, as defined by Pardon et al. (2016b); (2) composting of initial residues from the previous palms and recycling back to the field; and (3) adjustment of N fertiliser rates according to legume understorey and initial residue N inputs. These scenarios involved changes in most of the management practice input variables. In order to test the sensitivity to climate variations, we ran each scenario with five climate series, by offsetting the climate record against planting date by one year in each run (Pardon et al., 2016b).

4.3. Results and discussion

4.3.1. General structure and outputs

IN-Palm is implemented in an Excel file and consists of 17 modules and needs 21 readily available input variables relating to the crop, understory, soil, land, weather, and management of fertiliser and residues (Table 4.1). Seven of the 10 risk modules were developed in this work: R-Runoff-Erosion, R-NH_3-Organic, R-N_2-Mineral, R-NO_x-Mineral/Organic, R-N_2O-Baseline, R-NO_x-Baseline, and R-N_2-Baseline. Seven intermediate modules were also developed, in order to estimate intermediate variables needed to run the risk modules. Details of structure and operation are provided in a technical report (Pardon et al., in preparation).

IN-Palm calculates emissions and scores for each risk module, for one hectare of palms, 1 to 30 years old. All calculations are done monthly, except for 3 intermediate modules estimated annually, i.e. Litter Budget, Fraction of Soil Covered, and Palm N Uptake, as monthly calculations would increase complexity without improving precision. For each month, IN-Palm computes 5 main sets of calculations (Figure 4.2, Table 4.1). First, NH_3 volatilization from fertilisers is calculated. Second, intermediate variables on soil cover and water budget are calculated. Third, these intermediate variables are used to calculate denitrification from fertilisers (N_2O, N_2, NO_x), and N losses via runoff and erosion. Fourth, net N inputs released to soil and plant uptake are calculated to estimate soil mineral N. Fifth, soil mineral N is used to calculate baseline denitrification (N_2O, N_2, NO_x) and N leaching.

Table 4.1. Overview of IN-Palm structure: IN-Palm consists of 21 inputs and 17 modules.

Of the 17 modules, 11 use fuzzy decision trees, 3 use mass budget models, and 3 use regression models. Each module uses 1 to 33 inputs, being either user inputs or intermediate variables (*) calculated by other modules. C: Carbon, N: Nitrogen, FM: Fresh Matter, DM: Dry Matter, FFB: Fresh Fruit Bunches

Calculation steps			1		2				3				4			5			
Modules (10 risk modules; 7 intermediate modules)			1.1 R-NH_3-Mineral	1.2 R-NH_3-Organic	2.1 Litter Budget	2.2 Fraction of Soil Covered	2.3 Water Runoff	2.4 Soil Water Budget	3.1 R-N_2O-Mineral	3.2 R-N_2-Mineral	3.3 R-NO_x-Mineral/Organic	3.4 R-Runoff-Erosion	4.1 Palm N Uptake	4.2 Understorey Uptake/Fixation	4.3 Soil N Budget	5.1 R-N_2O-Baseline	5.2 R-N_2-Baseline	5.3 R-NO_x-Baseline	5.4 R-Leaching
Model type	Fuzzy decision tree		✓			✓	✓		✓	✓		✓	✓	✓		✓	✓		✓
	Mass budget				✓			✓							✓				
	Regression model			✓							✓							✓	
Variable classes	Input variables	Units																	
Crop factors	Age of palms (1 to 25)	years	D										D	I	I	I	I		I
	Yield	t FFB ha^{-1} yr^{-1}											D	I	I	I	I		I
Soil and land	Soil initial mineral N	kg N ha^{-1}												I	D	I	I		I
	Soil initial water	mm						D											
	Soil organic C	%							D	I	D			I	I	D	I	D	I
	Soil texture	-	D					D	D	I	D	D		I	I	D	I	D	I
	Slope	%					D	I	I	I		D		I	I	I	I		I
	Terraces (yes or no)	-					D	I	I	I		D		I	I	I	I		I
Weather	Number of rainy days	$month^{-1}$	D				D	I	I	I		D		I	I	I	I		I
	Monthly rainfall	mm					D	D	I	I		D		I	I	I	I		I
	Atmospheric N deposition	kg N ha^{-1} yr^{-1}										D		I	D	I	I		I
Fertilizer management	Rate/Date of mineral fertilizer	kg ha^{-1}	D						D	I	D	D		I	D	I	I		I
	Type of mineral fertilizer	-	D						D	I	D			I	I	I	I		I
	Placement of mineral fertilizer	-	D											I	I	I	I		I
	Rate/Date of organic fertilizer	t FM ha^{-1}		D	D	I	I	I	I	I	D	I		I	D	I	I		I
	Type of organic fertilizer	-			D	I	I	I	I	I	D	I		I	I	I	I		I
	Placement of organic fertilizer	-				D	I	I	I	I		I		I	I	I	I		I
Understorey and residue management	Fronds (placement or exported)	-			D	D	I	I	I	I		I		I	D	I	I		I
	Previous palms (yes or no)	-			D	I	I	I	I	I		I		I	D	I	I		I
	Understorey biomass	-			D	D	I	I	I	I		I			I	I	I		I
	Legume fraction	-												D	I	I	I		I
	*Fraction of soil covered	-				O	D	I	I	I		D		I	I	I	I		I
Soil & ecologica processes	*Litter amount	t DM ha-1			O	D	I	I	D	I		I		I	I	D	I		I
	*Water runoff	mm $month^{-1}$					O	D	I	I				I	I	I	I		I
	*Soil moisture	mm						O	D	D				I	I	D	I		I
	*Palm N uptake	kg N ha^{-1} $month^{-1}$											O	I	D	I	I		I
	*Understorey N uptake/fixation	kg N ha^{-1} $month^{-1}$												O	D	I	I		I
	*Soil mineral N	kg N ha^{-1} $month^{-1}$												D	O	D	I		D
	*Water drained	mm $month^{-1}$						O							I				D
N losses	*N_2O emissions	kg N ha^{-1} $month^{-1}$							O	D					D	O	D		I
	*N_2 emissions	kg N ha^{-1} $month^{-1}$								O					D		O		I
	*NO_x emissions	kg N ha^{-1} $month^{-1}$									O			I	D	I	I	O	I
	*NH_3 volatilization	kg N ha^{-1} $month^{-1}$	O	O										I	D	I	I		I
	*Runoff-Erosion	kg N ha^{-1} $month^{-1}$										O		I	D	I	I		I
	*N leaching	kg N ha^{-1} $month^{-1}$													D				O

* Intermediate variable

Direct input — Indirect input — Output

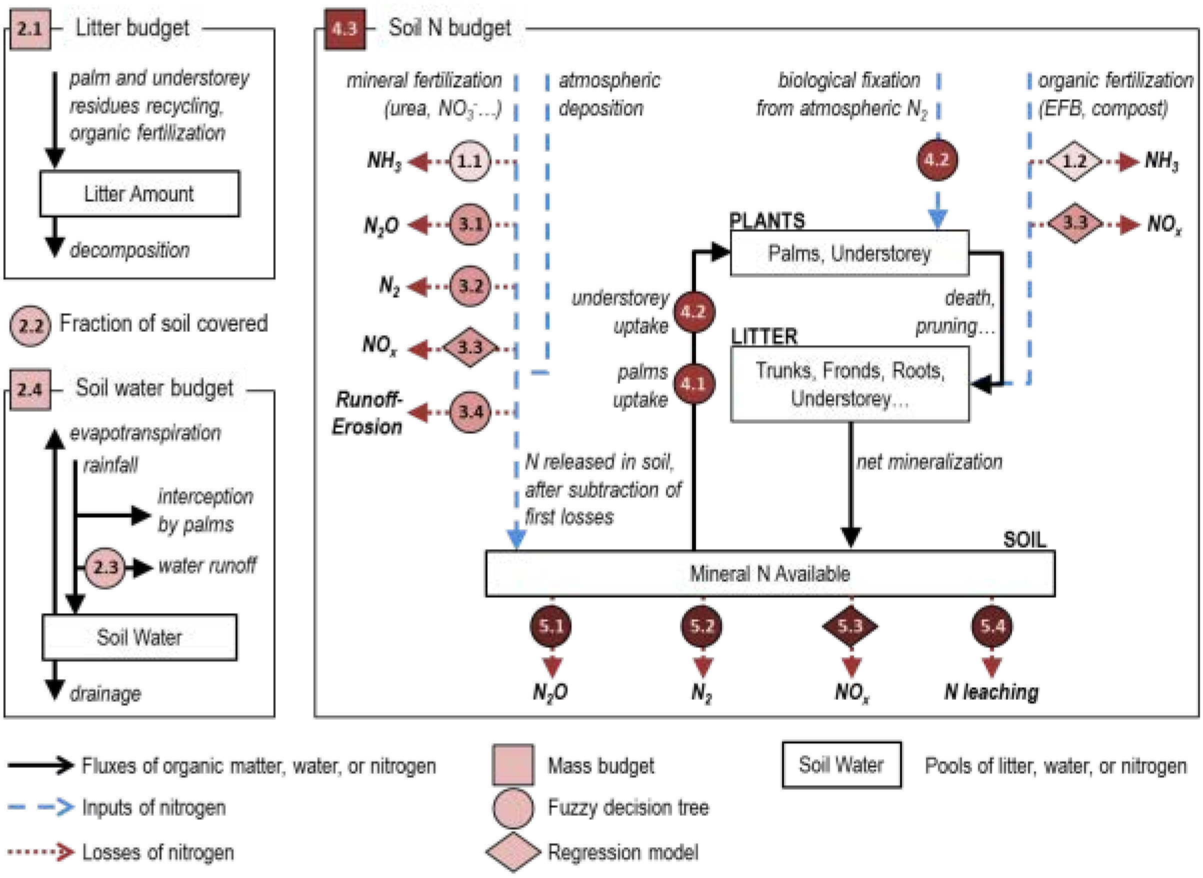


Figure 4.2. Fluxes and N losses calculated in IN-Palm.

Five main steps of calculation are computed for one hectare of palms for each month of the chosen year (1 to 30 years of age),: ① NH_3 volatilization from mineral and organic fertilisers; ② Soil cover and water budget estimations; ③ Denitrification from mineral and organic fertilisers, and N losses through runoff and erosion from mineral fertiliser and atmospheric deposition; ④ Soil mineral N estimation after net N release to soil and plant N uptake; and ⑤ Baseline denitrification and N leaching, from soil mineral N. EFB: Empty Fruit Bunches

Most of the risk module outputs are monthly emission factors, i.e. a percentage of N inputs or soil mineral N which is lost in the environment. For a given loss pathway, the monthly emission factor is transformed into a monthly N loss. Monthly losses are summed to obtain an annual loss and then converted into an annual score between 0 and 10. To convert a loss into a score we used the same function as Bockstaller and Girardin (2008, p. 35) based on a reference value of loss. For each loss pathway, we defined the reference value as equal to 50 % of the N losses, measured or modelled, associated with standard practices in a range of soil and climate conditions (Pardon et al., 2016a, 2016b). A score of 10 corresponds to no loss; 7 corresponds to the reference value of loss, i.e. emissions reduced by 50 % compared to standard practices; 4 corresponds to emissions with standard practices; and 0 corresponds to a loss more than three times higher than that associated with standard practices. As N losses are highly dependent on palm age, we calculated reference values for each age, in order to obtain more sensitive scores. Over the whole cycle, average reference values are, in kg N ha^{-1} yr^{-1}: 5 for NH_3, 2.1 for N_2O, 0.8 for NO_x, 5.1 for runoff-erosion and 20 for N leaching.

IN-Palm also provides recommendations on possible management changes to reduce N losses. According to the N balance and N losses calculated, critical conditions are identified, such as a potential lack of available N to match the plant needs, or high N losses. Warning messages in the Excel tool are then parameterized to pop up when these critical conditions occur. First, recommendations are displayed in order to better adapt N inputs to plant needs. Second, for scores below 7, recommendations are provided for potential management changes specific to reduce N losses via specific pathways.

Recommendations for improvements were most difficult to define for fertiliser application rate and date. Potential combinations of rates and dates are numerous, and the associated losses depend on many interacting processes over several months. Therefore, IN-Palm provides two more indicators to identify *a priori* (1) the riskiest month in which to apply the mineral fertilisers, and (2) the optimal month in the year and rate to apply fertilisers, aimed at reaching the expected yield while minimising losses. This calculation is done assuming only one application per year. More details on the recommendations are provided in the technical report (Pardon et al., in preparation).

Therefore, IN-Palm (1) is suitable for application to a wide range of oil palm growing environments, (2) is applicable to palms of any age, (3) is suitable for testing common management practices, and (4) uses reference values logically related to current practices. However, IN-Palm should be used carefully in some specific conditions.

IN-Palm was designed to be suitable in a wide range of oil palm growing environments, but it should be used carefully in situations where soil organic N content is high. In such situations, the actual dynamics of N fluxes and losses may differ from IN-Palm predictions, as it does not explicitly simulate soil organic N content but rather focuses on N release kinetics. Including this pool in IN-Palm would require new field data quantifying immobilisation, storage and mineralization dynamics of organic N under oil palm. Moreover, IN-Palm may not capture the effects of rare extreme weather events, such as intense rainfall events, due to its monthly time step calculations.

IN-Palm can be applied at all ages of palms, but should be interpreted with caution when assessing fertiliser management practices for very young palms of about 1-2 years, whose roots do not cover yet all the area. At that age the amount of soil mineral N actually available for palms may differ from IN-Palm predictions, as IN-Palm does not simulate the spatial distribution of N inputs and uptake within the plantation.

IN-Palm can test most of the common management practices in industrial plantations. However, it is not applicable for parts of the plantations where palm oil mill effluent is applied. We did not model this practice, as it applies to only a small proportion of plantation fields and is becoming less common as companies move to co-composting the effluent with empty fruit bunches, and because very little knowledge was available. In particular, very little information is available on emissions related to palm oil mill effluent during and after field application.

Finally, IN-Palm scores are calculated using as reference values 50 % of the losses under standard management practices. This approach is assumed to be conservative given that standard industrial management practices are already optimised in order to avoid economically excessive application of fertiliser. We also tested other approaches to define reference values, e.g. minimum value for each loss pathway encountered in the literature, or the lower end of uncertainty ranges. However, those reference values could be very low. For instance, the lower end of IPCC (2006) uncertainty range of 0.3 % applied to a standard annual fertiliser rate of 140 kg N ha^{-1} yr^{-1} would lead to a reference value of 0.42 kg N ha^{-1} yr^{-1} for N_2O. In this case, the indicator score for N_2O emissions would be insensitive to any kind of practice change.

4.3.2. Calculation of the 17 modules

In the 17 modules, three calculation approaches were used. In 11 modules we used a fuzzy decision tree modelling approach. When no data was available to design decision trees, we used existing regression models (3 modules). When modelled variables depended on their own values in a previous time step calculation, such as for soil water content, we used a mass budget approach, so as to reduce uncertainty propagation over the 30 years of calculations (3 modules) (Table 4.1, Figure 4.2). A detailed description of IN-Palm structure is provided in Appendix 3. Input/output variables, parameters, and references from the literature are summarised for each module in Tables A.3, A.4 and A.5 in Appendix 5. The modules run in the following order.

First, 2 modules are run to calculate volatilization from fertilisers. R-NH_3-Mineral is calculated with a fuzzy decision tree, using five input variables: fertiliser type, fertiliser placement, rain frequency, palm age and soil texture. The output is a monthly emission factor, from 2 to 45 %

of mineral N applied. R-NH_3-Organic is calculated with a regression model (Bouwman et al., 2002c), using the fertiliser rate as an input variable. The output is an emission factor of NH_3 from the N applied as organic fertiliser.

Second, 4 intermediate modules are run to calculate two main outputs, soil moisture and drainage; they are Litter Budget, Fraction of Soil Covered, Water Runoff, and Soil Water Budget. Litter Budget is calculated with a mass budget approach, accounting for inputs and decomposition kinetics of previous palm residues, pruned fronds and organic fertiliser. The output is an annual quantity of litter. Fraction of Soil Covered is calculated with a fuzzy decision tree, using four input variables: litter amount, understorey biomass, and placement of pruned fronds and organic fertilisers. The output is an annual percentage of soil covered, from 0 to 100 %. Water Runoff is calculated with a fuzzy decision tree, using 5 input variables: fraction of soil covered, rain amount, rain frequency, slope, and presence or absence of terraces. The output is a monthly runoff coefficient, from 1 to 20 % of rainfall. Finally, Soil Water Budget is calculated with a mass budget approach in the 1.5 m depth soil layer, accounting for all inputs to and outputs from the soil. The output values of this module are monthly soil moisture and drainage.

Third, 4 modules are run to calculate denitrification from fertilisers and N losses through runoff-erosion: R-N_2O-Mineral, R-N_2-Mineral, R-NO_x-Mineral/Organic, and R-Runoff-Erosion. R-N_2O-Mineral is calculated with a fuzzy decision tree, using five input variables: fertiliser rate, soil moisture, soil texture, soil organic C and litter amount. The output is a monthly emission factor, from 0.01 to 10.6 % of mineral N applied. R-N_2-Mineral is calculated with a fuzzy decision tree, using two input variables: N_2O emissions and soil moisture. The output is a monthly N_2/N_2O ratio, from 1.92 to 9.96. R-NO_x-mineral/organic is calculated with a regression model (Bouwman et al., 2002a), using six input variables: mineral and organic fertiliser type and rate, soil organic C and soil texture. This regression model directly calculates a quantity of NO_x without using an emission factor. Finally, R-Runoff-Erosion is calculated with a fuzzy decision tree, using six input variables: fraction of soil covered, rain amount, rain frequency, slope, soil texture and presence or absence of terraces. The output is a monthly emission factor, from 1 to 20 % of mineral N applied and N deposited from atmosphere. Indeed, in the main dataset used to design and calibrate this module, N losses through runoff and erosion were calculated jointly, as a percentage of mineral N applied and N deposited from atmosphere, without explicitly differentiating the share of N coming from soil.

Fourth, 3 intermediate modules are run to calculate soil mineral N content: Palm N uptake, Understorey N Uptake/Fixation, and Soil N Budget. Palm N Uptake is calculated with a fuzzy decision tree, using two input variables: expected yield and palm age. The output is an annual value of N uptake from soil, from 2.2 to 321 kg N ha^{-1} yr^{-1}. Understorey N Uptake/Fixation is calculated with a fuzzy decision tree, using three input variables: the understorey type, i.e. legume or natural vegetation, the understorey biomass, and the mineral N remaining in soil after palm uptake. The outputs are monthly values of N fixation rate, from 0 to 90 %, and N uptake from soil. Finally, Soil N Budget is calculated with a mass budget approach, accounting for all N inputs to, and outputs from, the soil mineral N pool. Thus, Soil N Budget is calculated in two steps: the first estimating the N available in soil after palm uptake, for Understorey N Uptake/Fixation calculation; and the second estimating the N available in soil after understorey uptake, to calculate the N available in soil for losses.

Fifth, 3 modules are run to calculate baseline denitrification and N leaching: R-N_2O-Baseline, R-N_2-Baseline, R-NO_x-Baseline and R-Leaching. R-N_2O-Baseline is calculated with a fuzzy decision tree, using the same input variables as R-N_2O-Mineral, except the fertiliser rate. The output of the module is a monthly emission factor, from 0.1 to 1.1 % of mineral N available in soil. R-N_2-Baseline uses the same decision tree as for R-N_2-Mineral, but the N_2/N_2O ratio is affected to baseline losses of N_2O, instead of losses from fertiliser. R-NO_x-Baseline uses the same regression model as R-NO_x-Mineral/Organic, but it accounts only for emissions not induced by fertilisers. Finally, R-Leaching is calculated with a fuzzy decision tree, using drainage as input variable. The output of the module is a monthly emission factor, from 0 to 20 % of mineral N available in soil.

The main uncertainties in module calculations were the emissions induced by compost application, palm N uptake, understorey N uptake and fixation, and the influence of spatial factors on leaching. Uncertainty of emissions from compost may be reduced with new field data on NH_3 volatilization and N_2O emissions. This improvement would be useful, as composting is becoming more common in oil palm plantations. Palm N uptake is a very high internal flux, and also very uncertain, as no direct measurements are available. Measurements of N uptake at different ages, using for instance ^{15}N techniques, could help reduce uncertainty. Understorey N uptake and biological N_2 fixation is also a potentially high and very uncertain internal flux. To reduce uncertainty, useful measurements could involve the response of N fixation to soil mineral N in field conditions, and the testing of other factors potentially driving fixation rate, such as soil moisture and pH. Lastly, leaching calculations could be better adapted to the oil palm system by accounting for fertiliser placement. However, this issue requires further investigations into the response of leaching to fertiliser placement, as the processes are complex, notably involving variable plant uptake depending on the relationship between long-term management and the development and distribution of palm roots. Thus controversies emerge when trying to identify favourable and unfavourable placement.

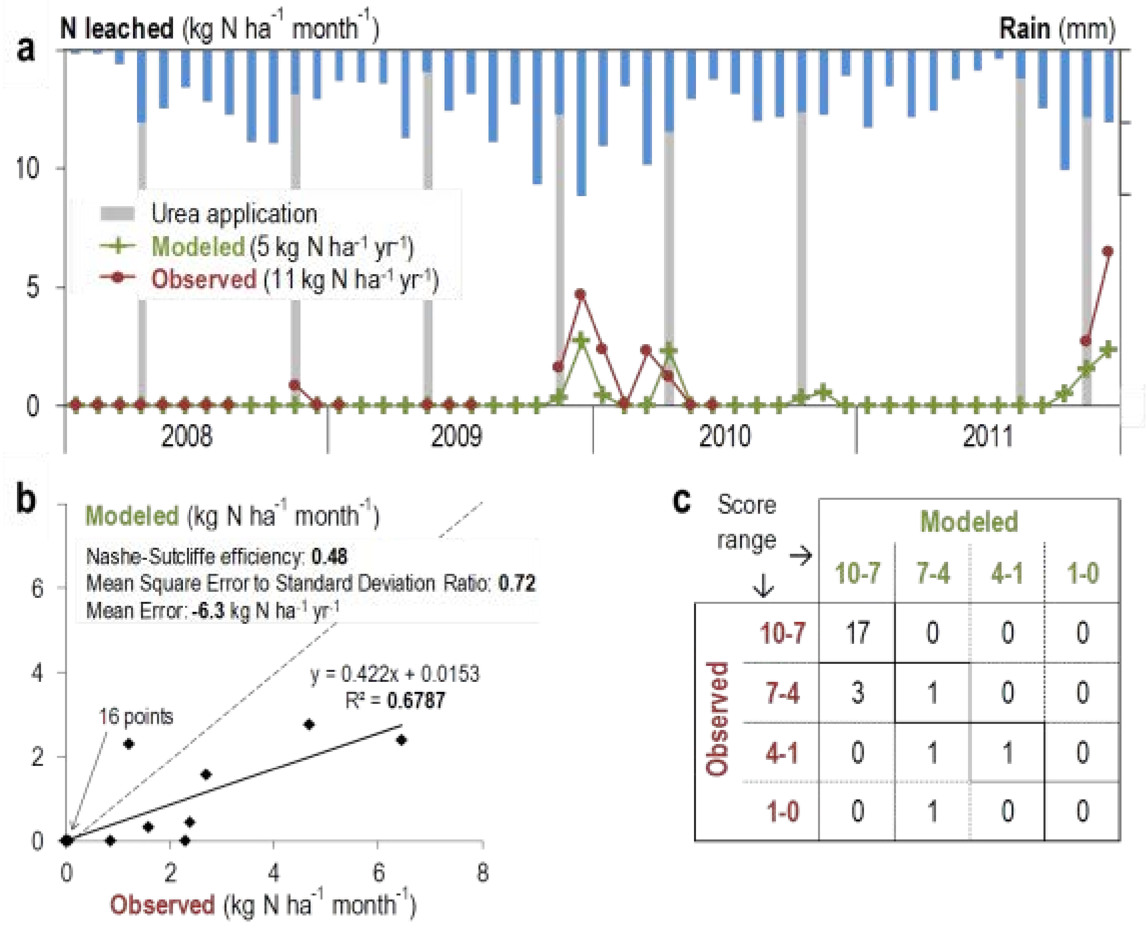
4.3.3. Validation of the R-Leaching module against field data

Model efficiency was acceptable according to the statistics calculated, but there was a tendency to underestimate N leaching. The visual representation showed that IN-Palm predicted most of the time the months in which leaching was actually observed (Figure 4.3a). The coefficient of determination of the linear regression (R^2) was 0.68 (Figure 4.3b). The Nashe-Sutcliffe efficiency was 0.48 and the Mean Square Error to Standard Deviation Ratio was 0.72, both indicating acceptable predictions (Moriasi et al., 2007). Moreover, in the likelihood matrix comparing scores obtained by IN-Palm to scores calculated from observed values, predicted values were good in 79 % of cases (Figure 4.3c).

However, the Mean Error index of about -6.3 kg N ha^{-1} yr^{-1}, i.e. 56 % of observed losses, showed an underestimation of leaching by IN-Palm. This tendency to underestimate leaching was also observed in the likelihood matrix. There are two possible explanations for this underestimation. First, IN-Palm may not have captured the effect of short and intense rain events observed at the study site. Second, high and uncertain internal fluxes, such as palm N uptake, estimated at 267 kg N ha^{-1} yr^{-1} in 2009 by IN-Palm, may have been slightly overestimated.

Given the significant effect of palm age on N fluxes and losses, a validation of this module with field measurements from a young plantation would be very helpful. Such measurements could record responses of leaching to different management scenarios involving key practices, such as residue and soil cover management, and fertiliser placement. A validation of this module in industrial plantations managed in soils with contrasting textures would be also of interest to assess the robustness of IN-Palm.

The validation of this module is strategic, given that N leaching is a very uncertain flux in oil palm (Pardon et al., 2016b). However, the validation of other modules would be beneficial in order to further investigate the robustness of IN-Palm and/or highlight further areas for improvement.



Score range	10-7	7-4	4-1	1-0
10-7	17	0	0	0
7-4	3	1	0	0
4-1	0	1	1	0
1-0	0	1	0	0

Figure 4.3. Modelled values from R-Leaching module vs. observed field measurements.

(a) Visual representation of modelled and observed values of N leaching, for the 24-month period in which at least 3 samples were analysed per week; (b) linear regression of modelled vs. observed values, and efficiency statistics; and (c) the 24 scores distributed in the likelihood matrix.

4.3.4. Scenario testing and management for N loss reduction

IN-Palm estimated annual average losses of 60, 59 and 41 kg N ha^{-1} yr^{-1}, for standard management practices, composting of initial palm residue from the previous cycle, and fertiliser adjustment according to understorey and residue inputs, respectively (Figure 4.4). There was high variability in annual losses, ranging from 1 to 247 kg N ha^{-1}, and depending on scenario, palm age, and weather. The indicator also estimated that 7, 123 and 23 kg N ha^{-1} were fixed from the atmosphere by the legume, for the 3 scenarios, respectively.

According to these simulations, the composting of initial residues and the adjustment of fertiliser according to other N inputs could be worthwhile options to pursue. Composting initial residues enhanced N fixation by the legume due to the reduction of N inputs at the beginning of the cycle. Nevertheless, annual average N losses did not reduce, due to higher losses under adult palms when the spreading of compost was concomitant with standard rates of mineral fertiliser application. These two results suggest that fertiliser could be saved under young and adult palms, by replacing part of this fertiliser by N fixation and compost applications. However, this management option would also involve more logistical challenges and costs for the composting process. Adjusting fertiliser rate according to N inputs from legumes and initial residues could reduce annual average N losses by 19 kg N ha^{-1} yr^{-1}, due to a possible 57 % reduction in fertiliser rate over the 3rd to the 10th year. This result suggested that fertiliser costs could be reduced. However, legume fixation was increased by only 16 kg N ha^{-1} compared to standard management practices, as high amounts of soil mineral N from initial residue were still inhibiting fixation over the first few years.

In terms of modelling, these results confirmed the importance of accounting for dynamics of N within the field in perennial agroecosystems, such as residue N release and variations in legume N fixation, for identifying potential ways of reducing N losses. In terms of environmental assessment, further investigation would be needed before concluding on these management tracks. Notably, environmental impact assessment should also account for emissions of N and other compounds induced out of the field, as done in life cycle assessments. For instance, N_2O, NO_3 and methane (CH_4) may be emitted during the composting process (Peigné and Girardin, 2004), or non-renewable carbon dioxide (CO_2) may be emitted during the production of fertilisers.

Therefore, IN-Palm efficiently identified optimal options in a given context while accounting for climate uncertainty. This utility will be further tested by the users themselves in PT SMART palm plantations in Sumatra.

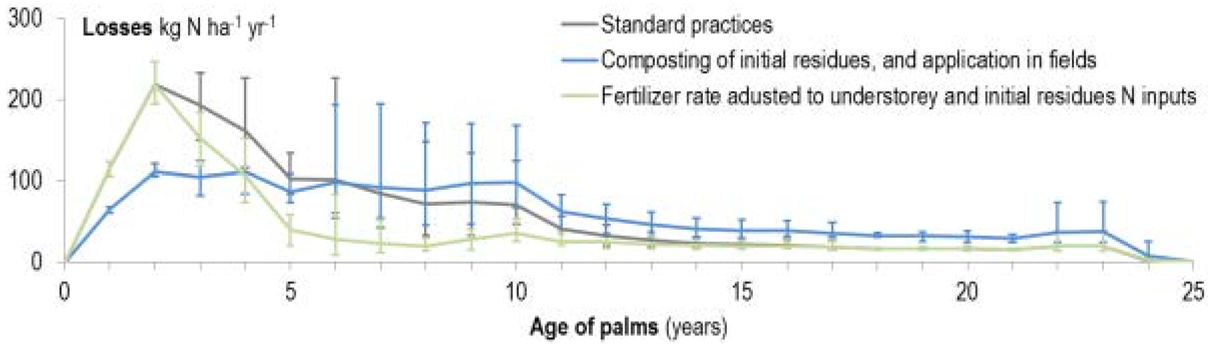


Figure 4.4. Nitrogen losses simulated by IN-Palm in three management scenarios.

Losses include all N loss pathways: NH_3 volatilization, N lost through runoff-erosion, N_2O, N_2, and NO_x emissions and N leached. Error bars represent minimum-maximum losses, depending on climate. N: Nitrogen

4.4. Conclusion

We developed an agri-environmental indicator, IN-Palm, to estimate all N losses throughout the oil palm crop cycle. The indicator uses 21 readily available input variables in most of oil palm companies, and provides scores and management recommendations to reduce N losses. Predictions of N leaching against measured data in Sumatra, Indonesia, were acceptable. We showed that IN-palm provided an efficient means of testing management scenarios and identifying practices likely to reduce N losses. Field measurements are unsuitable to monitor large scale plantations and the accuracy of existing process-based models for oil palm is too low to be used as management tools. Therefore, our indicator constitutes a useful tool for managers and scientists. This kind of agri-environmental indicator, easily adaptable to new crops in contexts of limited knowledge, can be of great utility to address the current need of reducing our global environmental impact. In particular, N fluxes could be used as inventory flows in palm oil life cycle assessments of environmental impacts.

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Finally, we thank all experts who helped us to improve the design, and assess the calibration and utility of this new version of IN-Palm: Murom Banabas, Victor Baron, Bernard Dubos, Neil Huth, Christophe Jourdan, Emmanuelle Lamade, Jean Ollivier, Hsiao-Hang Tao, Alif Saifudin, Eti Testiati, Putri Aulia Wahyuningsih and Rudy Harto Widodo.

We developed IN-Palm, to help managers and scientists to estimate N losses to the environment and identify best management practices in oil palm plantations. We validated this indicator using a field dataset of N leaching from a plantation in Sumatra, Indonesia. IN-Palm has also shown efficient to help testing management changes, accounting for palm age and local environmental conditions. These results showed that INDIGO® method and the fuzzy decision tree modelling approach were efficient to develop useful agri-environmental indicators even in a context of knowledge scarcity.

General discussion

I discuss key points of the research in the following sections. I identify management options that would potentially reduce N losses in oil palm plantations and deserve further investigation. I discuss the different ways of using IN-Palm and the future potential improvements to increase its accuracy to estimate N loss. I pinpoint new field measurements necessary to address the knowledge gaps, improve IN-Palm and test management options. Finally, I discuss the use of the INDIGO® framework, and the future potential coupling of IN-Palm to life cycle assessment and adaptation for other end-users or other crops.

6.1. Potential management options to reduce N losses in oil palm

Our research identified the potential drivers of N loss, the most critical conditions for their occurrence, and potential management changes to reduce N losses and fertiliser expenditures.

The drivers of N loss in the APSIM-Oil palm simulation model were shown to depend on site characteristics, age of the palms and climate (Chapter 3). This is likely to be also the case in the field, so recommendations for, and implementation of, management practices to reduce N loss should always be adapted to local conditions. The most influential parameters for N losses identified by sensitivity analyses of simulation models were N mineral fertiliser rate, soil characteristics affecting water dynamics, i.e. clay content and drainage coefficient, and crop variables related to N fixation/uptake and release, i.e. oil palm N uptake and fraction of legume in groundcover vegetation (Chapters 2 and 3). For young palms, legume fraction and soil organic C content were important drivers, while after 10 years of age the most important drivers were N fertiliser rate and drainage coefficient (Chapter 3).

Overall, three critical sets of conditions for N loss were identified. First, high soil C content and/or high rainfall could generate, unsurprisingly, particularly high emissions according to the sensitivity analysis of APSIM-Oil palm (Chapter 3). Second, the young phase of oil palm plantations, from replanting to about 6-7 years of age, is the most critical period of the cycle, according to field measurements and models (Chapter 1, 2, 3 and 4). During this period, the N uptake from palms is still low, but a large amount of initial residues from the palms of the previous cycle is left in the field, fertiliser is applied, and the legume cover is vigorous. On average, 31 % of the losses occurred during the first 3 years of the cycle, and N leaching accounted for about 80 % of the losses, according to the 11 models compared (Chapter 2). Third, some critical conditions may occur when palms are more than 6-7 years of age, in areas with sparse or no soil cover or where high amounts of organic and mineral fertilisers are applied, according to field measurements (Chapter 1).

We identified four main groups of management options to reduce N loss and fertiliser expenditures, each of which deserves further investigation: (1) mineral N fertiliser inputs could be reduced whilst not significantly affecting yield, in conditions where N is not the limiting factor, (2) the palm residues going back to the soil over the first years of the cycle could be exported, or composted and recycled back to the fields after 6-7 years of age, (3) the legume cover could be managed to make the best use of its N uptake, fixation and release capabilities, and (4) the placement and timing of synthetic and organic fertiliser application may impact on N losses.

First, mineral N fertiliser could be reduced whilst not significantly affecting yield, in conditions where N input is not the limiting factor. For instance, little or no response of oil palms to N fertiliser were reported in several studies (Chew and Pushparajah, 1995; Dubos et al., 2016; Huth et al., 2014). In such cases, fertiliser trials complemented by simulations, such as with APSIM-Oil palm, could help determine an optimal rate of fertiliser to apply, depending on the site characteristics. However, such management change may be done with caution, providing that the long-term fertility of soils is maintained.

Second, the palm residues going back to the soil over the first years of the cycle could be exported, or composted and recycled back to the fields after 6-7 years of age. About 80 t of dry matter ha^{-1} of above-ground initial residue from the previous cycle is usually left on the soil to decompose at replanting (Khalid et al., 1999a). In a plantation yielding 22 t fresh fruit bunches ha^{-1} yr^{-1}, about 2 t of dry matter ha^{-1} yr^{-1} of empty fruit bunches are produced and usually recycled back to the fields to decompose (assuming that empty fruit bunches correspond to 22.5 % of the weight of fresh fruit bunches, and 64 % of empty fruit bunches are moisture, from Corley and Tinker, 2003; Gurmit et al., 1999; Redshaw, 2003). In critical periods when high N losses occur, such as during the first years of the cycle, this biomass could be diverted toward bioenergy chains (Paltseva et al., 2016; Wiloso et al., 2015). Another possibility could be to use empty fruit bunches, and/or a part of the initial residues, for composting, which is an increasing practice. However, the export of empty fruit bunches may not have a significant influence on N loss, as shown in APSIM-Oil palm simulations (Chapter 3). Moreover, these management options would involve additional labour and logistical costs for transport and composting process, and environmental impacts associated with transport and composting should also be taken into account to assess these practices.

Third, the legume cover could be managed to make the best use of its N uptake, fixation and release capabilities. For instance, a denser or earlier sowing of the legume might help to catch the excess N accumulating in soil from the mineralisation of initial residues. Another option could be to enhance the atmospheric N fixed by the legume cover and released to the soil, to save fertiliser. For instance, a preliminary test with IN-Palm suggested that, by adjusting the fertiliser rate according to N inputs from legumes and initial residues, a reduction of about 57 % of the fertiliser rate over the 3rd to the 10th year could reduce N losses by 19 kg N ha^{-1} yr^{-1}, without affecting the yield (Chapter 4). Fixation of atmospheric N by the legume cover may be further stimulated by exporting some or all of the felled palm residues. These legume management practices may also have positive side-effects, such as for pest control or soil erosion reduction after replanting (Chapter 3). Another option could be to interplant another crop that would use the surplus N over the first years of the oil palm growth cycle. For instance, fast-growing trees like balsa could be sowed at replanting and harvested after about 5-6 years. However, these management options need further research to better understand the N uptake, fixation and release dynamics of the legume cover in the specific context of oil palm.

Fourth, the placement and timing of synthetic and organic fertiliser applications may have an impact on N losses, as mentioned in the literature (Banabas et al., 2008; Foster and Dolmat, 1986; Schroth et al., 2000). However, spatial interactions between N inputs and other parameters are complex and no clear conclusion is available in the literature regarding the best location to apply fertilisers. The effect of placement on N loss may depend on the spatial distribution of rain between stemflow and throughfall, compaction of the soil in the weeded circle, root distribution, and organic matter inputs, which may modify the capacity of the soil to retain nutrients. The distribution of roots depends on palm age, soil type and management practices such as legume establishment and fertiliser placement (Agamuthu and Broughton, 1985; Corley and Tinker, 2015; Foster and Dolmat, 1986; Nelson et al., 2006; Schroth et al., 2000). Therefore, more investigation is needed to assess this potential management option to reduce N loss.

Finally, further research is needed to better explore and assess the impact of these management options on N loss. Assessment of management changes should also account for other environmental impacts induced throughout the supply chain, and technical and financial implications.

6.2. Future use and development of IN-Palm

IN-Palm was designed to be easy to use and sensitive to management practices. We discussed four main ways of using this agri-environmental indicator: (1) as a research tool complementary to other models to investigate processes, (2) as an operational tool to assess fertiliser plans, (3) as an operational tool to identify potential management changes to reduce N losses, and (4) potentially as an emission model for life cycle assessment in future work.

First, IN-Palm can aid understanding of the complex N dynamics occurring over the growth cycle, as all the monthly and annual fluxes are shown in graphs and tables. For instance, the complex dynamics of N uptake, fixation and release by the legume cover in the field can be better understood by analysing IN-Palm outputs. Second, IN-Palm may be used together with leaf analysis, to assess the potential N losses associated with planned fertiliser applications. Third, IN-Palm may be used to identify management changes with potential to reduce N loss. For instance, it is possible to estimate the least risky months for applying fertiliser in a given field, depending on soil characteristics, weather and other management practices implemented, such as the placement of pruned fronds and empty fruit bunches. Fourth, IN-Palm could be potentially used to estimate emissions of N through the different loss pathways, in order to help reducing uncertainty in life cycle analyses. Finally, IN-Palm should be used carefully in two particular cases: in situations where soil organic N content is high, as IN-Palm does not explicitly simulate soil organic N content; and when assessing fertiliser management practices for very young palms of about 1-2 years, whose roots do not cover yet all the area, as IN-Palm does not simulate the spatial distribution of N inputs and uptake within the plantation.

We identified three main approaches for improving IN-Palm in the future: (1) to reduce the main uncertainties in its calculations of N losses, (2) to account explicitly for the soil organic N pool, and (3) to continue the validation work.

First, the main uncertainties in calculations in IN-Palm are the emissions induced by compost application, palm N uptake, understorey N uptake and fixation, and the influence of spatial factors on N leaching. A reduction of these uncertainties could improve the reliability and precision of the predictions. Second, the explicit modelling of the soil organic N pool in IN-Palm could widen the utility of IN-Palm. This would increase its reliability in contexts with high soil N organic content. Third, given the significant effect of palm age and site characteristics on N fluxes and losses, the leaching module of IN-Palm should also be validated against field data under young palms, and at sites with different environmental conditions. Others modules of losses could also be validated, such as for NH_3 volatilisation, which is one of the highest loss pathways when urea is applied, and N_2O emissions, which is one of the most uncertain loss pathways. Finally, IN-Palm is planned to be validated by end-users in fields in a plantation in Sumatra, Indonesia. This validation is important to ensure that this tool achieves its objectives of being an operational tool easy to use and sensitive to the main commonly-used practices.

Therefore, new field measurements are necessary in order to improve the reliability of IN-Palm, and to further investigate potential management practices to reduce N loss.

6.3. Future field measurements to reduce knowledge gaps in N loss estimates

We identified six key field measurements to undertake to reduce uncertainty, improve IN-Palm, and further investigate potential management changes to reduce N losses: (1) response of N_2O emission and N leaching to legume cover and initial residue management in plantations of less than 10 years of age, (2) response of N_2O emission and N leaching to fertiliser management and soil types in plantations of more than 10 years of age, (3) measurements of palm N uptake in relation to age and yield, (4) measurements of legume N uptake and fixation in relation to soil mineral N content, (5) measurements of NH_3 volatilisation and N_2O emissions following compost application, and (6) measurements of the mineralisation dynamics of soil organic N.

First, there are little data on N loss for palms under 10 years old (Chapter 1). Yet N_2O emissions and N leaching are likely to be higher under young palms than older ones, according to previous measurements (Ishizuka et al., 2005; Foong et al., 1983 and Foong, 1993) and the sensitivity analysis of APSIM-Oil Palm (Chapter 3). Residues of felled palms and legume cover management are likely to play a significant role in N dynamics and losses over the first year of the cycle (Chapters 1, 2 and 3), but dynamics and interactions are complex and not yet fully understood. Field experiments investigating the response of N_2O emissions and N leaching to the presence or absence of initial residues, and the legume cover fraction, would be of great interest. Soil mineral N and organic C content and drainage would also be important variables to measure under young plantations, when measuring N_2O and N leaching (Chapter 3). Such studies could help to understand better the processes involved, especially interactions between N release from initial residue and legume fixation rate. They would be useful to validate IN-

Palm for N_2O emissions and N leaching under young palms, and to further investigate the management options related to initial residues and legume cover.

Second, N_2O emissions and N leaching for palms more than 10 years old are very variable in time and space and the drivers of this variability are not yet fully understood (Chapters 1, 3 and 4). Field experiments investigating the response of N_2O emissions and N leaching to soil types and fertiliser management would be of great interest. Knowing the effect of fertiliser placement on N losses would be particularly useful. Spatial distribution of soil compaction, soil organic matter content, palm roots and rainfall would be important parameters to measure. Such studies could help to identify the main spatial drivers of N losses in mature plantations, especially interactions between fertiliser placement and N losses, to validate IN-Palm for N_2O emissions and N leaching for other fertiliser management practices and soil types, and to identify the best management options in terms of fertiliser placement.

Third, no direct measurements of palm N uptake were found in the literature (Chapter 1). Palm N uptake is generally inferred from budgets accounting for the N exported in fresh fruit bunches, the N recycled through pruned fronds and other residues, and the N stored in the palm itself. This kind of calculation provides an annual average palm N uptake over the whole cycle, but it does not provide any information about the variability of palm N uptake over time, especially for palms under 10 years of age, which have not yet reached a steady state. Yet, the magnitude of this flux was reported to be large and variable, ranging from 40 to 380 kg N ha^{-1} yr^{-1} (several studies in Chapter 1), and uncertainties about its estimation may significantly impact calculation of the N balance. Field experiments using ^{15}N tracing techniques to measure palm N uptake in relation to palm age, genotype and yield would be of great interest. Such studies could reduce the uncertainty in estimating palm N uptake, to improve the reliability of palm N uptake in IN-Palm, and to further investigate potential adjustments of fertiliser management practices to meet palm need.

Fourth, legume cover is likely to play a significant role in the regulation of soil mineral N in young palm plantations, but no direct measurements are available in the literature to estimate the response of N fixation rate to soil mineral N content (Chapter 1). In IN-Palm, a level of inhibition of atmospheric N fixation was fixed at a soil mineral N content of 60 kg N ha^{-1}, but this value was measured for pea in temperate climate conditions (Voisin et al., 2002). Field measurements of the response of N fixation rate to soil mineral N and fertiliser applications, and to other potential drivers such as soil moisture and pH, would be of great interest. Very little information is also available about legume cover turnover of leaves, stems and roots, and the speed of decomposition and mineral N release to the soil of these residues. Such studies could be useful to better understand interactions between felled palm residue decomposition, fertiliser application and legume N fixation rate, to improve the reliability of the understorey module in IN-Palm, and to further investigate potential management practices to make the best use of the uptake, fixation and release capabilities of the legume cover.

Fifth, little information is available about N losses following compost application in the field (Chapter 1). Yet composting is becoming more common in oil palm plantations. Field measurements of NH_3 volatilisation and N_2O emissions following compost application, and rate of decomposition and N release to soil would be of great interest. Nitrogen content and C/N ratio of compost, soil characteristics such as pH, C content, texture, moisture, and rainfall following application would also be important parameters to measure. Such studies could be useful to improve the sensitivity and reliability of IN-Palm estimates to compost application, and to further investigate the best conditions for applying compost in the field.

Sixth, little information is available about the mineralisation of soil organic N (Chapter 1). The measurements in the literature involve various soil depths and various land-uses before oil palm establishment, which impedes clear conclusions. Yet, the amount of soil organic N mineralised could be significant in some situations, up to 421 kg N ha^{-1} yr^{-1} after replanting (Khalid et al., 1999c). High soil organic N content and mineralisation rate could explain the absence of yield response to N fertiliser in some cases (Chapter 3). Field measurements of soil organic N immobilisation, storage, and mineralisation dynamics under oil palm could be of great interest. Such knowledge would help to better estimate the role of soil organic N in N supply, to include this pool explicitly in IN-Palm, and to further investigate potential adjustments of N fertiliser application based on soil organic N content.

In general, measurements combining several N loss pathways would be very useful for better understanding the trade-offs between loss pathways, and for simultaneously validating several modules of IN-Palm with a given dataset. It would be important to record accurate long-term climate series during the trials, as the inter- and intra-annual variability of climate may impact the magnitude and ranking of drivers (Chapter 3). Finally a network of experimental trials with long term monitoring in various contexts would be needed, as N losses and optimal management practices depend on pedo-climatic and technical conditions (Chapters 1 and 3).

6.4. INDIGO® framework and life cycle assessment

We highlighted in this research work the high uncertainties, complex processes and knowledge gaps in N fluxes and losses in oil palm (Chapter 1 and 2). In this context of knowledge scarcity about a complex system, we built IN-Palm, an agri-environmental indicator for N losses, whose predictions of N leaching were acceptably close to field measurements (Chapter 4). This result points to the efficiency of the INDIGO® framework for building relevant assessment tools, even in contexts of knowledge scarcity.

One of the key aspects of the INDIGO® framework was its ability to combine all available knowledge. Besides the literature review, the model comparison, and expert knowledge, the sensitivity analysis of simulation models appeared to be a particularly efficient tool for gathering complementary information (Chapters 3 and 4). The sensitivity analysis provided a series of 58 500 simulations in various conditions corresponding to the parameter space explored, which were used in IN-Palm to estimate the average palm N uptake, depending on yield and age, as this information was not available in the literature.

Another key aspect of the INDIGO® framework is the use of the fuzzy decision tree modelling approach, which has already been used in this method (e.g. van der Werf and Zimmer, 1998). Decision trees constitute a flexible structure that can be adapted to suit the type of available knowledge, while the calculations remain transparent and reproducible. The use of fuzzy logic is better adapted to tackle uncertainty than standard decision trees, as it allows continuous output spaces to be obtained, which are more realistic and sensitive to inputs, without requiring more knowledge. However, we could not apply this approach to the loss pathways for which too little data was available in the context of oil palm, i.e. NH_3 volatilisation from organic fertilisers, and NO_x emissions (Chapter 4).

Further work is needed to explore the interest of using such an agri-environmental indicator as an emission model for N losses in life cycle assessments. Indeed, an emission model more specific to oil palm peculiarities may help reduce uncertainty of assessments. However, the precise way of coupling an agri-environmental indicator to life cycle assessments, and the actual impact on results uncertainty should be further investigated.

Finally, IN-Palm could be easily adapted for other end-users, such as oil palm smallholders, or growers of other tropical perennial crops. Crops such as rubber, coffee, cocoa, and even sugar cane and bananas, share some characteristics with oil palm, such as the long growing cycle, the marked spatial heterogeneity and the large internal fluxes and pools of N. These tropical crops are also grown in similar pedo-climatic contexts. IN-Palm could hence be adapted by keeping most of its general structure, and adjusting specific parameters, such as crop residue turnover, content and decomposition speed, standard management practices, or rules of decision trees.

General conclusion

In this research, we estimated the main N fluxes and N losses in oil palm plantations, we identified their drivers, and we pointed out the research gaps in the literature. We compared 11 existing models for N loss prediction in oil palm, and we identified their ability to capture peculiarities of the oil palm system, their limits, and the main uncertainties in modelling. We identified the key drivers of N losses and yield in on one of the existing models, by performing an in-depth sensitivity analysis. Finally, we built and validated IN-Palm, an agri-environmental indicator for N losses in oil palm plantations.

This research constitutes a comprehensive synthesis of the available knowledge and models for N fluxes and losses in oil palm plantations. One of the main results is a novel agri-environmental indicator, IN-Palm, complementary to existing models, and efficient for testing management practices to reduce N losses and perform environmental assessments in oil palm plantations. This indicator can be a useful base for further adaptations for other tropical perennial crops. Other indicators, complementary to IN-Palm, could also be developed for perennial crops to tackle other critical anthropogenic perturbations exceeding the planetary boundaries, for instance soil quality or biodiversity loss.

The INDIGO® method and fuzzy decision tree modelling approach were shown to be very well adapted for building agri-environmental indicators in contexts of knowledge scarcity. We demonstrated that such agri-environmental indicators can be operationally-oriented, sensitive to local practices and environmental conditions, as well as potentially useable as emission models for holistic approaches such as life cycle assessment. They are therefore very useful tools in agriculture, and especially tropical agriculture, to address the challenge of urgently decreasing the environmental impact of agriculture while increasing food production.

Appendices

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Chapter 1 - Key unknowns in nitrogen budget for oil palm plantations: A review

Lénaïc Pardon, Cécile Bessou, Paul N. Nelson, Bernard Dubos, Jean Ollivier, Raphaël Marichal, Jean-Pierre Caliman and Benoît Gabrielle. Published on the 29th of February, 2016 in *Agronomy for Sustainable Development* 36. doi:10.1007/s13593-016-0353-2 https://link.springer.com/article/10.1007/s13593-016-0353-2

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Lénaïc Pardon, Cécile Bessou, Nathalie Saint-Geours, Benoît Gabrielle, Ni'matul Khasanah, Jean-Pierre Caliman, and Paul N. Nelson. Published on the 30th of September, 2016, in *Biogeosciences* 13, 5433–5452. doi:10.5194/bg-13-5433-2016 https://www.biogeosciences.net/13/5433/2016/bg-13-5433-2016.pdf

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Lénaïc Pardon, Neil I. Huth, Paul N. Nelson, Murom Banabas, Benoît Gabrielle and Cécile Bessou. Published on the 23th of May, 2017 in *Field Crops Research* 210, 20–32.

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http://www.sciencedirect.com/science/article/pii/S0378429016307195

Appendix 2. Parameter ranges for the Morris' sensitivity analysis of chapter 2

Table A.1. Nominal, minimum and maximum values of inputs variables and parameters, used for the Morris' sensitivity analysis.

EF: emission factor; C: carbon; N: nitrogen; BNF: biological nitrogen fixation; EFB: empty fruit bunches, i.e. organic fertiliser.

Input variables and parameters	Nominal (min.-max.)*	Unit	References*
Rainfall	2407 (1500-3000)	mm.yr-1	Ecozones, from FAO (2001)
Mean temperature	28 (20-30)	°C	Ecozones, from FAO (2001)
Soil bulk density	1430 (860-1550)	$kg.m^{-3}$	(Soil taxanomy, from USDA, 1999) (Khasanah et al., 2015)
Soil carbon content	1.68 (0.6-2.38)	%	(Corley and Tinker, 2003, p.84) (Khasanah et al., 2015) (Soil taxanomy, from USDA, 1999)
Soil clay content	31 (1.6-35)	%	(Soil taxonomy, from USDA, 1999)
Soil C/N	11 (10-12)	-	(Nemecek and Schnetzer, 2012)
Soil N organic / N total	0.85 (0.68-1)	-	±20% (Nemecek and Schnetzer, 2012)
Soil N mineralisation rate	1.6 (1.28-1.92)	%	±20% (Roy et al., 2005)
Soil N organic	5500 (1700-5700)	$kg N.ha^{-1}$	(Nemecek and Schnetzer, 2012) (Soil taxanomy, from USDA, 1999)
Soil pH	4.5 (4-6)	-	(Corley and Tinker, 2003, p.84)
Oil palm rooting depth	1 (0.5-5)	m	(Jourdan and Rey, 1997);(Schroth et al., 2000); (Sommer et al., 2000); (Ng et al., 2003); (Corley and Tinker, 2015); (Nelson et al., 2006); (Lehmann, 2003); (Paramananthan, 2015)
Oil palm N uptake	189 (40-380)	kg N ha^{-1} yr^{-1}	(Xaviar, 2000);(Goh et al., 2003);(Tan, 1976); (Tan, 1977);(Ng, 1977);(Pushparajah and Chew, 1998); (Henson, 1999); (Ng et al., 1999); (Ng and Thamboo, 1967); (Ng et al., 1968); (Foster and Parabowo, 2003)
N released by felled palms (above- and below-ground)	275 (0-321)	kg N ha^{-1} yr^{-1} (N is released in two years)	(Khalid et al., 1999a);(Khalid et al., 1999b); (Redshaw, 2003); (Schmidt, 2007)
N released by palm residues (fronds, roots, etc.)	108 (0-182)	kg N ha^{-1} yr^{-1}	(Corley and Tinker, 2015); (Redshaw, 2003); (Carcasses, 2004); (Turner and Gillbanks, 2003); (Schmidt, 2007); (Dufrêne, 1989); (Lamade et al., 1996); (Henson and Chai, 1997); (Jourdan et al., 2003)
Mineral fertiliser amount	94 (25-206)	kg N ha^{-1} yr^{-1}	(Henson, 2004); (Banabas, 2007); (Choo et al., 2011); (Foster, 2003); (FAO, 2004, In Schmidt, 2007); (Carcasses, 2004); (Yusoff and Hansen, 2007); (United Plantations Berhad, 2006); (Wicke et al., 2008)
Urea rate in mineral fertiliser	25 (0-100)	%	(FAO, 2004, In Schmidt, 2007); (Carcasses, 2004)
Organic fertiliser amount (EFB)	184 (0-228)	kg N ha^{-1} yr^{-1}	(Banabas, 2007); (Redshaw, 2003)
Atmospheric N deposition	18 (8-20)	kg N ha^{-1} yr^{-1}	(Agamuthu and Broughton, 1985); (Chew et al., 1999); (Trebs et al., 2006)
Biological N fixation	150 (0-190)	kg N ha^{-1} yr^{-1}	(Giller and Fairhurst, 2003); (Ruiz and López, 2014); (Broughton, 1977); (Agamuthu and Broughton, 1985);
Legume N uptake	66 (0-150)	kg N ha^{-1} yr^{-1}	(Agamuthu and Broughton, 1985)
N released by legume residues	120 (0-190)	kg N ha^{-1} yr^{-1}	(Agamuthu and Broughton, 1985); (Pushparajah, 1981)

EF (IPCC 2006) Leaching and runoff, from mineral and organic fertilisers and BNF	30 (10-80)	%	(IPCC, 2006)
EF (IPCC 2006) NH_3 from mineral fertiliser	10 (3-30)	%	(IPCC, 2006)
EF (IPCC 2006) NH_3 from organic fertiliser	20 (5-50)	%	(IPCC, 2006)
EF (IPCC 2006) N_2O from mineral and organic fertilisers, BNF and plant residues	1 (0.3-3)	%	(IPCC, 2006)
EF (Mosier 1998) Leaching and runoff from mineral and organic fertilisers	30 (3-57)	%	±90%
EF (Mosier 1998) NH_3 from mineral fertiliser	10 (1-19)	%	±90%
EF (Mosier 1998) NH_3 from organic fertiliser	20 (2-38)	%	±90%
EF (Mosier 1998) N_2O from mineral and organic fertilisers, BNF and plant residues	1.25 (0.125-2.375)	%	±90%
EF (Asman 1992) NH_3 from Ammonium Sulfate	8 (0.8-15.2)	%	±90%
EF (Asman 1992) NH_3 from Urea	15 (1.5-28.5)	%	±90%
EF (Schmidt 2007) NH_3 volatilisation from Ammonium Sulfate	2 (0.2-3.8)	%	±90%
EF (Schmidt 2007) NH_3 volatilisation from Urea	30 (27-48)	%	(Corley and Tinker, 2003, In Schmidt, 2007 p102)
EF (Agrammon 2009) NH_3 from leaves	2 (0.2-3.8)	kg N ha^{-1} yr^{-1}	±90%
EF (Agrammon 2009) NH_3 from organic fertiliser	35 (30-80)	%	(Agrammon Group, 2009, In (Nemecek et al., 2014)
EF (Nemecek 2007) NO_x emissions from N_2O emissions	21 (2.1-39.9)	%	±90%
EF (Crutzen 2008) N_2O from mineral fertiliser and BNF	4 (3-5)	%	(Crutzen et al., 2008)
EF (EMEP 2013) NO_x from mineral fertiliser	2.6 (0.5-10.4)	%	(Stehfest and Bouwman, 2006), In European Environment Agency, 2013)
EF (EMEP 2013) NH_3 from Ammonium Sulfate, low pH	1.3 (0.13-2.47)	%	±90%
EF (EMEP 2013) NH_3 from Ammonium Sulfate, high pH	27 (2.7-51.3)	%	±90%
EF (EMEP 2013) NH_3 from Urea, low pH	24.3 (2.43-46.17)	%	±90%
EF (EMEP 2013) NH_3 from Urea, high pH	24.3 (2.43-46.17)	%	±90%
EF (Vinther and Hansen 2004) N_2O from mineral and organic fertilisers, BNF and plant residues	1 (0.1-1.9)	%	±90%
Parameter (Vinther and Hansen 2004) N_2/N_2O rate	3 (0.3-5.7)	%	±90%
Parameter (Meier 2014) N Use Rate	70 (7-133)	-	±90%
Parameter 1 (Shcherbak et al., 2014)	0.0181 (0.017-0.019)	-	(Shcherbak et al., 2014)
Parameter 2 (Shcherbak et al., 2014)	6.58 (6.45-6.71)	-	(Shcherbak et al., 2014)

*When no references are mentioned, the range was set arbitrary to ±90%, otherwise the range is taken from the references.

Appendix 3. IN-Palm technical report

IN-Palm: an agri-environmental indicator to assess potential nitrogen losses in oil palm plantations

Technical report

Lénaïc Pardon, Christian Bockstaller, Raphaël Marichal, Ribka Sionita, Paul Netelenbos Nelson, Benoît Gabrielle, Jean-Paul Laclau, Pujianto, Jean-Pierre Caliman, Cécile Bessou

Table of Contents

List of Figures

List of Tables

1. User instructions

IN-Palm is an agri-environmental indicator specific to oil palm plantations. It uses 21 readily available input variables on crop factors, soil, weather and management practices, to simulate the risk of nitrogen (N) losses in environment, through 6 loss pathways: ammonia (NH_3) volatilisation; N losses through runoff-erosion; nitrous oxide (N_2O), dioxide (N_2) and nitrogen oxides (NO_x) emissions; and N leaching. Calculations are done for one hectare of palms, for an age of palms chosen by the user, from 1 to 30-year-old.

This indicator is built in an Excel file containing 28 sheets of 3 main types: user interface sheets, in blue; user tools in orange; and calculation sheets, in red (see Table 1.1). The file does not use any "macro", but only formulas clearly accessible in the sheets. A password, 'qwerty', locks the user interface sheets, to avoid unintentional changes except input values. In all sheets, blue cells are input variables, green cells are output variables, and orange cells are parameters.

Table 1.1. The 28 sheets of the IN-Palm Excel file, and their description.

User interface sheets are in blue, user tools are in orange, and calculation sheets are in red.

A	**User interface (inputs and outputs)**	
	Instructions	Information - Reference, foreword and disclaimer, content of the Excel file
	≤ 10 years	**Input sheet for young palms** (results highly depend on previous years management practices)
	> 10 years	**Input sheet for old palms** (results do not highly depend on previous years management practices)
B	**User sheets (information, tools)**	
	Pictures	Help - Pictures for the user to understand better management practices choices to fill the input sheets
	Weather	Tool - For calculating monthly rainfall and rain frequency, if this data is not readily available
	Structure	Information - Structure of the indicator, list of modules, input variables and intermediate variables
	Fuzzy modules testing	Tool - For visualising the behaviour of each fuzzy modules
C	**Calculation sheets (parameters, modules, scores, recommendations)**	
	General parameters:	
	Inputs summary & Parameters	Centralisation of input values and general parameters (values, references)

	Membership functions	Parameters shared by all fuzzy tree models

① Volatilisation (from mineral and organic fertiliser)

1.1.	R-NH3-Mineral	Fuzzy decision tree model, NH3 emissions from mineral fertiliser
1.2.	R-NH3-Organic	Regression model (Bouwman et al., 2002c), NH3 emissions from organic fertiliser

② Preliminary calculations of soil moisture and drainage

2.1.	Litter Budget	Mass budget approach (can be short-cut for advanced testing of modelling approach)
2.2.	Fraction of Soil Covered	Fuzzy decision tree model
2.3.	Water Runoff	Fuzzy decision tree model
2.4.	Soil Water Budget	Mass budget approach

③ Denitrification and runoff-erosion (from mineral and organic fertilisers, and atmospheric depositions)

3.1.	R-N2O-Mineral	Fuzzy decision tree model, N2O emissions from mineral fertiliser
3.2.	R-N2-Mineral	Fuzzy decision tree model, N2 emissions from mineral fertiliser
3.3.	R-NOx-Mineral/Organic	Regression model (Bouwman et al., 2002a), NOx emissions from mineral and organic fertiliser
3.4.	R-Runoff-Erosion	Fuzzy decision tree model

④ Preliminary calculations of soil mineral N

4.1.	Palm N Uptake	Fuzzy decision tree model
4.2.	Understorey N Uptake/Fixation	Fuzzy decision tree model (fixation rate can be locked to a fix value, for advanced testing of modelling approach)
4.3.	Soil N Budget	Mass budget approach (can be short-cut for advanced testing of modelling approach)

⑤ Denitrification baseline and N leaching (from mineral N available in soil)

5.1. 5.2. 5.3.	R-N2O-Basline, R-N2-Basline and R-Nox-Baseline	Fuzzy decision trees (N2O and N2), and regression model (NOx), emissions from soil mineral N available
5.4.	R-Leaching	Fuzzy decision tree model, emissions from soil mineral N available

Indigo® scores calculation & recommendations

	Indigo® scores	Score between 0 and 10, for each loss pathway
	Recommendations	Recommendations of practices for adapting N inputs to plant needs, and reducing N losses
	Optimal fertiliser ≤ 10 years	Calculation of the risk of mineral fertiliser application, and estimation of the optimal rate & date of fertiliser application to reach expected yield, while minimising losses

	Optimal fertiliser > 10 years	Idem

1.1. How to run IN-Palm?

1.1.1. Choosing the inputs

Depending on the age of the palms of the plot simulated, go to sheet '≤ 10 years' or '> 10 years'. The inputs, listed in Table 1.2, are located on the left column of these sheets, in blue cells (Figure 1.1). Inputs are separated in two parts: soil and land preparation inputs, associated with the plot (Figure 1.1a); and management practices and weather, depending on years (Figure 1.1b).

For the sheet '≤ 10 years', input values for weather and management practices have to be filled for each year, from 1 to the actual age of the palms. This is because before 10 years of age, practices from previous years, such as initial residue from a previous palm cycle or legume establishment, may have a significant impact on N dynamics and losses over several years. For the sheet '> 10 years', input values for weather and management practices have to be filled only for the actual year simulated, and for the previous year for specific practices, such as empty fruit bunch application. This is because after 10 years the palm plantation reaches a steady state, where it is possible to assume that practices implemented before the previous year have no significant impact on N dynamics and losses.

To fill input values, in case weather data is not available with the required format, i.e. monthly rain amount and frequency, the sheet 'Weather' can be used to calculate monthly values from a daily dataset. In both user interface sheets, a spatial representation of the plantation is proposed on the top right-hand corner of the input variables column (Figure 1.1c). This representation is only illustrative, to help the user visualise its management choices, and calculations are not based on it. To complete this visual representation, some pictures of management options are proposed in the sheet 'Pictures' (Table A.2, in Appendix 4).

In the sheet '≤ 10 years', it is possible to perform ex-ante scenarios with the same weather data every year by pasting this weather data for age 1 (Figure 1.1b) and ticking 'Duplicate the 1st year weather data' in the calculation options located in the top left-hand corner of the input column (Figure 1.1d). When the box is ticked, rain amount, rain frequency and atmospheric deposition filled in for age 1 are used in calculations for all ages up to 10 years. Thus, weather values already filled for other ages are not used anymore in calculations until the box is unticked.

Other calculation options located in the top left-hand corner of the input column can be used for advanced testing of the modelling approach (Figure 1.1d). Their utility is described in the section 1.2 “How to dig in the structure and calculations?”.

Table 1.2. List of the 21 input variables and their possible values.

FFB: Fresh Fruit Bunches, FM: Fresh Matter, DM: Dry Matter, N: Nitrogen, C: Carbon

Variable classes	Input variables	Units	Ranges of classes
Crop factors	Age of palms	years	1-30
	Expected yield after 3 years	t FFB ha^{-1} yr^{-1}	0-40
Soil and land	Soil initial mineral N	kg N ha^{-1}	-
	Soil initial water	mm	-
	Soil organic C	%	0-10
	Slope	%	0-30
	Terraces	-	Yes No
	Soil texture	-	Sand Loamy Sand Sandy Loam Loam Silt Loam Silt Clay Loam Sandy Clay Loam Silty Clay Loam Silt Clay Clay Sandy Clay
Weather	Number of rainy days	month-1	-
	Monthly rainfall	mm	-
	Atmospheric N deposition	kg N ha^{-1} yr^{-1}	-
Fertiliser	Rate/Date of mineral fertiliser	kg ha^{-1}	-
management	Type of mineral fertiliser	-	Urea Ammonium Sulfate Ammonium Chloride Ammonium Nitrate Sodium Nitrate
	Placement of mineral fertiliser	-	In the circle, buried In the circle, not buried In the circle + windrow Evenly distributed
	Rate/Date of organic fertiliser	t FM ha^{-1}	-
	Type of organic fertiliser	-	Compost Empty fruit bunches
	Placement of organic fertiliser	-	In the circle In the harvesting path Spread (anti-erosion)
Understorey and residue management	Fronds	-	Exported In heaps In windrows Spread (anti-erosion)
	Previous palms	-	No (1^{st} cycle) (zero residue) Exported (below-ground residue) Shredded, left on soil (below- and above-ground residue)

Understorey biomass	-	Very high (about 12 t DM ha^{-1}) High (about 9 t DM ha^{-1}) Medium (about 6 t DM ha^{-1}) Low (about 3 t DM ha^{-1}) No (bare-soil)
Legume fraction	-	Very high (about 100 %) High (about 75 %) Medium (about 50 %) Low (about 25 %) No (no legume)

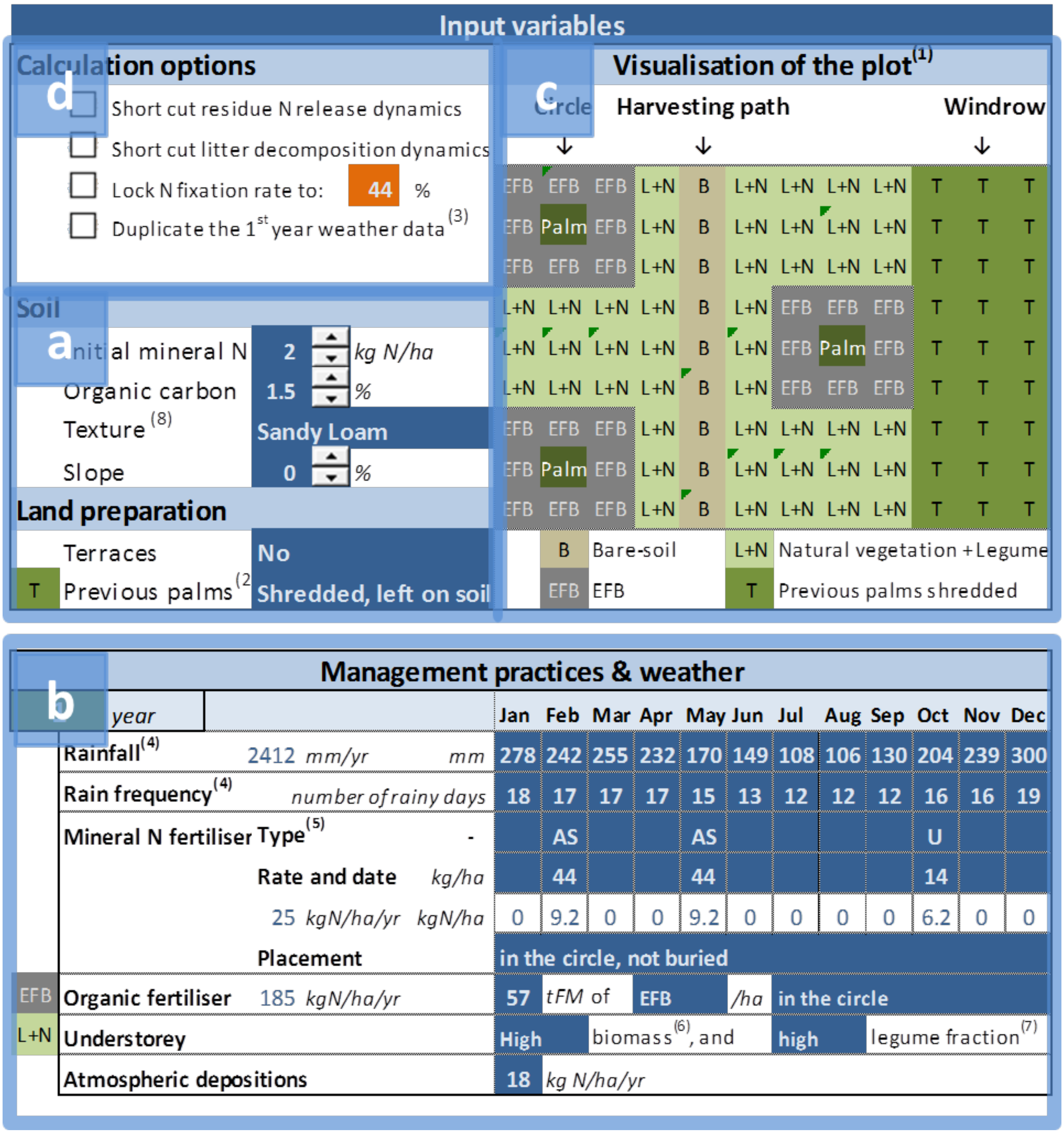

Figure 1.1. Input variables are located in the left column of sheets '≤ 10 years' or '> 10 years'. They consist of (a) soil and land preparation inputs, (b) management practices and weather, (c) spatial representation of the plantation, and (d) calculation options. FM: Fresh Matter, EFB: Empty Fruit Bunches, N: Nitrogen

1.1.2. Consulting outputs

Once an input variable is changed, new outputs are automatically displayed on the right column of the sheets '≤ 10 years' or '> 10 years' (Figure 1.2). Outputs are divided in two categories: N and water dynamics and N losses, and recommendations for adapting N inputs and reducing N losses.

1.1.2.1. N and water dynamics, N losses and scores

Nitrogen and water dynamics and N losses are presented by some general annual values, losses in kg N ha^{-1} yr^{-1}, scores between 0 and 10, and the details of N and water dynamics over the chosen year.

General values, N losses and scores are displayed for the chosen year on the top left-hand corner of the output column (Figure 1.2a). General values are soil mineral N and soil water at the end of the year, amount of N fixed by the legume understorey from the atmosphere, and fraction of soil covered. N losses and associated scores are displayed for each loss pathway. For a given loss pathway, a score of 4 corresponds to a level of N losses equivalent to losses with standard management practices, according to available measurements and simulations (see Table 1.3 for scores interpretation, and section 4.1 for calculations and references).

Monthly N and water dynamics over the chosen year are synthesised in the lower part of the output column in graphs and tables (Figure 1.2b). Three graphs present N dynamics: the total amount of N released in soil, the amount of N taken up by plants from soil, and N losses. Additional monthly indicators display the fixation rate of the legume fraction, and the amount of soil mineral N available for plants (dotted line in the graph “N taken up from soil”). When soil mineral N available for plants is below plant needs, a red bar is displayed in the graph, indicating that N may lack. When soil mineral N available for plants is higher than plant needs, a yellow bar is displayed, indicating that N may be in excess. The rules used to identify N lack or excess are explained in section 4.2. It is to note that when soil mineral N available for plants is below zero, this means that the expected yield may not be reached due to a limiting N supply, or that plants may take up some N from the soil organic stock.

Finally, one graph presents four monthly water factors driving N losses (Figure 1.2c): rain amount, rain frequency, soil moisture, and drainage. A risk of applying fertiliser is shown on this graph, using a red scale. When fertiliser application on a given month leads to high losses, a dark red bar is displayed on this month. When fertiliser application on a given month leads to low losses, a clear red bar is displayed on this month. The calculations done to assess the risk of application are explained in section 4.4.

For the sheet ‘≤ 10 years’, some more graphs and tables also synthesise the dynamics of N fluxes and losses over the 10 years (located below the section c of the output column, Figure 1.2). If the actual age of the palms simulated is below 10, the user only has to consider results displayed for years below the actual age.

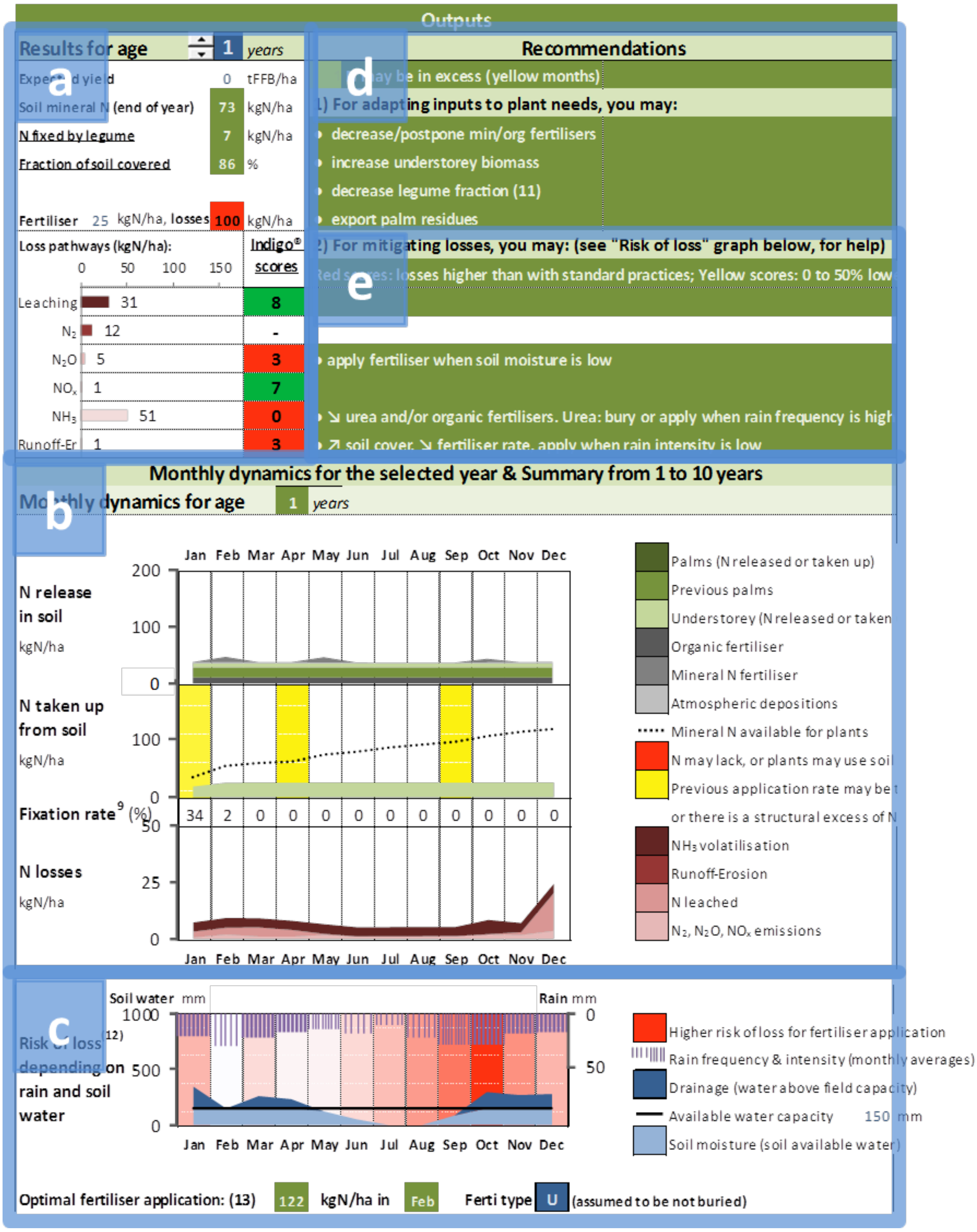

Figure 1.2. Outputs are located in the right column of sheets '≤ 10 years' or '> 10 years'.

They consist of (a) general results of N losses and scores for the chosen year, (b) three graphs synthesising the monthly N dynamics and the identification of potential N lack or excess, (c) a graph synthesising the water dynamics and the riskiest months for fertiliser application, (d) recommendations to better adapt N inputs to plants need, and (e) recommendations to reduce N losses. For (c), the highest risk of losses is in red, the lowest risk of losses is in white. Four environmental factors driving the different loss pathways are represented: rain amount, rain frequency, soil moisture and drainage. Management practices may also influence the risk pattern for fertiliser application, by enhancing or limiting sensitivity to a given loss pathway (e.g. spreading pruned fronds reduces the sensitivity to runoff, and hence reduces the risk of loss in months subject to runoff, compared to other months).

Table 1.3. Interpretation of scores.

Score	Interpretation
10	No losses
7 to 10	Losses reduced by more than 50% compared to standard practices
7	Losses reduced by 50 % compared to standard practices
4 to 7	Losses reduced by less than 50% compared to standard practices
4	Losses equal to emissions with standard practices
0 to 4	Higher losses than with standard practices
0	Losses 3 times higher than with standard practices

1.1.2.2. Recommendation of management changes

IN-Palm provides recommendations of management changes to help adapting better N inputs to plant needs, reducing N losses, and finding the optimal rate and date of mineral fertiliser application.

First, IN-Palm displays recommendations to better adapt N inputs to plant needs in the top right-hand corner of the output column (Figure 1.2d). If the indicator identifies months when N may lack or be in excess, i.e. red or yellow months in the graph “N taken up from soil” (Figure 1.2b), it proposes management changes to increase or decrease N inputs (Table 1.4). If neither N lack nor N excess are identified by the indicator, it displays a message saying that N supply may fit plant needs, within a range of ±5 kg N ha^{-1}.

Table 1.4. Potential recommendations given by IN-Palm to adapt N inputs to plant needs.

Conditions	Recommendations displayed
If N is in excess	● Decrease/postpone min/org fertilisers ● Decrease understorey biomass ● Decrease legume fraction* ● Export palm residues
If N is lacking	● Increase/split min/org fertilisers ● Decrease understorey biomass ● Increase legume fraction ● Do not export palm residues
If N does not lack, nor is in excess	● Soil mineral N may not lack compared to plant needs

* Decreasing legume fraction may enhance N uptake from soil by the understorey, due the fact that the legume tends to fix N from the atmosphere instead of taking it up from the soil. However, this change may not produce this expected result if soil is rich in mineral N. In this case, legume may already take up all its N from the soil, and decreasing legume fraction may even reduce the overall N taken up from soil by the understorey, because, in IN-Palm, legume N need is assumed to be higher than non-legume N need. Indeed, for a given amount of standing biomass, N content is higher in a legume than in a non-legume, and so it is for N uptake in IN-Palm.

Second, IN-Palm displays recommendations of management changes to reduce N losses (Figure 1.2e). These recommendations depend on scores and loss pathways (Table 1.5). If all scores are higher than 7, they all appear in green, and the indicator only informs the user that N losses are reduced by 50 % or more compared to standard practices. Otherwise, when at least one score is below 7, management changes are proposed for the associated loss pathway. For instance, to reduce N loss through runoff and erosion, the user is proposed to increase soil cover or to apply fertiliser when rainfall intensity is lower, as these two factors are the management drivers of N losses through runoff and erosion used in IN-Palm calculations.

Table 1.5. Potential recommendations given by IN-Palm to reduce N losses.

Conditions	Recommendations displayed
If all scores are ≥ 7	● Losses are reduced by more than 50% compared to standard practices
If Leaching score < 7	● Reduce N inputs, apply fertiliser when risk of drainage is low, export palm residues
If N_2O score < 7	● Apply fertiliser when soil moisture is low, export palm residues
If NO_x score < 7	● Reduce mineral/organic fertilisers inputs
If NH_3 score < 7	● Reduce urea and/or organic fertilisers. Bury urea or apply when rain frequency is high.
If Runoff-Erosion score < 7	● Increase soil cover, reduce fertiliser rate, apply when rain intensity is low

Third, IN-Palm estimates for each month the optimal mineral fertiliser date and rate for the chosen year (Figure 1.2.c). The date of application corresponds to the month of the year with the lowest risk of loss, i.e. the clearer red bar in the graph "Risk of losses". The rate of application corresponds, for this month, to a rate of enough but not too much N to achieve the expected yield. This estimation is done assuming only one application per year; however, lower annual rates and losses may be reached by the user, by splitting applications.

1.2. How to dig in the structure and calculations?

1.2.1. Exploring the structure and calculations

The general structure of the indicator is presented in the sheet 'Structure'. The parameters used by several modules are grouped in the sheets 'Summary of inputs and parameters', and 'Membership functions' (Table 1.1). In the whole Excel file, the references for parameters are provided next to the values (orange cells). The list of input variables, parameters, output variables and references are also synthesised in the tables A.3, A.4 and A.5 in Appendix 5.

Each module is calculated on a given sheet. In general, the input variables of the module (blue cells), as well as its outputs (green cells), are located on the top of the sheet. On each module sheet, a graph allows for having a quick view of the outputs of the module over the 10 first years.

The scores are calculated in the sheet 'Indigo® scores', recommendations for adapting N inputs and reducing N losses are provided by the sheet 'Recommendations', and the risk pattern for fertiliser application and the optimal fertiliser rate and date are calculated in sheets 'Optimal fertiliser ≤ 10 years', and 'Optimal fertiliser > 10 years'.

1.2.2. Testing the indicator behaviour

Some tools are available for testing the indicator behaviour, and the impact of some modelling choices on the outputs.

The sheet 'Fuzzy module testing' allows for testing the behaviour of a given fuzzy decision tree module. For a given tree selected by the user, this tool helps to have a quick overview of the output space, to check the response of the output space to input value changes, and to identify easily not realistic or not desirable behaviours. Moreover, this sheet illustrates how fuzzy logic improves the output space compared to standard decision trees.

Finally, for advanced testing about the modelling approach, it is possible to short-cut three calculation steps, from the user interface sheet '≤ 10 years', in the top left-hand corner (Figure 1.1d). The residue N release dynamics to soil, calculated in the Soil N Budget module, can be short cut. When this module is short cut, calculations are done assuming that the whole N from plant residues is released to the soil in less than one year, instead of several years depending on residue type in the normal calculation. Similarly, the residue decomposition dynamics, calculated by the Litter Budget module, can be short cut. When this module is short cut, calculations are done assuming that all the plant residues are decomposed in less than one year, instead of several years depending on residue type. Finally, the legume fixation rate can be locked to a given value, by short cutting its calculation done by the Understorey N Uptake/Fixation.

2. Advantages and computation of fuzzy decision tree models

In IN-Palm, 11 modules among 17 use the fuzzy decision tree modelling approach (see Pardon et al., under review, for more details on the modelling choices and references).

2.1. The fuzzy decision tree modelling approach

On the contrary to process-based or regression models, which apply equations to input values in order to yield outputs, decision tree models apply logical IF-THEN statements to input values (Breiman, 1984). For instance, a logical statement may be: "IF Rain ≥ 10 mm day^{-1}, AND Fraction of Soil Covered < 50 %, AND Slope ≥ 12.5 % AND there are no Terraces, THEN Runoff Coefficient is very high" (Figure 2.1, Standard decision tree). Such a logical statement is called a rule, or a branch of the tree; Rain, Fraction of Soil Covered, Slope and Terraces are input variables, or factors (Figure 2.1a); and Runoff Coefficient is the conclusion of the rule, or the leaf of the branch (Figure 2.1c). A set of rules covering all possible combinations of input variables is called a decision tree.

Input variables can take different values, either nominal or numerical, included in two or more classes. For instance, the classes of Terraces are "presence" and "absence", the classes of Fraction of Soil Covered are "< 50" or "≥ 50" %. The input variables, their respective classes and the rules applied to these input variables are parameters of the decision tree model, defined by the modeller. For a given combination of input values, only one rule of the tree is true, and the output of the model is the conclusion of this rule. In this example, given the input values, the output is "very high" (Figure 2.1d).

An important advantage of decision tree models is that they can easily integrate empirical expert knowledge as rules. Hence, decision trees allow for obtaining quantitative outputs, even when processes are not fully understood or when mathematical relationship between inputs and outputs is not available. This is particularly adapted to contexts of knowledge scarcity, which is the case for N dynamics and losses in oil palm. However, due to their structure, decision trees can only yield a limited number of outputs, lower or equal to the number of rules. The output space of a decision tree is hence discontinuous, which may lead to unrealistic behaviours or uncertain outputs (Figure 2.1e).

Fuzzy logic (Zadeh, 2008) applied to decision trees allows for obtaining continuous output spaces from exactly the same tree structure (Figure 2.1, Fuzzy decision tree). It is then possible to obtain more sensitive and precise outputs, without requiring more knowledge to build the tree structure (Olaru and Wehenkel, 2003). With fuzzy logic, when the value of an input variable, such as Fraction of Soil Covered, belongs to the class “< 50”, while being close to the class “≥ 50”, it is considered as belonging to both classes “< 50” and “≥ 50”, to some extent. An input value has hence a so-called membership degree to each class, which is defined using equations called membership functions.

For a given combination of input variables, all rules and their associated conclusions are considered as potentially true. A truth value is assigned to each rule, deduced from all the membership degrees of the input values to the classes of this rule (Figure 2.1b). Finally, the output of the model is an aggregation of all the conclusions, depending on their truth values (Figure 2.1d). Several methods are possible for the calculation of truth values and the aggregation of conclusions (see section 2.2 for the description of the methods used in IN-Palm).

Eventually, a standard tree and a fuzzy tree using the same set of rules can yield very different outputs for particular combinations of input values close to the edges of classes. In the example presented in Figure 2.1, Runoff Coefficient is estimated at 1 and 6.6 % of rain, with the standard tree and the fuzzy tree, respectively.

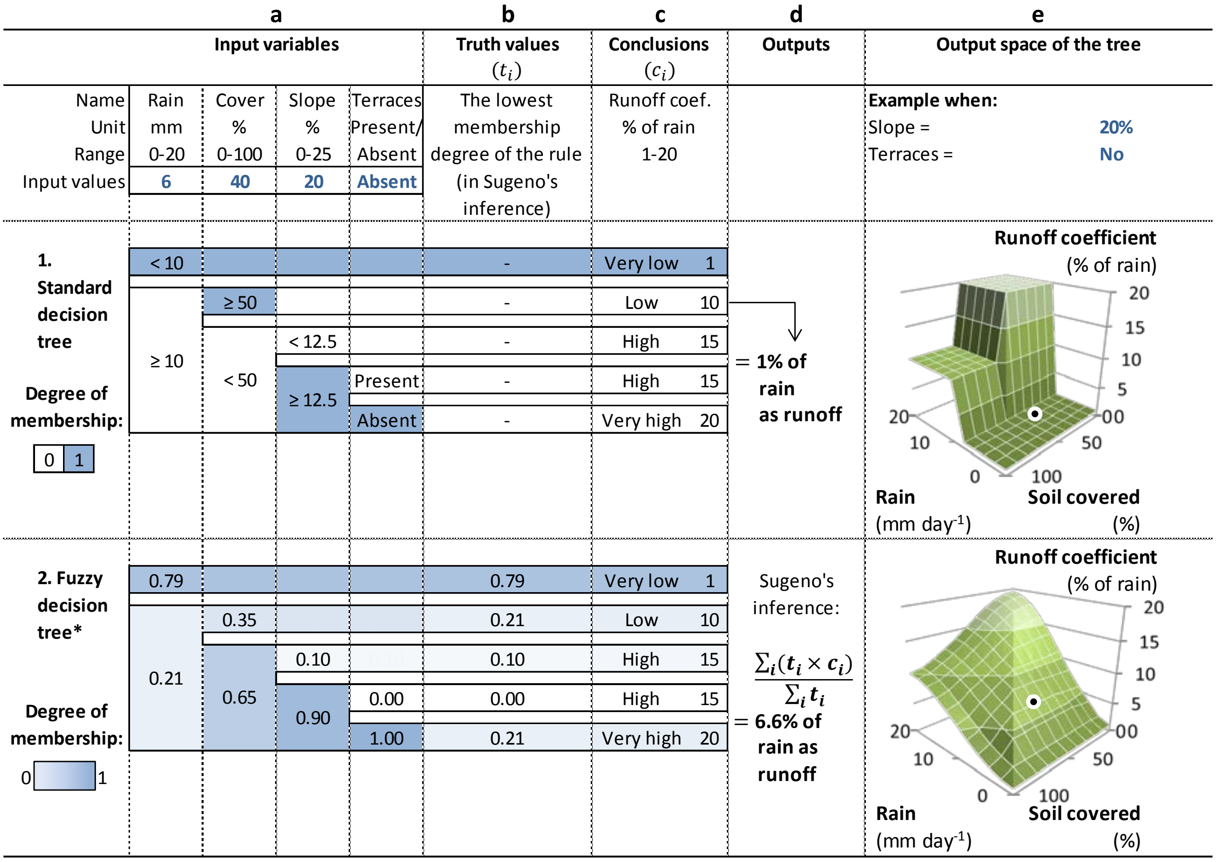

Figure 2.1. Standard decision tree vs. fuzzy decision tree: example for the Water Runoff module of IN-Palm. For a given combination of input variables (a), truth values are calculated for all rules in the fuzzy tree (b) while only one conclusion is valid for the standard tree (c). With the same rules, output values can be very different (d) due to different output spaces between trees. In Sugeno's inference (1985), the truth value t_i of a rule i is defined as the lowest membership degree of input values for this rule; and the output is the average of all the truth values t_i, weighted by their respective conclusion values c_i. For sake of clarity, only the membership degrees are represented in the fuzzy decision tree, but the classes are the same as for the standard tree, i.e. "< 10" vs. "≥ 10", "≥ 50" vs. "< 50", etc.

2.2. Membership functions in IN-Palm

In IN-Palm, each fuzzy decision tree uses 1 to 6 input variables (see section 3 for the detailed tree structures). Two classes were defined for all the input variables: Favourable and Unfavourable. When an input value falls into the Favourable class, the resulting N losses tend to be low, and when it falls into the Unfavourable class, the losses tend to be high.

In a fuzzy decision tree, input values can be considered as pertaining to both classes. Two membership functions are hence necessary to calculate the membership degree of a given input value to each class. Membership degrees are values between 0 and 1. By definition, when the membership degree is equal to 0, the input value does not belong to the given class. When it is between 0 and 1, it partially belongs to the class. When it is equal to 1, it fully belongs to the class. In IN-Palm, the same two cosine membership functions are used for all input variables of all decision trees, as in van der Werf and Zimmer (1998) (Figure 2.2):

Equation (1): $Membership\ degree_{Favourable} = \frac{1}{2} \times [1 + \cos\ (input\ value \times \pi + \pi)]$

Equation (2): $Membership\ degree_{Unfavourable} = \frac{1}{2} \times [1 + \cos\ (input\ value \times \pi)]$

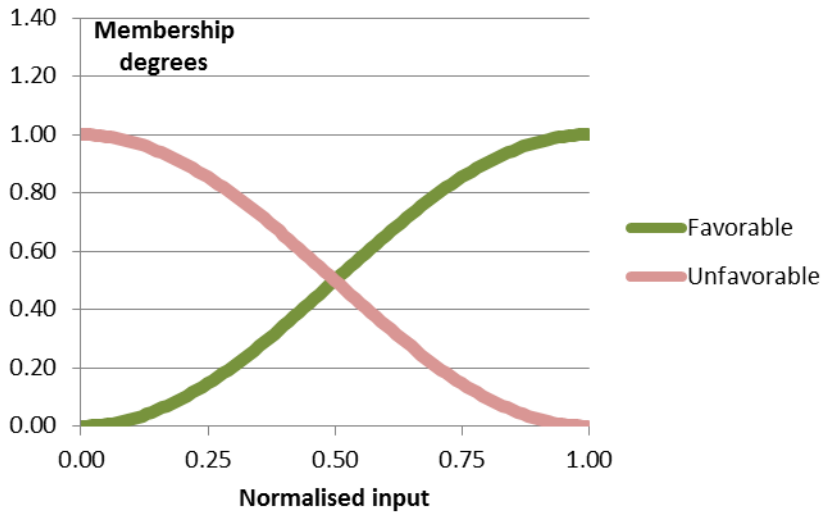

Figure 2.2. Representation of the two cosine membership functions associated with the classes Favourable and Unfavourable.

For any input value between 0 and 1, the membership functions yield the membership degrees of the input value to the two classes.

2.3. Computational steps of the fuzzy decision tree models in IN-Palm

Three steps are computed to calculate the output of a decision tree from a given set of input values: 1) calculation of the membership degrees of input values, 2) calculation of the truth values of rules, and 3) calculation of the output.

1) Input values are generally expressed in various units, either nominal or numerical. As the inputs of the membership functions are numerical values between 0 and 1, a first step is necessary to convert input values. Numerical input values are normalised between 0 and 1, with respect to upper and lower limits defined for each input variable (e.g. for Rain: 0 to 20 kg N ha^{-1} yr^{-1}, Figure 2.1). Nominal input values are converted into numerical values between 0 and 1 using conversion tables defined for each case (e.g. for Terraces: “Absence” → 0, “Presence” → 1). Upper and lower limits for numerical input variables, and conversion tables for nominal variables, are detailed for each decision tree in section 3.

All the normalised values are used to calculate membership degrees by using the membership functions (Figure 2.3). An input values has hence a membership degree to the Favourable class, and a membership degree to the Unfavourable class.

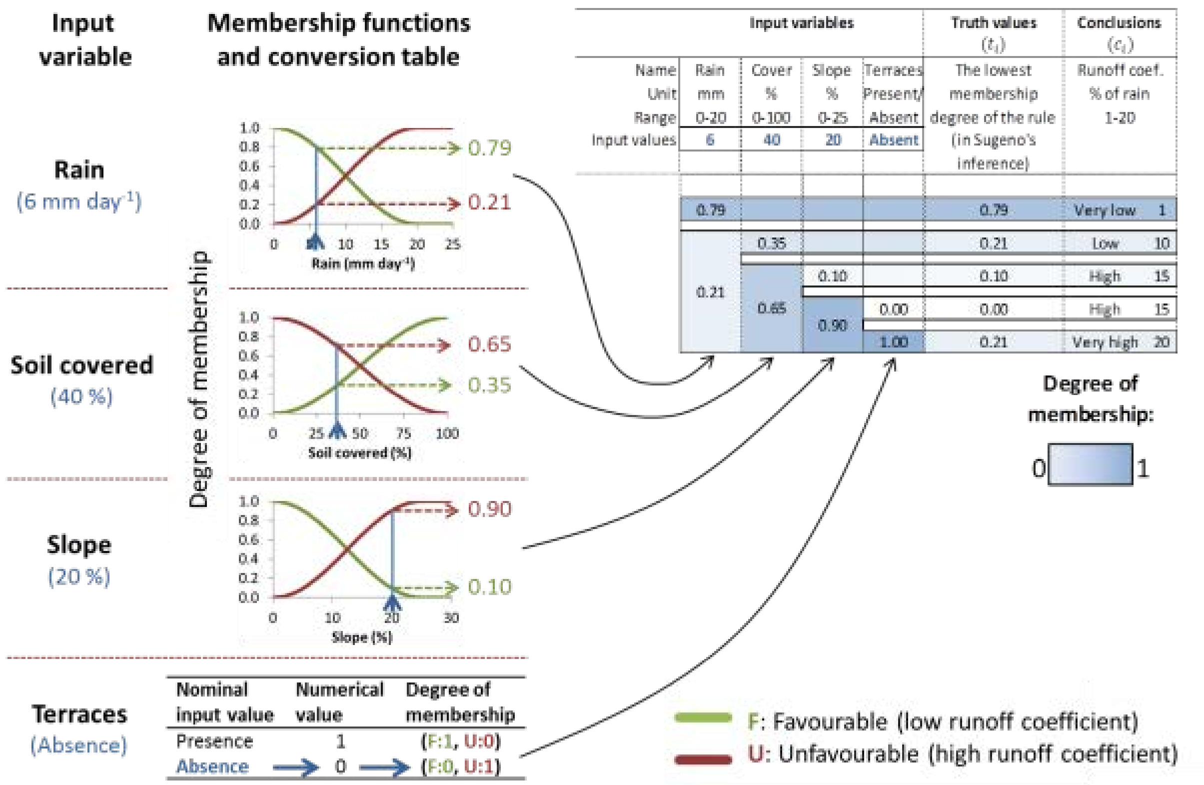

Figure 2.3. Calculation of membership degrees of input values to the Favourable and Unfavourable classes.

2) In IN-Palm, truth values are calculated for each rule with the "MIN operator", following Sugeno's inference method (1985). The truth value of a rule i is equal to the lowest membership degree associated with each of the n input variables (Figure 2.1b):

Equation (3): $Truth\ value_i = \min_{1 \le j \le n} (Membership\ degree_j)$

3) Finally, the output of the tree is an aggregation of all the conclusions of the rules, weighted by their respective truth values, following Sugeno's inference method (1985) (Figure 2.1d):

Equation (4): $Output = \frac{\sum_i (Truth\ value_i \times Conclusion_i)}{\sum_i Truth\ value_i}$

3. Structure of the 17 modules

Seventeen modules are calculated in IN-Palm, among which 11 use fuzzy decision tree models, 3 use mass budget models, and 3 use regression models. Five main steps of calculation are computed for one hectare of palms of 1 to 30-year-old, for each months of the chosen year: (1) NH_3 volatilisation from mineral and organic fertilisers; (2) soil cover and water budget estimations; (3) denitrification from mineral and organic fertilisers, and N losses through runoff-erosion from mineral fertiliser and atmospheric deposition; (4) soil mineral N estimation after N release in soil and plants N uptake; and (5) denitrification baseline and N leaching, from soil mineral N.

3.1. Ammonia volatilisation from mineral and organic fertiliser

Module 1.1 R-NH3-Mineral

The volatilisation of NH_3 from mineral fertiliser application is estimated using a fuzzy decision tree (Figure 3.1). This decision tree consists in 7 rules and uses 5 input variables: mineral fertiliser type (urea or other types), mineral fertiliser placement (buried or not buried), rain frequency (rainy days month^{-1}), palms age (years), and soil texture (fine, medium or coarse).

For mineral fertiliser type, placement, and soil texture, nominal values are converted into numerical values between 0 and 1 in order to compute the decision tree (e.g. “medium soil texture” is converted into 0.5, Table 3.1).

The output of the decision tree is a monthly emission factor ranging from 2 to 45 % of the mineral fertiliser rate applied. References used for tree structure, tree calibration and output range, are detailed in Tables A.4 and A.5 in Appendix 5.

Factors and classes

Factor	Mineral fertiliser type	Mineral fertiliser placement	Rain frequency	Palms age	Soil texture
Unit	-	-	rainy days month^{-1}	years	-
Unfavorable limit	0	0	7.5	4	0
Favorable limit	1	1	30	10	1

Rule number	Structure of the tree					Emission factor (% of N applied)	
1	F					Very_low	2
2	U	F				Very_low	2
3	U	U	F			Low	13
4	U	U	U	F	F	Low	13
5	U	U	U	F	U	Medium	24
6	U	U	U	U	F	High	34
7	U	U	U	U	U	Very_high	45

Figure 3.1. Decision tree for NH_3 volatilisation from mineral fertiliser application

The tree consists in 7 rules and 5 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of NH_3 volatilisation from mineral fertiliser N applied.

Table 3.1. Conversion of nominal input variables into numerical values for NH_3 volatilisation

Factors	Nominal input variable	Numerical value
Mineral fertiliser type	Urea	0
	Ammonium sulfate	1
	Ammonium chloride	1
	Ammonium nitrate	1
	Sodium nitrate	1
Mineral fertiliser placement	in the circle, buried	1
	in the circle, not buried	0
	in the circle + windrow	0
	evenly distributed	0
Soil texture	Fine	1
	Medium	0.5
	Coarse	0

Module 1.2 R-NH3-Organic

The volatilisation of NH_3 from organic fertiliser application is estimated using the regression model of (Bouwman et al., 2002c) (Equation 5).

Equation (5): $Annual\ volatilisation = Organic\ N\ fertiliser\ rate\ \times e^{(\sum_i correction\ factor_i)}$

This model uses 1 input variable, being the organic N fertiliser rate (kg N ha^{-1} $year^{-1}$); and 6 correction factors, being organic fertiliser type, crop type, application mode, soil pH, soil cation exchange capacity and climate. In IN-Palm, all the correction factors are set to fix values to fit oil palm conditions (see Table A.4 in Appendix 5 for correction factor values).

The output is an annual emission factor from organic N fertiliser rate. For monthly calculations of the N budget, this annual value is divided by twelve months.

3.2. Preliminary calculations for soil moisture and drainage

Module 2.1 Litter Budget

The Litter Budget module uses a mass budget approach applied to litter flows in the plantation, following the equation (6). This module uses, as input variables, all inputs to and outputs from the litter pool.

Equation (6): $Litter\ (n+1) = Litter\ (n) + Inputs\ (n+1) - Decomposition\ (n+1)$,

with $n+1$ being the age of palms, and all variables being expressed in ton of dry matter ha^{-1}. The initial amount of litter, before accounting for palm residues from the previous cycle, is set as zero by default. The inputs include previous palms residue, current palm and understorey residues, and organic fertiliser.

Two types of parameters were necessary to estimate inputs: the mass of initial residue from previous palm residues and the annual turnover rates of other plant residues. $Decomposition$ is calculated for each residue type following the equation of Moradi et al. (2014), which is specific to oil palm residues.

The output of this module is an annual value of litter amount, expressed in ton of dry matter ha^{-1}. References used for mass of initial residue, turnover rates and decomposition speed are detailed in Tables A.4 and A.5 in Appendix 5.

Module 2.2 Fraction of Soil Covered

The fraction of soil covered is estimated using a fuzzy decision tree (Figure 3.2). This decision tree consists in 18 rules and uses 6 input variables: understorey biomass (t of dry matter ha^{-1}), amount of litter from fronds (t of dry matter ha^{-1}), fronds placement, amount of litter from organic fertiliser (t of dry matter ha^{-1}), organic fertiliser placement, and amount of litter from previous palms (t of dry matter ha^{-1}).

Litter amount from initial residue, fronds and organic fertiliser are from the Litter Budget module. For understorey biomass, fronds placement and organic fertiliser placement, nominal values are converted into numerical values between 0 and 1 in order to compute the decision tree (e.g. “fronds in windrows” is converted into 0.5, Table 3.2).

The output of the decision tree is an annual fraction of soil covered between 0 and 1. References used for tree structure, tree calibration and output range, are detailed in Tables A.4 and A.5 in Appendix 5.

Factors and classes								
Factor	Under-storey biomass	Fronds litter*	Fronds placement	Organic fertiliser litter*	Organic fertiliser placement	Previous palms litter*		
Unit	tDM ha^{-1}	tDM ha^{-1}	-	tDM ha^{-1}	-	tDM ha^{-1}		
Unfavorable limit	0	0	0	0	0	20		
Favorable limit	12.4	9	1	25	1	88		
Rule number	Structure of the tree						Emission factor	fraction
1	F						Very_high	1.00
2	U	F	F	F	F		Very_high	1.00
3	U	F	F	F	U	F	Very_high	1.00
4	U	F	F	F	U	U	High	0.75
5	U	F	F	U		F	High	0.75
6	U	F	F	U		U	Medium high	0.60
7	U	F	U	F	F	F	High	0.75
8	U	F	U	F	F	U	Medium high	0.60
9	U	F	U	F	U	F	Medium high	0.60
10	U	F	U	F	U	U	Medium low	0.40
11	U	F	U	U		F	Medium low	0.40
12	U	F	U	U		U	Low	0.15
13	U	U		F	F	F	Medium high	0.60
14	U	U		F	F	U	Medium low	0.40
15	U	U		F	U	F	Medium low	0.40
16	U	U		F	U	U	Low	0.15
17	U	U		U		F	Low	0.15
18	U	U		U		U	Very_low	0.00

Figure 3.2. Decision tree for fraction of soil covered

The tree consists in 18 rules and 6 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is an annual fraction of soil covered. DM: dry matter, *Intermediate variable calculated by another module

Table 3.2. Conversion of nominal input variables into numerical values for fraction of soil covered

Factors	Nominal input variable	Numerical value
Understorey biomass	No	0
	Low	3.1
(t of dry matter ha^{-1})	Medium	6.2
	High	9.3
	Very high	12.4
Fronds placement	Exported	0
	In heaps	0
	In windrows	0.5
	Spread (anti-erosion)	1

Organic fertiliser placement	No fertiliser	0
	In the circle	0
	In the harvesting path	0.5
	Spread (anti-erosion)	1

Module 2.3 Water Runoff

Water runoff is estimated using a fuzzy decision tree (Figure 3.3). This decision tree consists in 5 rules and uses 4 input variables: rain intensity (mm), fraction of soil covered (0 to 1), slope (%), and terraces (presence or absence).

Rain intensity corresponds to the monthly average of rain per rainy day. It is estimated by dividing the monthly rainfall by the number of rainy days. For terraces, the nominal value is converted into numerical values between 0 and 1 in order to compute the decision tree (e.g. “presence of terraces” is converted into 1, Table 3.3).

The output of the decision tree is a monthly runoff coefficient, ranging from 1 to 20 % of rain. References used for tree structure, tree calibration and output range, are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes						
Factor	**Rain intensity**	**Fraction of soil covered***	**Slope**	**Terraces**		
Unit	mm	-	%	-		
Unfavorable limit	20	0	25	0		
Favorable limit	0	1	0	1		
Rule number	**Structure of the tree**				**Emission factor**	
					runoff coefficient (%)	
1	F				Very_low	1
2	U	F			Low	10
3	U	U	F		High	15
4	U	U	U	F	High	15
5	U	U	U	U	Very_high	20

Figure 3.3. Decision tree for water runoff

The tree consists in 5 rules and 4 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a monthly runoff coefficient (% of rainfall). *Intermediate variable calculated by another module

Table 3.3. Conversion of nominal input variables into numerical values for water runoff

Factors	Nominal input variable	Numerical value
Terraces	Presence	1
	Absence	0

Module 2.4 Soil Water Budget

The Soil Water Budget module uses a mass budget approach applied to water flows, following the equation (7) adapted from Corley and Tinker (2003). This module uses, as input variables, all inputs to and outputs from the soil water pool.

Equation (7): $W\ (m+1) = W\ (m) + \ Rain\ (m+1) - Intercepted\ water\ (m+1) - Water\ runoff\ (m+1) - Evapotranspiration\ (m+1) - Drainage\ (m+1)$,

with W the plant available water and m a given month of the year. Calculations are done monthly, and variables are expressed in mm month^{-1}. For the sheet "≤ 10 years", the initial plant available water is set by default at the plant available water capacity at planting, and water budget calculations are done up to the 10th year. For the sheet "> 10 years", the initial plant available water is an input variable set by the user.

The parameters used for calculations are: water intercepted by the canopy and eventually evaporated (0% of rain for year 1, linearly increasing every year, up to 11% after 10 years), potential evapotranspiration (140 mm month^{-1}), soil depth where most of fine roots are located (1.5 m), plant available water capacity and soil water saturation capacity. The two latter hydraulic properties are inferred from soil texture using pedotransfer relationships.

$Water\ runoff$ is estimated by the Water Runoff module. $Evapotranspiration$ is estimated depending on plant available water in soil after accounting for rain, intercepted water and water runoff. Evapotranspiration is equal to potential evapotranspiration if plant available water is higher than potential evapotranspiration, otherwise evapotranspiration is equal to plant available water. Finally, $Drainage$ is estimated depending on the surplus of water above plant available capacity, after accounting for rain, intercepted water, water runoff and evapotranspiration. Drainage is equal to the surplus of water, or is equal to zero if there is no surplus. Drainage corresponds to the amount of water percolated below the 1.5 m depth, and hence lost for palms.

The output values of this module are monthly plant available water and drainage. The plant available water is used to estimate soil moisture for R-N_2O-Mineral and R-N_2O-Baseline modules. Drainage is used to estimate soil saturation for R-N_2-Mineral and R-N_2-Baseline modules, and for R-Leaching module. References used for parameters are detailed in Tables A.4 and A.5 in Appendix 5.

3.3. Denitrification from fertilisers and runoff-erosion

Module 3.1 R-N2O-Mineral

Emissions of N_2O from mineral fertiliser application are estimated using a fuzzy decision tree (Figure 3.4). This decision tree consists in 32 rules and uses 5 input variables: soil moisture (% of maximal level of water in soil), soil texture (fine, medium or coarse), soil organic C (%), litter amount (t of dry matter ha^{-1}), and mineral fertiliser rate (kg N ha^{-1} $month^{-1}$).

For soil moisture, the maximal level of water in soil corresponds to saturation (plant available water capacity + water saturation capacity). For soil texture, the nominal value is converted into a numerical value between 0 and 1 in order to compute the decision tree (e.g. “medium soil texture” is converted into 1, Table 3.4).

The output of the decision tree is a monthly emission factor, ranging from 0.01 to 10.6 % of mineral fertiliser rate applied. References used for tree structure, tree calibration and output range are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes							
Factor	**Soil moisture***	**Soil texture**	**Soil organic C**	**Litter amount***	**Mineral fertiliser**		
Unit	% of water capacity + saturation	-	%	tDM ha^{-1}	kg N ha^{-1} $month^{-1}$		
Unfavorable limit	100	0	3	130	250		
Favorable limit	0	1	1	10	0		
Rule number	**Structure of the tree**					**Emission factor**	% of N applied
1	F	F	F	F	F	Very_low	0.01
2	F	F	F	F	U		0.02
3	F	F	F	U	F		1.3
4	F	F	F	U	U	Low	2.1
5	F	F	U	F	F		1.3
6	F	F	U	F	U	Low	2.1
7	F	F	U	U	F		2.5
8	F	F	U	U	U	Medium low	4.2
9	F	U	F	F	F		1.3
10	F	U	F	F	U	Low	2.1
11	F	U	F	U	F		2.5
12	F	U	F	U	U	Medium low	4.2
13	F	U	U	F	F		3.7
14	F	U	U	F	U	Medium high	6.4
15	F	U	U	U	F		5.0
16	F	U	U	U	U	High	8.5
17	U	F	F	F	F		1.3
18	U	F	F	F	U	Low	2.1
19	U	F	F	U	F		2.5
20	U	F	F	U	U	Medium low	4.2
21	U	F	U	F	F		2.5
22	U	F	U	F	U	Medium low	4.2
23	U	F	U	U	F		3.7
24	U	F	U	U	U	Medium high	6.4
25	U	U	F	F	F		2.5
26	U	U	F	F	U	Medium low	4.2
27	U	U	F	U	F		3.7
28	U	U	F	U	U	Medium high	6.4
29	U	U	U	F	F		5.0
30	U	U	U	F	U	High	8.5
31	U	U	U	U	F		6.2
32	U	U	U	U	U	Very_high	10.6

Figure 3.4. Decision tree for N_2O emissions from mineral fertiliser

The tree consists in 32 rules and 5 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of N_2O emissions from N applied as mineral fertiliser. N: nitrogen, DM: dry matter, *Intermediate variable calculated by another module

Table 3.4. Conversion of nominal input variables into numerical values for N_2O emissions from fertiliser

Factors	Nominal input variable	Numerical value
Soil texture	Coarse	0.5
	Medium	1
	Fine	0

Module 3.2 R-N_2-Mineral

Emissions of N_2 from mineral fertiliser application are estimated using a fuzzy decision tree (Figure 3.5). This decision tree consists in 2 rules and uses 1 input variable being soil saturation (% of soil water saturation capacity).

The output of the decision tree is a monthly ratio of N_2/N_2O, ranging from 1.92 to 9.96. This ratio is then applied to N_2O emissions from mineral fertiliser to estimate monthly N_2 emissions from mineral fertiliser. References used for tree structure, tree calibration and output range are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes			
Factor	**Soil saturation***		
Unit	% of saturation capacity		
Unfavorable limit	100		
Favorable limit	0		
Rule number		**Emission factor** N_2/N_2O ratio	
1	F	Low	1.92
2	U	High	9.96

Figure 3.5. Decision tree for N_2/N_2O ratio

The tree consists in 2 rules and 1 factor. Two limits of classes are defined for the factor: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of N_2/N_2O ratio. *Intermediate variable calculated by another module

Module 3.3 R-NO_x-Mineral/Organic

Emissions of NO_x from mineral and organic fertiliser applications are estimated using the regression model of (Bouwman et al., 2002a) (Equation 8).

Equation (8): $Annual\ NOx\ emission = e^{(-1.527\ +\ \sum_i correction\ factor_i)}$

This model uses 6 input variables: mineral N fertiliser rate (kg N ha^{-1} $month^{-1}$), organic N fertiliser rate (kg N ha^{-1} $year^{-1}$), mineral and organic fertiliser types, soil texture and soil organic C content (Table A.4 in Appendix 5).

Following the method described in (Bouwman et al., 2002a), the fertiliser rates and types are combined to provide one correction factor for the mineral fertiliser application and one correction factor for the organic fertiliser application. In IN-Palm, the organic fertiliser type is set as “Animal manure”, as it is the closest option to oil palm conditions. This regression model estimates together emissions from fertiliser applications and baseline emissions, therefore baseline emissions are subtracted here to account only for fertiliser-induced emissions.

The output of this module is hence an annual emission of N losses from fertiliser and organic application, directly expressed in kg N ha^{-1} $year^{-1}$. For monthly calculations of the N budget, this annual value is divided by twelve months.

Module 3.4 R-Runoff-Erosion

Losses of N through runoff-erosion from mineral fertiliser application and atmospheric deposition are estimated using a fuzzy decision tree (Figure 3.6). This decision tree consists in 9 rules and uses 5 input variables: rain intensity (mm), soil texture (fine, medium or coarse), fraction of soil covered (0 to 1), slope (%) and terraces (presence or absence).

Rain intensity corresponds to the monthly average of rain per rainy day. It is estimated by dividing the monthly rainfall by the number of rainy days. For soil texture and terraces, nominal values are converted into numerical values between 0 and 1 in order to compute the decision tree (e.g. “medium soil texture” is converted into 0.5, Table 3.5).

The output of the decision tree is a monthly emission factor, ranging from 1 to 20 % of mineral fertiliser rate applied and atmospheric deposition. References used for tree structure, tree calibration and output range, are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes						
Factor	Rain intensity	Soil texture	Fraction of soil covered*	Slope	Terraces	
Unit	mm	-	-	%	-	
Unfavorable limit	20	0	0	25	0	
Favorable limit	0	1	1	0	1	
Rule number	Structure of the tree					Emission factor % of N applied
1	F					Very_low 1
2	U	F	F			Very_low 1
3	U	F	U	F		Very_low 1
4	U	F	U	U	F	Medium high 10
5	U	F	U	U	U	High 15
6	U	U	F			Low 2.5
7	U	U	U	F		Low 2.5
8	U	U	U	U	F	High 15
9	U	U	U	U	U	Very_high 20

Figure 3.6. Decision tree for N losses though runoff-erosion from mineral fertiliser and atmospheric deposition

The tree consists in 9 rules and 5 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of N lost through runoff-erosion from N applied as mineral fertiliser and atmospheric deposition. *Intermediate variable calculated by another module

Table 3.5. Conversion of nominal input variables into numerical values for N losses through runoff-erosion

Factors	Nominal input variable	Numerical value
Soill texture	Fine	1
	Medium	0.5
	Coarse	0
Terraces	Presence	1
	Absence	0

3.4. Preliminary calculations for soil mineral N

Module 4.1 Palm N Uptake

The palm N uptake is estimated using a fuzzy decision tree (Figure 3.7). This decision tree uses 2 input variables: palms age (years, from 1 to 30) and yield (t of fresh fruit bunches ha^{-1} yr^{-1}).

The correspondence between N uptake and yield used by this module was estimating using 58 500 APSIM-Oil palm simulations of 20 years done in three sites in Papua New Guinea. First, the lowest and highest classes of yield were defined for each age, spanning from 82 to 100 % of the 58 500 simulations, depending on age (92 % in average). Second, the average simulated N uptake was calculated for each age for the lowest and the highest classes of yield. For ages higher than 20 years, the classes of yield and their corresponding N uptake are equal to the ones for 20 year-old.

The output of the decision tree is an annual palm N uptake (kg N ha^{-1} yr^{-1}) depending on palms age and expected yield. References used for tree structure, tree calibration and output range, are detailed in Table A.4 and A.5 in Appendix 5.

		Factor		Output	
Variable	**Age**	**Yield**		**Palm N uptake**	
Unit	years	t FFB ha^{-1} yr^{-1}		kg N ha^{-1} yr^{-1}	
Classes	-	**Unfavorable limit**	**Favorable limit**	**Low**	**High**
Annual values	0	0	0	0	0
	1	0	0	2	2
	2	0	0	10	10
	3	0	5	22	53
	4	5	15	81	140
	5	10	25	167	225
	6	15	35	187	282
	7	15	35	203	297
	8	15	40	205	311
	9	15	40	214	308
	10	15	40	214	311
	11	15	40	215	316
	12	15	40	213	318
	13	15	40	216	319
	14	15	40	212	321
	15	15	40	205	321
	16	15	40	210	320
	17	15	40	212	318
	18	15	40	205	308
	19	15	40	199	300
	20	15	40	189	287
	21	15	40	198	299
	22	15	40	198	299
	23	15	40	198	299
	24	15	40	198	299
	25	15	40	198	299

Figure 3.7. Decision tree for palm N uptake

The tree consists in 2 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is an annual palm N uptake depending on the expected yield. N: nitrogen, FFB: fresh fruit bunches

Module 4.2 Understorey N Uptake/Fixation

The understorey N uptake/fixation is estimated using a fuzzy decision tree (Figure 3.8). This decision tree consists in 2 rules and uses 1 input variable, being the soil mineral N available for understorey (kg N ha^{-1} yr^{-1}).

The soil mineral N available for understorey is calculated by the Soil N Budget module (see following section). The output of the decision tree is a monthly percentage of N entering in the understorey biomass by fixation from the atmosphere. This N fixation rate is then used to deduce the N fixed and the N taken up from soil by the understorey. References used for tree structure, tree calibration and output range, are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes	
Factor	**Soil mineral N available***
Unit	kg N ha^{-1} yr^{-1}
Unfavorable limit	60
Favorable limit	0

Rule number		**Emission factor**	
			% of N fixed
1	F	High	90
2	U	No_fixation	0

Figure 3.8. Decision tree for understorey N fixation

The tree consists in 7 rules and 5 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a percentage of N in understorey biomass which has been fixed from the atmosphere. N: nitrogen, *Intermediate variable calculated by another module

Module 4.3 Soil N Budget

The soil N budget module uses a mass budget approach applied to N flows in the plantation, following the equation (9). This module uses, as input variables, all inputs to and outputs from the soil mineral N pool.

Equation (9):
$$Soil\ mineral\ N\ (m+1) = Soil\ mineral\ N\ (m) + Fertiliser\ N\ net\ release\ (m+1) + Atmospheric\ deposition\ N\ net\ release\ (m+1) + Litter\ N\ net\ release\ (m+1) - Palm\ N\ uptake\ (m+1) - Understorey\ N\ uptake\ (m+1) - N\ losses\ (m+1),$$

with m a given month of the year, and all variables being in kg N ha^{-1} yr^{-1}.

The initial amount of mineral N in soil is an input variable set by the user. Inputs from fertiliser, atmospheric deposition and litter are net release, after subtracting the first losses through NH_3 volatilisation, N_2, N_2O, NO_x emissions and runoff-erosion. $Litter\ N\ net\ release$ includes organic fertiliser inputs and accounts implicitly for the immobilisation of N in the litter.

The parameters used for calculations are, for each residue type: the N content, the annual rate of turnover, and the speed of net N release through decomposition (from 1 to 3 years).

$Palm\ N\ uptake$ is estimated by the Palm N Uptake module, depending on palms age and the expected yield. $Understorey\ N\ uptake$ is calculated by the Understorey N Uptake/Fixation, depending on the soil mineral N available after accounting for N net release from fertiliser, atmospheric deposition and litter, and palm N uptake. Finally, $N\ losses$ from baseline denitrification and N leaching are calculated, depending on soil mineral N available after accounting for all other inputs to and outputs from the soil. As $Palm\ N\ uptake$ and $Understorey\ N\ uptake$ are calculated depending on palm expected yield and understorey biomass set by the user, the total N uptake from plants may be higher than the actual amount of mineral N available in soil. In this case, the level of soil mineral N can become negative, indicating that plants may take up some N from the soil organic N pool to reach the expected palm yield and understorey biomass. When soil mineral N is negative, N losses through baseline denitrification and leaching are zero.

The output of this module is a monthly value of mineral N available in soil, expressed in kg N $ha^{-1}\ yr^{-1}$. References used for parameters are detailed in Table A.4 and A.5 in Appendix 5.

3.5. Denitrification-baseline and N leaching from soil mineral N

Module 5.1 R-N_2O-Baseline

Baseline emissions of N_2O from soil mineral N available are estimated using a fuzzy decision tree (Figure 3.9). This decision tree has the same structure and factors as the one used in the R-N_2O-Mineral module, except that the mineral fertiliser rate factor is not accounted for.

The output is a monthly emission factor, ranging from 0.1 to 1.1 % of mineral N available in soil for losses. References used for the output range are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes					
Factor	Soil moisture*	Soil texture	Soil organic C	Litter amount*	
Unit	% of water capacity + saturation	-	%	tDM ha-1	
Unfavorable limit	100	0	3	130	
Favorable limit	0	1	1	10	
Rule number	Structure of the tree				Emission factor % of soil mineral N
1	F	F	F	F	Very_low 0.1
2	F	F	F	U	Low 0.4
3	F	F	U	F	Low 0.4
4	F	F	U	U	Medium 0.6
5	F	U	F	F	Low 0.4
6	F	U	F	U	Medium 0.6
7	F	U	U	F	Medium 0.6
8	F	U	U	U	High 0.9
9	U	F	F	F	Low 0.4
10	U	F	F	U	Medium 0.6
11	U	F	U	F	Medium 0.6
12	U	F	U	U	High 0.9
13	U	U	F	F	Medium 0.6
14	U	U	F	U	High 0.9
15	U	U	U	F	High 0.9
16	U	U	U	U	Very_high 1.1

Figure 3.9. Decision tree for N_2O emissions from soil mineral N available

The tree consists in 16 rules and 4 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of N_2O from N applied as mineral fertiliser. N: nitrogen, DM: dry matter, *Intermediate variable calculated by another module

Module 5.2 R-N_2-Baseline

Baseline emissions of N_2 from soil mineral N available are estimated using the same fuzzy decision tree as the one used in the R-N_2-Mineral module. Here, the N_2/N_2O ratio determined in the R-N_2-Mineral module is applied to N_2O emissions from soil mineral N available, to estimate monthly N_2 emissions from soil mineral N available.

Module 5.3 R-NO_x-Baseline

Baseline emissions of NO_x from soil are estimated using the regression model of Bouwman et al. (2002a) as well as used in the R-NO_x-Mineral/Organic module. Here, only the baseline emissions are accounted for, by using zero rates for mineral and organic fertiliser applications.

Module 5.4 R-Leaching

N losses through leaching are estimated using a fuzzy decision tree (Figure 3.10). This decision tree consists in 2 rules and uses 1 input variable, being the level of water above field capacity (% of soil water saturation capacity).

The output of the decision tree is a monthly emission factor, ranging from 0 to 20 % of soil mineral N available for losses. References used for tree structure, tree calibration and output range are detailed in Table A.4 and A.5 in Appendix 5.

Factors and classes	
Factor	**Water above field capacity***
Unit	% of saturation capacity
Unfavorable limit	50
Favorable limit	0

Rule number		**Emission factor** % of soil mineral N	
1	F	No	0
2	U	High	20

Figure 3.10. Decision tree for N leaching from soil mineral N available

The tree consists in 2 rules and 1 factor. Two limits of classes are defined for the factor: Favorable and Unfavorable. The output of the decision tree is a monthly emission factor of soil mineral N available for losses. *Intermediate variable calculated by another module

4. Calculation of INDIGO® scores and management recommendations

4.1. INDIGO® scores calculations

For each of the 5 loss pathways simulated, the annual loss calculated in kg N ha^{-1} yr^{-1} is converted into a score following the INDIGO® method (Bockstaller et al., 1997; Bockstaller and Girardin, 2008) in the sheet "Indigo scores". In IN-Palm the conversion is done using the same conversion function as in Bockstaller and Girardin (2008, p. 35), based on a reference value of loss R (Figure 4.1):

Equation (10):
$$\begin{cases} if\ loss < 2R: & Score = -\frac{3 \times loss}{R} + 10 \\ if\ 2R < loss < 6R: & Score = -\frac{loss}{R} + 6 \\ if\ loss > 6R & Score = 0 \end{cases}$$

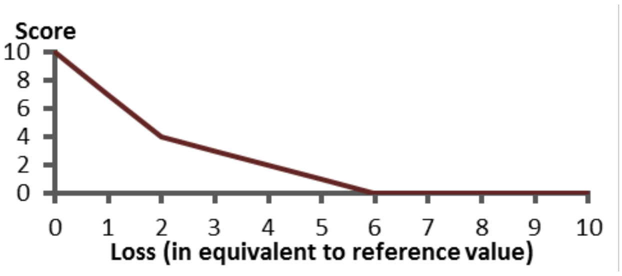

Figure 4.1. Representation of the function to convert a loss of nitrogen into a score.

The reference value of loss R is defined for each loss pathway, and for each age of the palm, as equal to 50 % of the N loss, measured or modelled, associated with standard practices in a range of soil and climate conditions (Table 4.1). The losses of N measured and modelled were calculated over a cycle of 25 years, considering an average annual fertiliser rate of 94 kg N ha^{-1} yr^{-1} (75% ammonium sulfate, 25% urea) (Pardon et al., 2016b, 2016a). Beyond 25 years, the reference values are defined as equal as the one for 25 years.

Table 4.1. Reference value of N loss for each loss pathway, depending on palms age.

Reference values are equal to 50 % of the N loss, measured or modelled, associated with standard management practices.

Age of palms	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NH3	0	7	9	4	4	5	5	5	5	5	5	5	5	5	5	5
N2O	0	2.4	2.8	2.7	2.7	2.6	2.2	2.1	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.9
NOX	0	0.7	0.9	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Runoff-Erosion	0	0.3	0.6	0.9	2.0	3.8	5.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Leaching	0	56	45	35	38	30	20	14	15	13	16	16	16	16	14	14

Age of palms	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
NH3	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
N2O	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0
NOX	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Runoff-Erosion	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Leaching	15	15	15	15	14	14	15	15	16	20	20	20	20	20	20

4.2. Identification of N lack and excess compared to plant needs

For a given combination of input values, the sheet "Recommendations" identifies the months where N inputs may potentially lack or be in excess compared to oil palm and understorey needs. The calculation is done assuming an acceptable error range of ± 5 kg N ha^{-1}, for each month of the year, as the N may lack a given month and be in excess another month.

A lack of N indicates that the expected yield may not be achieved, or that plants may take up N from the organic pool of the soil to achieve the expected yield. An excess of N indicates that the previous fertiliser rate may be too high, the following fertiliser application may be too early, or that there is a structural excess of N due to previous years input.

Months with a lack of N appear in red and months with an excess of N appear in yellow in the graph "N taken up from soil" (Figure 1.2b, section 1). The higher the magnitude of the lack or the excess, the darker the red or yellow colours are shown on this graph. The lower the lack or the excess, the clearer are the colours. A set of rules is used to identify lack and excess of N inputs (Table 4.2).

Table 4.2. Rules to identify lacks and excesses of N inputs compared to plant needs.
These rules are applied for each month of the year. N: Nitrogen

If the condition below is true…	then IN-Palm displays the following message:
Soil mineral N after plants uptake < -5 kg N ha^{-1}	● N may lack (red months)
Soil mineral N after plants uptake > 5 kg N ha^{-1} AND mineral fertiliser is applied the following month	● N may be in excess (yellow months) The previous fertiliser rate may be too high, or the following application may be too early.
Soil mineral N after plants uptake > 100 kg N ha^{-1} AND no mineral fertiliser was applied earlier this year	● N may be in excess (yellow months) There is a structural excess of N due to previous years input.
If none of these conditions are true…	then soil mineral N may not lack compared to plant needs.

4.3. Identification of potential management changes

IN-Palm identifies potential management changes in the sheet "Recommendations", using sets of rules, to help adapting better N inputs to plant needs (Table 4.3) and reducing N losses (Table 4.4). Rules are applied on annual values, such as annual scores of losses, fraction of soil covered, annual fertiliser application rate, N lack or excess at least over one month in the year, etc.

Table 4.3. Rules to identify management changes to adapt N inputs to plant needs.

These rules are applied for the whole year. N: Nitrogen

If the condition below is true…	then IN-Palm recommends the following management changes:
N may be in excess AND (mineral fertiliser rate > 0 OR organic fertiliser rate > 0)	● decrease/postpone min/org fertilisers
N may lack	● increase/split min/org fertilisers
N may lack AND level of understorey biomass is not zero (not bare-soil)	● decrease understorey biomass (to decrease understorey N uptake from soil)
N may be in excess AND level of understorey biomass is not at its maximum (not “very high”)	● increase understorey biomass (to increase understorey N uptake from soil)
N may lack AND fraction of legume < 100 %	● increase legume fraction (to increase N fixation from atmosphere)
N may be in excess AND fraction of legume > 0 %	● decrease legume fraction (to decrease N fixation from atmosphere)
N may lack AND (pruned fronds are exported OR initial residues from the previous cycle are exported)	● do not export palm residues
N may be in excess AND (pruned fronds are not exported OR initial residues from the previous cycle are not exported)	● export palm residues

Table 4.4. Rules to identify management changes to reduce N losses.

The decision tree is applied for the whole year. N: Nitrogen

If the condition below is true…	then IN-Palm recommends the following management changes:
Score for N leaching < 7 AND (mineral fertiliser > 0 OR organic fertiliser > 0)	● reduce N inputs, apply fertiliser when risk of drainage is low
Score for N leaching < 7 AND mineral fertiliser = 0 AND organic fertiliser = 0 AND (pruned fronds are not exported OR initial residues from the previous cycle are not exported)	● export palm residues
Score for N2O emissions < 7 AND (mineral fertiliser > 0 OR organic fertiliser > 0)	● apply fertiliser when soil moisture is low
Score for N2O emissions < 7 AND mineral fertiliser = 0 AND organic fertiliser = 0 AND (pruned fronds are not exported OR initial residues from the previous cycle are not exported)	● export palm residues
Score for NOx emissions < 7 AND (mineral fertiliser > 0 OR organic fertiliser > 0)	● ↘ mineral/organic fertilisers inputs
Score for NH3 volatilisation < 7 AND (mineral fertiliser > 0 OR organic fertiliser > 0)	● ↘ urea and/or organic fertilisers. Urea: bury or apply when rain frequency is high
Score for Runoff-Erosion < 7 AND mineral fertiliser > 0 AND fraction of soil covered < 100 %	● ↗ soil cover, ↘ fertiliser rate, apply when rain intensity is low
Score for Runoff-Erosion < 7 AND mineral fertiliser > 0 AND fraction of soil covered = 100 %	● ↘ fertiliser rate, apply when rain intensity is low

4.4. Calculation of the temporal distribution of the risk of applying fertiliser

IN-Palm calculates the risk of applying mineral fertiliser for each month of the year, in the sheets "Optimal fertiliser ≤ 10 years" and "Optimal fertiliser > 10 years". For each month, the indicator simulates an application of fertiliser, using the soil, weather and management conditions chosen by the user. It simulates an application in January and records the N loss occurring over the year following the application, then, it simulates an application in February and records the N loss, and so on up to the twelfth simulation in December. As the annual N loss differs between each of the twelve simulations, the rate of N fertiliser necessary to achieve the N balance also depends on the month of application. The rate is automatically adapted to each month of application, using iterative calculations, until reaching an optimal annual rate of enough but not too much N to achieve the expected yield.

After calculating the optimal rate and the associated N loss for each month of application, the indicator identifies the lowest and the highest losses and their associated application months. The distribution of the risk of applying fertiliser over the year is represented with a scale of red on a graph in the user interface sheets "≤ 10 years" and "> 10 years" (Figure 4.2). The riskiest month is coloured with the darkest red, the safest month with the clearest red.

For an application done a given month, IN-Palm calculates the N loss based on the dynamics and interaction of many soil and weather factors over the year following fertiliser application. In order to help the user understand the temporal dynamics, the main environmental drivers of N loss are represented in the graph for each month (Figure 4.2). In the following example, rain frequency, which influences NH_3 volatilisation, is high in January and low in June; rain intensity, which influences runoff-erosion, is highest in February and lowest in July; soil moisture, which influences N_2O and N_2 emissions, is high between October and April and low between May and September; and water drainage, which influences N leaching, occurs between October and January and March and April. The overall conclusion of the calculation is that the riskiest month for applying fertiliser is October, and the safest one is February.

Management practices can also impact the distribution of the risk over the year, by modifying the sensitivity of the system to a loss pathway or another. For instance, increasing the fraction of soil covered can reduce the sensitivity to runoff and erosion, hence decrease the risk of applying fertiliser in months with high rain intensity.

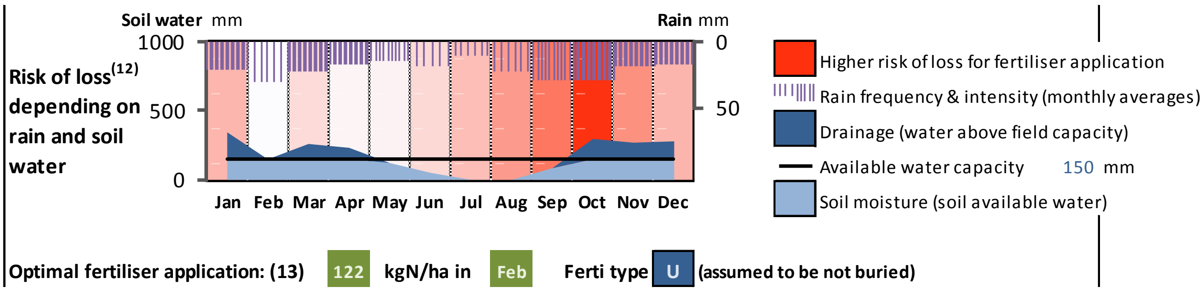

Figure 4.2. Visualisation of the risk of applying fertiliser, for each month of the year.

The darker red corresponds to the riskiest month to apply mineral fertiliser with respect to N loss, and the clearer red corresponds to the safest month. N loss depends on the dynamics and interaction of weather, soil and management factors, over the year following mineral fertiliser application.

4.5. Calculation of optimal fertiliser application rate and date

IN-Palm calculates an optimal fertiliser application rate and date in the sheets "Optimal fertiliser ≤ 10 years" and "Optimal fertiliser > 10 years". These values are deduced from the calculation of the temporal distribution of the risk of applying mineral fertiliser (see section 4.4).

The optimal rate corresponds to an annual rate of enough but not too much N to achieve the expected yield. This rate is valid for the soil, weather and management conditions defined by the user, and for the safest application month identified by IN-Palm to limit N losses. This rate is calculated assuming only one application per year, and lower annual rates may be reached by splitting applications.

The optimal rate calculated by IN-Palm may be zero if the amount of soil mineral N available for palms is sufficient to reach the expected yield. This may be the case when initial residues from the previous cycle are left on the soil to decompose, leading to a high net release of N; or when the legume fraction is very high, leading to a high N fixation from atmosphere and release to soil.

Appendix 4. Pictures of fields to help the user in IN-Palm

Table A.2. Pictures to illustrate management practices choices to fill the input sheets

1. Young age

Immature phase with very high understorey biomass, very high legume fraction, on terraces

Sumatra, Riau region, April 2016

Immature phase, with medium understorey biomass, medium legume fraction, and shredded trunks left on the soil to decompose

4 months after replanting

Sumatra, Riau region, April 2016

Manual application of urea in the weeded circle, with medium understorey biomass in the field

4 months after replanting

Sumatra, Riau region, April 2016

2. Adult

No understorey biomass, pruned fronds in windrows and empty fruit bunches spread (anti-erosion placement)

Slope of 5 degres

Sumatra, Riau region, April 2016

Low understorey biomass, pruned fronds spread (in windrows + anti-erosion placement)

Slope of 5 degres

Sumatra, Riau region, April 2016

Harvesting in an adult plantation, with high understorey biomass

Papua New Guinea

3. Fertiliser application under adult palms

Empty fruit bunches applied in rows along the harvesting path, with fronds in windrows, medium understorey biomass and bare-soil in circles

Sumatra, Riau region, April 2016

Urea applied manually under mature palms (see white spots), in the circles around palms which are covered with low understorey biomass

Sumatra, Riau region, April 2016

Urea applied evenly (mechnical application) under mature palms, with fronds in windrows, medium understorey biomass, no legume fraction

Sumatra, Riau region, April 2016

Appendix 5. Summary of all parameters of IN-Palm

Table A.3. Input and output variables for each module

Module	Variable type	Variable	Time step	Default value, range, or classes	Unit	References for regression models, and fuzzy decision tree output ranges
R-NH_3-Mineral (volatilization from mineral fertilizer)	Input	Mineral fertilizer rate and date	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	Mineral fertilizer type	month	a	-	-
	Input	Mineral fertilizer placement	year	b	-	-
	Input	Number of rainy days	month	-	$month^{-1}$	-
	Input	Soil texture	-	c	-	-
	Input	Age of palms	years	1 to 30		-
	Output	Emission factor of N loss	month	2 to 45	%	(Bouchet, 2003; Chan and Chew, 1984; Synasami et al., 1982)
R-NH_3-Organic (volatilization from organic fertilizer)	Input	Organic fertilizer rate and date	year	-	kg N ha^{-1} yr^{-1}	
	Input	Organic fertilizer type	year	Animal manure	-	
	Input	Crop type	-	Upland crop	-	
	Input	Application mode	year	Broadcast	-	
	Input	Soil pH	-	≤ 5.5	-	Regression model of Bouwman et al. (2002a)
	Input	Soil CEC	-	≤ 16	cmol kg^{-1}	
	Input	Climate	-	Tropical	-	
	Output	N loss	year	-	kg N ha^{-1} yr^{-1}	
Litter Budget	Input	*Litter amount beginning of year	year	-	t DM ha^{-1}	
	Input	Organic fertilizer type	year	Compost or EFB	-	
	Input	Organic fertilizer rate and date	year	-	t DM ha^{-1} yr^{-1}	
	Input	Understorey biomass	year	No (bare-soil), Low, Medium, High, Very high (12 t DM ha^{-1})		
	Input	Previous palm residue	year	Yes, No	t DM ha^{-1} yr^{-1}	
	Input	Pruned fronds	year	Yes, No	t DM ha^{-1} yr^{-1}	
	Output	Total litter amount end of year	year	-	t DM ha^{-1}	
	Output	Previous palms litter	year	-	t DM ha^{-1}	

	Output	Pruned fronds litter	year	-	t DM ha^{-1}	-
	Output	Organic fertilizer litter	year	-	t DM ha^{-1}	-
Fraction of Soil Covered	Input	Understorey biomass	year	No (bare-soil), Low, Medium, High, Very high (12 t DM ha^{-1})		
	Input	*Previous palm litter	year	20 to 88	t DM ha^{-1}	
	Input	*Pruned fronds litter	year	-	t DM ha^{-1}	
	Input	*Organic fertilizer litter	year	-	t DM ha^{-1}	
	Input	Pruned fronds placement	year	In heaps / In windrows / Spread		
	Input	Organic fertilizer placement	year	Circle / Harvesting path / Spread		
	Output	Fraction of soil covered	year	0 to 100	%	
Water Runoff (fraction of rainfall lost as runoff)	Input	Rain	month	-	mm	-
	Input	Number of rainy days	month	-	$month^{-1}$	-
	Input	Slope	-	0 to 30	%	-
	Input	Terraces	-	Yes, No	-	-
	Input	*Fraction of soil covered	month	0 to 100	%	-
	Output	Runoff coefficient	month	1 to 20	%	(Sionita et al., 2014)
Soil Water Budget	Input	*Available water beginning of month	month	-	mm	-
	Input	Rain	month	-	mm	-
	Input	Soil texture	-	c	-	-
	Input	*Water runoff	month	-	mm	-
	Output	Water drained	month	-	mm	(Banabas et al., 2008; Foong, 1993 *In* Corley and Tinker, 2003, p. 56; Kee et al., 2000 *In* Banabas et al., 2008; Pardon et al., 2017)
	Output	Available water end of month	month	-	mm	
N_2O-Mineral and R-N_2O-Baseline (emissions from mineral fertilizer and soil mineral N)	Input	Mineral fertilizer rate and date	onth		kg N ha^{-1} $month^{-1}$	
	Input	*Soil mineral N available for losses	onth		kg N ha^{-1}	
	Input	*Soil moisture (% of available water capacity + saturation capacity)	onth	0 to 100	%	
	Input	Soil texture		c	-	
	Input	Soil organic C content		0 to 10	%	
	Input	*Litter amount	ar	-	t DM ha^{-1}	

	Output	Emission factor of N loss from mineral fertilizer	month	0.01 to 10.6	%	(Banabas, 2007; Ishizuka et al., 2005; Stehfest and Bouwman, 2006)
	Output	Emission factor of N loss from soil mineral N	month	0.1 to 1.1	%	
R-N_2-Mineral and R-N_2-Baseline (emissions from mineral fertilizer and soil mineral N)	Input	*N_2O emissions from fertilizer	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	*N_2O emissions from soil mineral N	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	*Soil saturation (% of saturation capacity)	month	0 to 100	%	-
	Output	N_2/N_2O ratio	month	1.92 to 9.96	-	(Vinther, 2005, p. 2)
R-NO_X-Mineral/Organic and R-NO_x-Baseline (emissions from mineral and organic fertilizer, and soil mineral N)	Input	Mineral fertilizer rate and date	month	-	kg N ha^{-1} $month^{-1}$	
	Input	Organic fertilizer rate and date	year	-	kg N ha^{-1} yr^{-1}	
	Input	Mineral fertilizer type	month	a	-	
	Input	Organic fertilizer type	year	Animal manure	-	Regression model of Bouwman et al. (2002b)
	Input	Soil texture	-	c	-	
	Input	Soil organic C content	-	0 to 10	%	
	Output	N loss from mineral and organic fertilizers	year	-	kg N ha^{-1} yr^{-1}	
R-Runoff-Erosion (from mineral fertilizer and atmospheric depositions)	Input	N from atmospheric deposition	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	Mineral fertilizer rate	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	Rain	month	-	mm	-
	Input	Number of rainy days	month	-	$month^{-1}$	-
	Input	Soil texture	-	c	-	-
	Input	Terraces	-	Yes, No	-	-
	Input	*Fraction of soil covered	year	0 to 100	%	-
	Input	Slope	-	0 to 30	%	-
	Output	Emission factor of N loss	month	1 to 2	%	(Kee and Chew, 1996; Maena et al., 1979; Sionita et al., 2014)
Palm N Uptake	Input	Yield	year	0 to 40	t FFB ha^{-1} yr^{-1}	-
	Input	Age of palms	year	1 to 30	years	-
	Output	Palm N uptake	year	2.2 to 321	kg N ha^{-1} yr^{-1}	(Pardon et al., 2017)
Understorey N Uptake/Fixation	Input	Soil mineral N available	month	-	kg N ha^{-1}	-
	Input	Legume fraction	year	No (0 %), Low, Medium, High, Very high (100 %)		-
	Input	Understorey biomass	year	No (bare-soil), Low, Medium, High, Very high (12 t DM ha^{-1})		-

	Output	Fixation rate	month	0 to 90	%	(Agamuthu and Broughton, 1985; Bouillet, 2007, unpublished data; Mathews and Leong, 2000 *In* Corley and Tinker, 2003, p. 292; Pipai, 2014, p. 45)
	Output	N fixed by the legume	month	-	kg N ha^{-1} yr^{-1}	
	Output	N taken up by soil	month	-	kg N ha^{-1} yr^{-1}	
Soil N Budget	Input	*Soil mineral N beginning of month	month	-	kg N ha^{-1}	-
	Input	*N release in soil from mineral and organic fertilizers, and residues	month	-	kg N ha^{-1} $month^{-1}$	
	Input	*Losses from NH_3, N_2O, N_2 and NO_x from fertilizers, and runoff-erosion	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	*Palm N uptake	month	2.2 to 321	kg N ha^{-1} yr^{-1}	-
	Input	*Understorey N uptake	month	-	kg N ha^{-1} $month^{-1}$	-
	Output	N available for palms	month	-	kg N ha^{-1}	-
	Output	N available for understorey	month	-	kg N ha^{-1}	-
	Output	N available for N losses	month	-	kg N ha^{-1}	-
	Output	N available end of month	month	-	kg N ha^{-1}	-
R-Leaching (N leached from soil mineral N)	Input	*Soil mineral N available for loss	month	-	kg N ha^{-1}	-
	Input	*Drainage (water above field capacity)	month	-	mm	-
	Output	Emission factor of N loss	month	0 to 20	%	(Ah Tung et al., 2009; Chang and Abas, 1986; Foong et al., 1983; Foong, 1993; Henson, 1999; Ng et al., 1999; Omoti et al., 1983)

* Intermediate variable calculated by another module.
In **bold**: sources of N to which emission factors are applied to estimate N losses
a: Mineral fertilizer types. Urea, Ammonium Sulfate, Ammonium Nitrate, Ammonium Chloride, Sodium Nitrate
b: Mineral fertilizer placement. In the circle, buried ; In the circle ; not buried, In the circle + windrows, Evenly distributed
c: Soil textures. Sand, Loamy Sand, Sandy Loam, Loam, Silt Loam, Silt, Clay Loam, Sandy Clay Loam, Silty Clay Loam, Silty Clay, Clay, Sandy Clay
N: Nitrogen, C: Carbon, FFB: Fresh Fruit Bunches, EFB: Empty Fruit Bunches, DM: Dry Matter

Table A.4. Parameters and their classes for each fuzzy decision tree module

Fuzzy decision tree	Parameter name	Unit	Unfavourable class	Favourable class	References for structure and class limits
R-NH_3-Mineral	Mineral fertilizer type	-	Urea	Other	(Chan and Chew, 1984; Synasami et al., 1982)
	Mineral fertilizer placement	-	Not buried	Buried	(Bouwman et al., 2002a)
	Rain frequency	rainy days $month^{-1}$	≤ 7.5	≥ 30	(Chan and Chew, 1984)
	Age of palms	years	≤ 4	≥ 10	(Bouwman et al., 2002a)
	Soil texture (a)	-	Coarse	Fine	(Chan and Chew, 1984; Synasami et al., 1982)
Fraction of Soil Covered	Understorey biomass	t DM ha^{-1}	No (0 t DM ha^{-1})	Very High (12.4 t DM ha^{-1})	(Redshaw, 2003; Schmidt, 2007)
	*Pruned fronds litter	t DM ha^{-1}	0	≥ 9	(Henson, 1999 *In* Corley and Tinker, 2003, p. 293)
	Pruned fronds placement	-	Concentrated	Spread	-
	*Organic fertilizer litter	t DM ha^{-1}	0	≥ 25	(Redshaw, 2003; Schmidt, 2007)
	Organic fertilizer placement	-	Concentrated	Spread	-
	*Previous palm litter	t DM ha^{-1}	≤ 20	≥ 88	(Agamuthu and Broughton, 1985; Bouillet, 2007, unpublished data; Mathews and Leong, 2000 *In* Corley and Tinker, 2003, p. 292)
Water Runoff	Rain intensity	mm	≥ 20	0	(Sionita et al., 2014)
	*Fraction of soil covered	-	0	1	(Pardon et al., 2016; Sionita et al., 2014)
	Slope	%	≥ 25	0	(Sionita et al., 2014)
	Terraces	-	Absence	Presence	-
R-N_2O-Mineral and R-N_2O-Baseline	*Soil moisture (% of plant available water capacity + saturation water capacity)	%	100	0	(Ishizuka et al., 2005; Pardon et al., 2017; Stehfest and Bouwman, 2006)
	Soil texture (a)	-	Fine	Medium	(Banabas, 2007; Stehfest and Bouwman, 2006)
	Soil organic C content	%	≥ 3	≤ 1	(Pardon et al., 2017; Stehfest and Bouwman, 2006)
	*Litter amount	t DM ha^{-1}	≥ 130	≤ 10	-
	Mineral fertilizer rate and date	kg N ha^{-1} $month^{-1}$	≥ 250	0	(Pardon et al., 2016, 2017; Stehfest and Bouwman, 2006)
R-N_2-Mineral and R-N_2-Baseline	*Soil saturation (% of water saturation capacity)	%	100	0	(Davidson, 1993; Vinther, 2005, p. 2)

R-Runoff-Erosion	Rain intensity	mm	≥ 20	0	(Sionita et al., 2014)
	Soil texture (a)	-	Coarse	Fine	-
	*Fraction of soil covered	-	0	1	(Pardon et al., 2016; Sionita et al., 2014)
	Slope	%	≥ 25	0	(Sionita et al., 2014)
	Terraces	-	Absence	Presence	-
Palm N Uptake	Yield	t FFB ha^{-1} yr^{-1}	0	≥ 40	APSIM-Oil palm simulations (Pardon et al., 2017)
Understorey N Uptake/Fixation	*Soil mineral N available	kg N ha^{-1} yr^{-1}	≥ 60	0	(Pipai, 2014; Voisin et al., 2002 *In* Vocanson, 2006, p. 102)
R-Leaching	*Drainage (% of water saturation capacity)	%	≥ 50	0	-

*Intermediate variables calculated by another module

a: The simplified soil texture is inferred from FAO (2001). **Fine:** clay, sandy clay. **Medium:** clay loam, sandy clay loam, silty clay loam, silt clay. **Coarse:** sand, loamy sand, sandy loam, loam, silt loam, silt

FFB : Fresh Fruit Bunches, DM : Dry Matter, N: Nitrogen, C: Carbon

Table A.5. Parameters and their ranges for each budget module

Budget module	Parameter name	Unit	Parameter range or value	References
Litter Budget	Mass of initial residue	t DM ha^{-1}	20 to 88	(Khalid et al., 1999a, p. 29, 1999b)
	Annual rate of residue turnover	t DM ha^{-1} yr^{-1}	Depends on residue type	Fronds: (Henson, 1999, *In* Corley and Tinker, 2003, p. 293) Roots: (Dufrêne, 1989; Henson and Chai, 1997; Jourdan et al., 2003; Lamade et al., 1996) Understorey: (Agamuthu and Broughton, 1985, p. 120; Bouillet, 2007, unpublished data; Mathews and Leong, 2000, *In* Corley and Tinker, 2003, p. 292)
	Decomposition speed by residue type	"k" constant	Depends on residue type	"k" constant, from Moradi et al. model (2014)
	C/N by residue type	-	30 to 117	(Gurmit et al., 1999 *In* Corley and Tinker, 2003; Khalid et al., 2000; Redshaw, 2003; Rosenani and Hoe, 1996, *In* Moradi et al., 2014)
Soil Water Budget	Potential evapotranspiration	mm $month^{-1}$	140	Measurements: (Foong, 1993 *In* Corley and Tinker, 2003); simulations: APSIM-Oil palm (Pardon et al., 2017)
	Water intercepted by palms	% of rain	0 to 11	(Banabas et al., 2008; Kee et al., 2000 *In* Banabas et al., 2008)
	Soil depth	m	1.5	(Jourdan and Rey, 1996; Surre, 1968; Tailliez, 1971; Tinker, 1976, *In* Corley and Tinker, 2003, p. 60)
	Plant available water capacity	mm m^{-1}	Depends on soil texture	Pedotransfer relationships from Moody and Cong (2008, p. 48)
	Water saturation capacity	mm m^{-1}	Depends on soil texture	
Soil N Budget	N content of initial residue	kg N ha^{-1}	65 to 536	(Khalid et al., 1999a, p. 29, 1999b)
	Annual rate of residue recycling	kg N ha^{-1} yr^{-1}	Depends on residue type	Palm: (Carcasses, 2004; Pardon et al., 2016; Turner and Gillbanks, 2003) Understorey: (Agamuthu and Broughton, 1985, p. 120; Bouillet, 2007, unpublished data; Chiu, 2004; Mathews and Leong, 2000 *In* Corley and Tinker, 2003, p. 292)
	N release speed by residue type	years before total release	1 to 3	(Caliman et al., 2001; Carcasses, 2004; Kee, 2004; Khalid et al., 2000, 1999a; Lim and Zaharah, 2000; Moradi et al., 2014; Turner and Gillbanks, 2003) Understorey: (Agamuthu and Broughton, 1985, p. 120; Bouillet, 2007, unpublished data; Mathews and Leong, 2000 *In* Corley and Tinker, 2003, p. 292)

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Title: Modelling of the nitrogen budget of oil palm plantations to help reduce losses to the environment. Case study in Sumatra, Indonesia

Keywords: oil palm, nitrogen balance, agri-environmental indicator, life cycle assessment, perennial crop, tropical climate

Abstract: Humanity faces the challenges of urgently decreasing the environmental impact of agriculture, shifting diets and increasing food production. Oil palm is a tropical perennial crop emblematic of these challenges. While its cultivation can be associated with environmental impacts, oil palm can produce 3 to 7 t of edible oil ha^{-1} in optimal conditions, which is 7 to 10 fold higher than in annual oil crops. In this context, improving palm oil production sustainability is crucial for both reducing negative environmental impacts and ensuring food security.

Application of synthetic nitrogen (N) fertilisers was identified as a major source of environmental impacts associated with the cultivation of oil palm. Life cycle assessments of palm oil have already been performed to help quantify impacts and identify potential improvements of management practices. However, the only available emission models to estimate N losses to environment are generally valid for annual crops and temperate climate conditions. The use of such general models in life cycle assessment may lead to very uncertain results or to low sensitivity of assessments to management practices.

The overall objective of this research work was to help identify management practices to reduce N losses in the environment. The core of the work was hence to develop a model that estimates all N losses in oil palm plantations, while being sensitive to management practices. The study focused on N fluxes in industrial oil palm plantations on mineral soils.

We performed four steps in order to complete the objectives of this research work. First, we conducted a literature review of all the existing knowledge about N fluxes and losses in plantations. Second, we compared 11 existing models that may be used to predict N losses in plantations. Third, we performed an in-depth Morris's sensitivity analysis of one of the models, the APSIM-Oil palm process-based model. Fourth, we used all the information identified in the previous chapters, together with expert knowledge, to build IN-Palm, an agri-environmental indicator for N losses in oil palm plantations. We used the INDIGO® method and the fuzzy decision tree modelling approach to develop IN-Palm, and we validated this indicator using a field dataset of N leaching from a plantation in Sumatra, Indonesia.

Our literature review and model comparison showed that oil palm peculiarities may impact significantly N dynamics and losses. We identified research gaps and uncertainties about N losses, their drivers and the modelling of oil palm peculiarities. We identified the main drivers of N losses and yield in the APSIM-Oil palm process-based model. We built IN-Palm, which uses 21 readily available input variables to estimate each N loss pathway. IN-Palm predictions of N leaching were acceptable, and IN-Palm has shown efficient to help testing management changes.

This research constitutes a comprehensive synthesis of the available knowledge and models for N fluxes and losses in oil palm plantations. One of the main results is a novel agri-environmental indicator, IN-Palm, operationally-oriented, sensitive to local practices and environmental conditions, as well as potentially useable as an emission model for holistic approaches such as life cycle assessment. The INDIGO® method and fuzzy decision tree modelling approach were shown to be very well adapted for building agri-environmental indicators in contexts of knowledge scarcity. This indicator can be a useful base for further research about using agri-environmental indicators to reduce uncertainty in life cycle assessment, and for future adaptations for other tropical perennial crops.

Titre : Modélisation du bilan azoté des plantations de palmiers à huile pour aider à la réduction des pertes dans l'environnement. Etude de cas à Sumatra, Indonésie.

Mots-clés : palmier à huile, bilan azoté, indicateur agri-environnemental, analyse cycle de vie, plante pérenne, climat tropical

Résumé : L'humanité fait face aux défis urgents de réduire l'impact environnemental de l'agriculture, de changer les régimes alimentaires et d'accroître la production alimentaire. Le palmier à huile est une plante pérenne tropicale emblématique de ces défis. Alors que sa culture peut être à l'origine d'impacts environnementaux, le palmier à huile peut produire, en conditions optimales, 7 à 10 fois plus d'huile alimentaire que les cultures oléagineuses annuelles. Dans ce contexte, améliorer la durabilité de la production d'huile de palme est crucial, tant pour réduire les impacts environnementaux négatifs que pour garantir la sécurité alimentaire.

L'application de fertilisants azotés (N) a été identifiée comme une source majeure d'impacts environnementaux dus à la culture du palmier. Des analyses de cycle de vie de l'huile de palme ont été réalisées pour quantifier les impacts et identifier des améliorations de pratiques agricoles. Cependant, les seuls modèles d'émissions disponibles pour estimer les pertes de N dans l'environnement sont généralement valides pour les cultures annuelles et en climat tempéré. L'utilisation de tels modèles dans l'analyse de cycle de vie peut mener à des résultats très incertains ou à une faible sensibilité aux pratiques.

L'objectif global de ce travail de recherche était d'aider à l'identification de pratiques pour réduire les pertes de N dans l'environnement. Le cœur du travail était le développement d'un modèle estimant toutes les pertes de N dans les plantations, tout en étant sensible aux pratiques. L'étude s'est concentrée sur les flux de N dans les plantations de palmiers sur sols minéraux.

Nous avons réalisé quatre étapes pour mener à bien cette recherche. Premièrement, nous avons mené une revue de littérature de tout le savoir existant concernant les flux et pertes de N dans les plantations. Deuxièmement, nous avons comparé 11 modèles existants, pouvant être utilisés pour prédire les pertes de N dans les plantations. Troisièmement, nous avons réalisé une analyse de sensibilité de Morris approfondie du modèle mécaniste APSIM-Oil palm. Quatrièmement, nous avons construit IN-Palm, un indicateur agri-environnemental pour les pertes de N dans les plantations. Nous avons utilisé la méthode INDIGO® et l'approche de modélisation par arbres de décisions flous pour développer IN-Palm, et nous avons validé cet indicateur en utilisant des mesures de lixiviation de N d'une plantation à Sumatra, Indonésie.

Notre revue de littérature et notre comparaison de modèles ont montré que les particularités du palmier à huile peuvent affecter significativement les dynamiques et pertes de N. Nous avons identifié des manques de recherche et des incertitudes sur les pertes de N, leurs déterminants et la modélisation des particularités du palmier. Nous avons identifié les déterminants des pertes de N et du rendement dans le modèle mécaniste APSIM-Oil palm. Nous avons développé IN-Palm, qui utilise 21 variables d'entré facilement accessibles pour estimer chaque voie de perte de N. Les prédictions de lixiviation de N par IN-Palm étaient acceptables, et IN-Palm s'est montré efficace pour tester des changements de pratiques agricoles.

Cette recherche constitue une synthèse exhaustive des connaissances et modèles disponibles pour les flux et pertes de N dans les plantations. L'un des principaux résultats est un nouvel indicateur agri-environnemental, IN-Palm, sensible aux pratiques et conditions locales, de même qu'utilisable en tant que modèle d'émission dans des approches holistiques. Cet indicateur peut être une base utile pour de futures recherches sur l'utilisation d'indicateurs agri-environnementaux pour réduire l'incertitude des analyses cycle de vie, et pour de futures adaptations à d'autres plantes pérennes tropicales.