International Environmental Modelling and Software Society (iEMSs)
8th International Congress on Environmental Modelling and Software
Toulouse, France, Sabine Sauvage, José-Miguel Sánchez-Pérez, Andrea Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2016-proceedings

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Modelling potential nitrogen losses in oil palm plantations with IN-Palm, an agri-environmental indicator

Pardon Lénaïc[a], Bockstaller Christian[b], Marichal Raphaël[a,c], Sionita Ribka[c], Nelson Paul[d], Gabrielle Benoît[e], Jean-Paul Laclau[f], Caliman Jean-Pierre[a,c], Bessou Cécile[a]

[a] CIRAD, UPR Systèmes de pérennes, F-34398 Montpellier, France
[b] LAE, INRA, Université de Lorraine, 68021 Colmar, France
[c] SMART Research Institute, Jl. Tengku Umar 19, Pekanbaru 28112,Indonesia
[d] College of Science and Engineering, James Cook University, Cairns, Australia
[e] AgroParisTech, INRA, UMR EcoSys,78850 Thiverval-Grignon, France
[f] CIRAD, UMR ECO&SOLS, Montpellier, France

Oil palm cultivation area is expected to increase until at least 2050. This expansion raises environmental concerns, not only regarding land-use change and its consequences, but also concerning potential impacts of losses of nitrogen such as ammonia volatilisation, nitrous oxide emission and nitrate leaching and runoff. The prerequisite to any work on the reduction of losses and identification of best practices is the development of an assessment tool. However, the available knowledge regarding nitrogen losses is limited for oil palm, which leads to high uncertainty in environmental assessment.

In this context, we chose to develop an agri-environmental indicator, IN-Palm, which aims at estimating the risk of nitrogen losses in oil palm plantations, using the INDIGO® method. This kind of operational model is built to assess environmental risks as well as being used as a decision support tool. The development of indicators is particularly relevant in such contexts of data scarcity, as it allows for harnessing the most of readily accessible data from a whole range of sources, i.e. measured or modelled, qualitative or quantitative, empirical or expert knowledge.

We adapted the indicator to characteristics of the oil palm system, such as the tropical climate, the long growth cycle of about 25 years and the high production of biomass. We designed it to be easily implementable with available data on climate and soil conditions, and sensitive to practices such as fertiliser application (type, rate and timing), legume cover establishment, and residue management. Future work will include a sensitivity analysis, a validation against experimental data of losses in Sumatra, and a validation by end-users in a plantation in Sumatra.

***Keywords**:* oil palm; nitrogen losses; agri-environmental indicator; modelling; INDIGO®; IN-Palm, environmental impact assessment

1 INTRODUCTION

Oil palm is an important crop for global production of vegetable oil and for the economies of tropical countries. The area of land under oil palm cultivation, currently approximately 19 Mha, has been rising at 660,000 ha year^{-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. Addition of N via fertilisers and biological fixation (by legume cover crops) is a common practice to achieve the yield potential of the crop. However, this addition is associated with potential risks of N losses into the hydrosphere and atmosphere. For instance, during the cultivation period, 48.7 % of the greenhouse gases emitted to produce 1 t of oil palm fruit are due to the addition of N fertiliser (Choo et al., 2011).

In order to reduce N losses, we must be able to assess the risk of losses and to identify best management practices. We hence chose to develop an agri-environmental indicator, IN-Palm, using the INDIGO® method (Bockstaller and Girardin, 2008). This method has the advantage of being suitable for situations in which knowledge is limited, as is the case for the N cycle and N losses in oil palm (Pardon et al., 2016). Compared to process-based models, agri-environmental indicators use a limited number of input variables, while harnessing the most of readily accessible data from a whole range of sources, i.e. measured or modelled, qualitative or quantitative, empirical or expert knowledge (Girardin et al., 1999). Another advantage of this method is that it is designed to be sensitive to practices. Therefore, even if the estimation of a loss made using an indicator is less precise than one made using a process-based model, it is sufficient to assess the environmental risk and to support decisions based on site-specific practice levers.

IN-Palm is being designed for managers of oil palm plantations in order to answer the question: “what are the best practices to implement in this field, this year, to reduce N losses, given the environmental conditions, the characteristics of the field, and long term consequences of previous practices?”. This indicator is adapted to characteristics of the oil palm system, such as the tropical climate, the long growth cycle of about 25 years and the high production of biomass. It is calibrated to an oil palm plantation in Sumatra, Indonesia. We designed it to be easily implementable with readily available climate and soil condition data and sensitive to practices such as fertiliser application (type, rate and timing), legume cover establishment, and residue management. Here, we present first the INDIGO® method conceptual baseline, the previous versions of the indicator and some suggested improvement tracks. Then, we present the new oil palm-adapted structure of the indicator following these tracks, and we discuss the next steps to finalise the indicator, i.e. sensitivity analysis and validation.

2 MATERIAL AND METHOD

2.1 INDIGO® method

The development of the INDIGO® method started in the 90’s (Bockstaller et al., 1997) and remains one of the most comprehensive approaches to assess the environmental impacts of agricultural systems by combining quantitative and qualitative data based on expert knowledge (Girardin et al., 1999). Moreover, its structure is easily adaptable to new cropping systems, allowing for the accounting of context-specific practices. The original version of the INDIGO® indicator of N losses for annual crops in temperate areas (Bockstaller and Girardin, 2008, Bockstaller et al., 2008) was adapted for perennial crops in temperate areas, e.g. for vine (Thiollet, 2003). A preliminary version of IN-Palm was then developed for oil palm in tropical context, based on the adaptation for vine (Carcasses, 2004, Caliman et al., 2007). We further based our work on the preliminary version of IN-Palm.

We followed the five steps identified by Girardin et al. (1999) in the development of an indicator: (1) the definition of the objectives and the identification of the end-users, (2) the construction of the indicator, (3) the selection reference values, (4) the sensitivity analysis, and (5) the validation. The construction of the indicator is a compromise between the available information (quality and reliability), the current state of scientific knowledge, and the requirement of the users for simplicity. The reference values represent minimum values of the indicator output for which the agroecosystem is considered to be sustainable (Bockstaller et al., 1997). As the indicator must be readily understandable by non-expert farmers, it was proposed that the outputs be expressed not in physical units, but in dimensionless scores on a scale between 0 and 10, calculated with respect to the reference values (Bockstaller et al., 1997). The sensitivity analysis aims to estimate the influence of an input variable or a parameter on the indicator output. Finally, the validation, as discussed by Addiscott et al. (1995), aims to evaluate if the indicator "is well founded and achieves the overall objectives or produces the intended effects". As indicators differ from simulation models in different aspects, validation procedures commonly used in modelling have to be adapted and three steps of validation were proposed by Bockstaller and Girardin (2003): the design validation by a panel of experts, the validation of the soundness of the indicator outputs, and the end-use validation by end-users.

2.2 Previous versions of IN, the INDIGO® indicator for N losses

The version of the indicator designed for vine, IN-Vine, was adapted from the original IN in the early 2000's (Thiollet, 2003). It consists of three risk modules (R) related to the N losses assessed: R-NH_3, R-NO_3 and R-N_2O. Each module is calculated for one field and for one specific year. Modules are calculated in a certain order because the N lost through one flux is assumed not to be any longer available for others loss processes. First, the R-NH_3 module is calculated, for each application of fertiliser, as the volatilisation occurs quickly in the days following the application. Second, the R-NO_3 module assesses N losses through leaching with two different calculations. The first calculation estimates the N leached from fertiliser inputs after applications at the end of winter and end of spring. The second calculation estimates the N leached from the mineral N stock in the soil during the drainage period in the autumn-winter period. Third, the R-N_2O module calculates the emissions of N_2O over the whole year, as a portion of the N inputs from fertilisers remaining after volatilisation.

For R-NH_3, an emission factor is determined by expert knowledge for each fertiliser application, depending on influential conditions associated with the application, such as temperature, fertiliser type, soil calcium carbonates content, and mode of application. For R-NO_3, the losses are determined for each application in spring with an emission factor calculated with a simplified version of the Burns' model (1976), depending mainly on the timing of the application with respect to the peak of absorption of N by the vine. In winter, the leaching loss is determined as a portion of the remaining stock of N in the soil, depending on fertiliser surplus, nitrogen mineralisation from soil organic matter and crop residues, vine N uptake, and deep drainage during this period. Finally, for R-N_2O, the losses are determined with an emission factor corrected by factors associated with tillage, placement (burying) and soil type, from Bouwman (1996).

For each of the three modules, the value of N loss is transformed into a score between 0 and 10, with 7 being the score equal to the reference value, which is defined as the sustainable threshold. For R-NH_3, the reference value is 20 kg N ha^{-1} yr^{-1}, which corresponds to the level of atmospheric N depositions above which effects such as soil acidification are observed (Bobbink and Roelofs, 1995). For R-NO_3, the reference value corresponds to the European legal limit of 50 mg of NO_3 l^{-1}. Finally, for R-N_2O, the reference value is 3 kg N ha^{-1} yr^{-1}, i.e. about one third of the maximal emissions measured by Bouwman (1996).

In 2004, IN-Vine was adapted to oil palm by Carcasses (2004). This adaptation aimed at accounting for peculiarities of the oil palm system (see section 2.3), although not all oil palm-specific parameters could be added in this preliminary version. The three modules, their order of calculation, and their reference values were kept unchanged compared to the version of Thiollet (2003). As it was done for one specific year of a mature plantation (>7-year-old), this version is not suitable for young plantations. Only the mode of calculation of each module was modified in this version to be relevant for oil palm.

For R-NH_3, the emission factors were adapted by expert knowledge to tropical conditions and practices in oil palm. Emission factors were modified according to the likelihood of having rainy days just after the time of the application, placement of the fertiliser (surface or buried), and texture and compactness of soil. For R-NO_3, the mode of calculation is based on a N budget approach, coupled with a simple water budget using the estimated monthly drainage as an input. The values of N contents of plant residues and palm uptake, necessary for the N budget, were updated with measured data for oil palm. For R-N_2O, the method remained the same, but it was less sensitive to actual practices than for annual temperate crops, as in general there is no soil tillage in oil palm.

2.3 Identification of key features in N cycling and N losses in oil palm

Oil palm plantations are usually established for a growth cycle of approximately 25 years. In steep areas, terraces can be established before planting. Palms are planted as 1-year-old seedlings, the plantation is considered immature during the 2-3 first years, and then mature when the palm canopy closes. A legume cover, e.g. *Pueraria phaseoloides*, is generally sown in order to provide quick ground cover and fix N from the atmosphere. The legume rapidly covers the whole surface, declines as the oil palm canopy grows, and is at least partially replaced by more shade-tolerant vegetation around the 6th year when the palm canopy closes. Harvesting of fresh fruit bunches starts after about 2-3 years. For each fresh fruit bunch harvested, one or two palm fronds are pruned and left in the field, mostly in windrows in every second inter-row. 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 chemical or mechanical weeding, while in the remaining area, vegetation is left to grow. N mineral and organic fertilisers are applied. 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 to parts of the plantation, either fresh or after co-composting. The old palms are felled and left in the field to decompose, and new seedlings are planted between them. Over the years, a spatial heterogeneity develops due to these practices. Three main zones can be differentiated: the harvesting path without vegetation cover, the weeded circles around palms with no or low vegetation, and the windrows where pruned fronds are left to decompose and covered by natural vegetation.

In oil palm plantations, internal fluxes are among the largest N fluxes (Pardon et al., 2016). They include palm N uptake, N released by residue decomposition, N fixed by the legume cover crop during the immature phase, and N released from felled palms from the previous cycle. Among N losses, N leaching and NH_3 volatilisation are the largest, but with a high variability depending on the age, the environmental conditions and management practices. Moreover, the losses through runoff and erosion are not negligible (Figure 1).

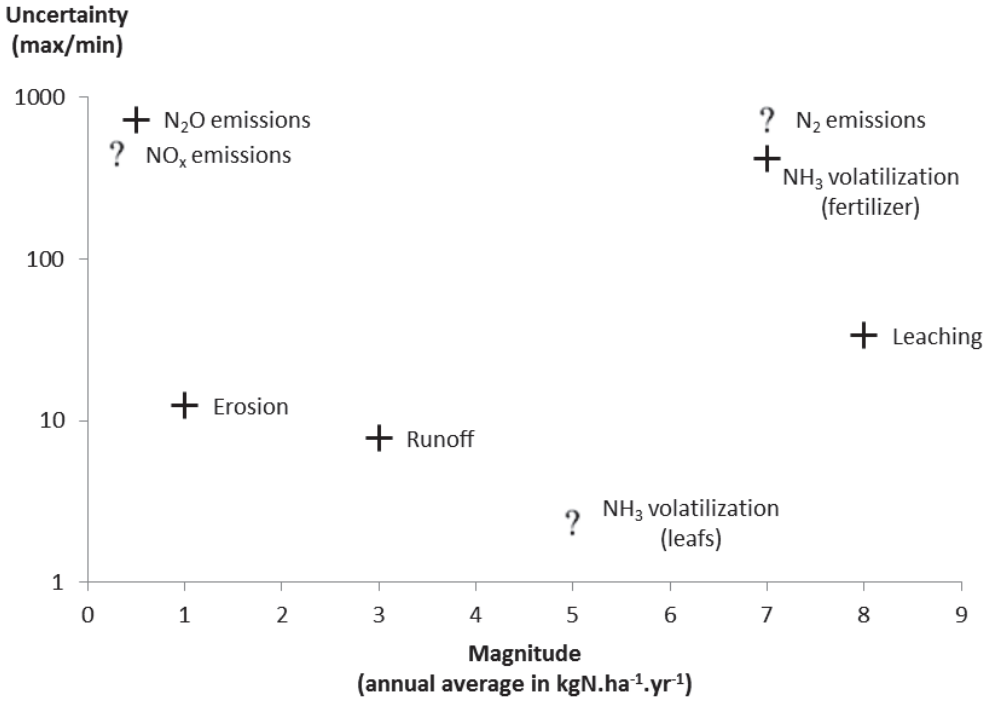

Figure 1. Uncertainty and magnitude of the N losses.
NH_3 volatilisation from fertiliser and leaching have high magnitude and high uncertainty. N_2O emissions have low magnitude but high variability. Uncertainties are calculated as the max/min ratio (logarithmic scale), and magnitudes are annual averages in kg $N.ha^{-1}.yr^{-1}$ estimated assuming an application of 100 kg $N.ha^{-1}.yr^{-1}$ of mineral N fertiliser. When no quantified estimates were available, approximations of uncertainty and magnitudes were done and are represented with "?". 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 volatilization from annual crops (Andersen et al., 2001).

A comparison of 11 models to estimate N losses in oil palm plantations showed that about 80% of the modelled N loss was lost via leaching (Pardon et al., in review). The most important uncertainty across models occurred for leaching and denitrification. Moreover, a peak of emissions was modelled over the first years of the cycle, but the timing and the magnitude were very variable across models. The timing depended mainly on whether or not the process of N immobilisation in soil was considered when modelling the decomposition of residues.

A sensitivity analysis of the APSIM-Oil palm simulation model (Huth et al., 2014) showed that the most influential parameters for prediction of N_2O emissions and N leaching depended on the age of the palms (Pardon et al, in preparation). Before 7 years of age the amount of legume cover, the rate of

mineral fertiliser, and the soil organic C content were the most influential parameters. After 7 years of age the rate of mineral fertiliser and the drainage were the most influential parameters.

Given the characteristics of oil palm system, and given the results of previous studies, several points are important in order to improve IN-Palm. The indicator should be able to assess the risks of N losses at all the ages of the 25-year cycle, as the N dynamics and drivers do not remain the same over the years. For instance, the modelling of legume crop N fixation and release is important in the immature phase. Then, the important internal N fluxes, such as the decomposition of organic matter and the concomitant immobilisation of N in soil and litter, should be considered to assess losses with more accuracy. The large amount of N in decomposing matter could enhance losses, but the immobilisation could also reduce losses by delaying the release of N. As the losses through leaching seem to be the highest, with a high variability, the indicator should model this loss pathway carefully. For instance, the most influential parameters, such as the speed of drainage, should be considered with accuracy. As the N losses have a high variability, the calculation of the modules should be sensitive to practices and spatial heterogeneity. For instance, the distribution of vegetation cover or placement of residues may affect runoff, erosion or denitrification. Finally, in terms of indicator structure, it should be important to add a module about runoff and erosion as this loss pathway is not negligible. Even if the magnitude of NO_x emission is lower, it could be taken into account as it is associated with environmental impacts. Losses should be calculated in separated modules, in R-NH_3, R-runoff-erosion, R-leaching, R-N_2O, and R-NO_x, in order to be able to calculate environmental impacts related with each of the loss pathways, and identify the combination of practices having most impact on each of them.

3 RESULTS

3.1 General structure and methods of calculation of modules

We adapted the indicator to estimate the risks of N losses for one specific year in the whole cycle of 25 years. We kept the same three modules, R-NH_3, R-leaching, R-N_2O, and we added two more modules, R-runoff-erosion and R-NO_x. The calculation of R-NH_3, R-runoff-erosion, R-N_2O and R-NO_x are done independently, because emission factors used from literature are a fraction of the input of mineral and organic fertilisers, or residues. R-leaching is calculated after the other modules, as it has a budget approach in which all the other losses are considered.

For R-NH_3, we kept the same method, with an emission factor defined by a decision-tree, but we updated the emission factors based on measured fluxes in the literature (Pardon et al., 2016). R-NH_3 is calculated for each application of mineral fertiliser and palm oil mill effluent, and separately for each of the three zones of the plantation, being the harvesting pathway, the weeded circle and the windrow. Indeed, mineral fertiliser is applied only in the weeded circle during the immature phase, but in the weeded circle and the windrow in the mature phase. The emission factor is determined for each application, depending on the fertiliser type and placement, the soil texture and compactness and the likelihood of having rainy days just after the time of the application.

For R-runoff-erosion, we used a similar approach to that of the R-NH_3 module, with an emission factor defined by a decision-tree. We set the values of emission factors based on measured fluxes in the literature (Pardon et al., 2016) and a set of data from a trial in Sumatra, Indonesia (Sionita, 2014). Calculations are done jointly for the three zones of the plantation because the available data was not specific to each zone. Calculations are done for each application of mineral fertiliser, and they also account for the portion of N contained in rainfall that is lost through runoff. The emission factor depends on the presence of terraces, the slope, the texture of soil, the ground vegetation cover density, the rainfall intensity at the time of the application, and the presence of residues with anti-erosion placement (empty fruit bunches or pruned fronds).

For R-N_2O and R-NO_x, we kept the same general method of an emission factor, with correction factors depending on environmental conditions and practices. However, we increased the sensitivity of the model using a wider set of co-factors, and we increased the reliability of the prediction using a subset of data corresponding to tropical conditions (Stehfest and Bouwman, 2006), with additions of available measurements in the literature (Pardon et al., 2016). We used the method developed by Philibert et al. (2013) to calibrate the statistical model. Calculations are done separately for the three zones of the plantation, for each application of mineral fertiliser, and also taking into account baseline emissions

from each zone. The factors taken into account are soil compactness, soil drainage, soil texture, soil C content, and annual rainfall.

For R-leaching, we used an N budget approach coupled with a simple water budget, focussing on N in the soil. Calculations are done at a monthly time step, separately for the three zones, for one specific year. The two pools considered are mineral N in soil and the N immobilised in soil and litter. The inputs to the mineral N pools are the mineral fertiliser application, the atmospheric deposition and the palm oil mill effluent application, after subtraction of losses through volatilisation, runoff-erosion, and denitrification (N_2O, NO_x, N_2). Another input is the mineralisation of organic N in soil and litter, coming from the decomposition of plant residues, empty fruit bunches, and compost. When inputs of organic matter occurred over previous years, such as empty fruit bunch application or felling of palms, their mineralisation is also taken into account. The outputs are the N taken up by plants and N leaching. For each application of organic matter (empty fruit bunches, compost) and residues (e.g. pruned fronds), the rate of immobilisation or mineralisation is estimated from the C:N ratio. Drainage is estimated through a simple water budget approach, depending on rainfall, runoff, and evapotranspiration. A portion of the soil mineral N that is not taken up by the vegetation cover is considered to be lost through drainage. As fluxes of N and water differ between the three zones, the N and water budgets are calculated independently for the three zones, in order to obtain a more accurate estimate.

3.2 Reference values and calculation of scores

One of the objectives of the indicator is to be used as a decision tool. Thus, it must clearly help to identify best practices, in order to deliver a useful message to the manager. Hence, the indicator must link the potential environmental impact of N losses to the actual practices implemented in the field. In order to qualify a set of practices as sustainable or not, it is necessary to determine a reference value of loss below which the environmental impact is considered as acceptable in terms of sustainability. The choice of the reference value must be scientifically sound regarding the environmental processes involved, but also subjective in light of potential room for improvement and distance-to-target in terms of sustainable practices.

At this stage, we keep exploring the possibilities to define a reference value for each module, accounting for both the scientific soundness and the local peculiarities. One interesting track to pursue could be the normalisation of environmental impacts against carrying capacity of ecosystems, using the planetary boundary references from Rockström et al. (2009). Then, the score from 0 and 10 is calculated for each module, with the same method as in the previous versions of the indicator, depending on the difference between the loss estimated and the reference value.

3.3 Inputs from the user

Four groups of input data are necessary from the user: soil, climate, plants and practices. For soil, the main inputs are the slope, texture, drainage, soil organic C content and compactness. For the climate, the inputs are monthly rainfall and annual atmospheric deposition of N. For plants, the inputs are oil palm planting density and expected yield. For practices, the inputs are presence or absence of terraces, presence or absence of previous felled palms, establishment or not of a legume cover, vegetation cover density in each zone, presence or absence of pruned fronds, anti-erosion placement of residues, fertiliser type (mineral, empty fruit bunches, palm oil mill effluent, compost), and fertiliser application (rate, timing, placement).

Parameters of the indicator are based on references from the literature, but they can be modified easily by the user if more relevant values are available for specific conditions. For example, parameters include N content and C:N of palm tissues, rate of N immobilisation depending on C:N ration of residues and legume N fixation rate.

4 DISCUSSION

The future work to finalise the indicator will include a sensitivity analysis and a validation based on three steps proposed by Bockstaller and Girardin (2003).

One of the objectives of the sensitivity analysis is to check whether the outputs are sensitive to all the input variables, to be sure that the input variables are necessary and sufficient to estimate losses. Another objective is to check whether the indicator is sensitive enough to management practices. Sensitivity analysis is straightforward for quantitative variables because the effect on the output of a continuous variation of the input (e.g. amount of nitrogen fertiliser) can be evaluated. However, it is less easily carried out for qualitative variables where the input may be a class (e.g. soil texture). In the case of indicators, qualitative variables are commonly used and the method of sensitivity analysis must be adapted. One track to be pursued could be one of the three approaches proposed by Carpani et al., (2012) to perform sensitivity analysis of hierarchical qualitative models: factorial designs combined with analysis of variance, Monte-Carlo sampling and conditional probabilities. Another possibility could be to test contrasting scenarios of practices, and to compare the variation of outputs from IN-Palm to the variations of outputs from other models of N losses.

The indicator will be validated in three steps. The first step is the design validation by a panel of experts to evaluate if the structure of the indicator is scientifically founded. The second step is the output validation to assess the soundness of the indicator outputs compared to field measurement data. For the latter point, the available dataset consist of leaching measurements under mature oil palm, carried out from 2008 and 2015 in Sumatra, Indonesia. Concentrations of nitrate and ammonium in soil solution were measured at three different depths, 0.3, 1 and 3 m, in the three zones of the plantation, being the harvesting path, the weeded circle and the windrow. This dataset will be used to validate the R-leaching module, which is an important module in the indicator as it corresponds to the highest losses, with high variability. The third step is the validation by end-users. It will be done across several estates in a plantation in Sumatra, Indonesia, from where the leaching dataset comes. It will aim to evaluate the usefulness of the indicator as a decision-support tool.

5 CONCLUSION

We adapted the preliminary version of IN-Palm taking into account accurately peculiarities of oil palm system and available knowledge about N cycle and drivers of N losses in plantations. IN-Palm is hence adapted to oil palm characteristics, such as the tropical climate, the long growth cycle of about 25 years and the high production of biomass which is recycled in the field. It assesses the risk of losses through NH_3, runoff-erosion, N_2O, NO_x, and leaching. In this context of data scarcity, the development of an indicator is an interesting option, and methods of calculation of losses are adapted to the limited knowledge about processes. The indicator is calibrated to an oil palm plantation in Sumatra, Indonesia. It is designed to be implementable with readily available input data, sensitive to practices, and useable to perform environmental impact assessments as well as to support decision-making process.

ACKNOWLEDGMENTS

The authors would like to thank the French National Research Agency (ANR) for its support within the frame of the SPOP project (http://spop.cirad.fr/) in Agrobiosphere program; ANR-11-AGRO-0007.We also thank Jacques Ranger, from the French National Institute for Agricultural Research in Nancy, who designed the trial of leaching measurements whose results will be used to validate the leaching module of IN-Palm.

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iEMSs 2016 Conference

Environmental modelling and software for supporting a sustainable future

Proceedings | Volume 2 | Pages 351-569

8th International Congress on Environmental Modeling and Software (iEMSs)

July 10–14, 2016

Toulouse, France

Proceedings of the 8th International Congress on Environmental Modelling and Software (iEMSs) July 10-14, 2016, Toulouse, FRANCE.

How to cite the full proceedings:

Sauvage, S., Sánchez-Pérez, J.M., Rizzoli, A.E. (Eds.), 2016. Proceedings of the 8th International Congress on Environmental Modelling and Software, July 10-14, Toulouse, FRANCE. ISBN: 978-88-9035-745-9

How to cite an individual paper:

Author, A., Author, B., Author, C…, 2016. This is the title of your paper. In: Sauvage, S., Sánchez-Pérez, J.M., Rizzoli, A.E. (Eds.), 2016. Proceedings of the 8th International Congress on Environmental Modelling and Software, July 10-14, Toulouse, FRANCE. ISBN: 978-88-9035-745-9

Peer Review:

Each paper has been peer reviewed by at least two independent reviewers with possible outcomes of reject, revise, and accept.

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