IN-Palm - Technical Report

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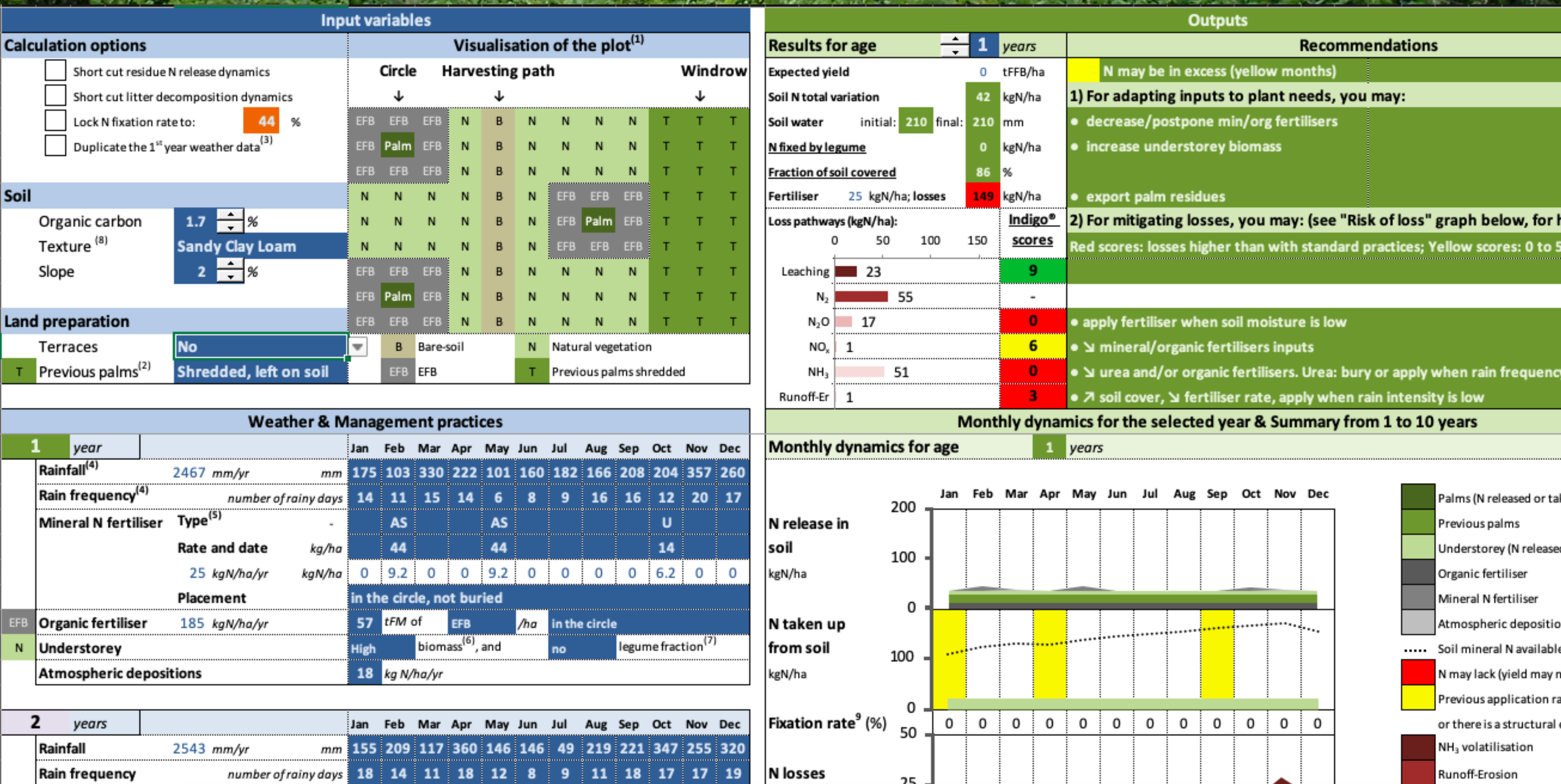
December 2019


An agri-environmental indicator

To assess potential nitrogen losses in oil palm plantations


Input variables

Calculation options

☐ Short cut residue N release dynamics
☐ Short cut litter decomposition dynamics
☐ Lock N fixation rate to: 44 %
☐ Duplicate the 1st year weather data(3)

Visualisation of the plot(1)

	Circle ↓			Harvesting path ↓						Windrow ↓	
EFB	EFB	EFB	N	B	N	N	N	N	T	T	T
EFB	Palm	EFB	N	B	N	N	N	N	T	T	T
EFB	EFB	EFB	N	B	N	N	N	N	T	T	T
N	N	N	N	B	N	EFB	EFB	EFB	T	T	T
N	N	N	N	B	N	EFB	Palm	EFB	T	T	T
N	N	N	N	B	N	EFB	EFB	EFB	T	T	T
EFB	EFB	EFB	N	B	N	N	N	N	T	T	T
EFB	Palm	EFB	N	B	N	N	N	N	T	T	T
EFB	EFB	EFB	N	B	N	N	N	N	T	T	T

B Bare-soil
N Natural vegetation
EFB EFB
T Previous palms shredded

Soil

Organic carbon 1.7 %
Texture (8) Sandy Clay Loam
Slope 2 %

Land preparation

Terraces No
T Previous palms(2) Shredded, left on soil

Weather & Management practices

1 year				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall(4)		2467 mm/yr	mm	175	103	330	222	101	160	182	166	208	204	357	260
Rain frequency(4)			number of rainy days	14	11	15	14	6	8	9	16	16	12	20	17
Mineral N fertiliser	Type(5)		-		AS			AS					U		
	Rate and date		kg/ha		44			44					14		
		25 kgN/ha/yr	kgN/ha	0	9.2	0	0	9.2	0	0	0	0	6.2	0	0
	Placement			in the circle, not buried											
EFB Organic fertiliser		185 kgN/ha/yr		57	tFM of	EFB		/ha	in the circle						
N Understorey				High	biomass(6), and			no	legume fraction(7)						
Atmospheric depositions				18	kg N/ha/yr										

2 years				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall		2543 mm/yr	mm	155	209	117	360	146	146	49	219	221	347	255	320
Rain frequency			number of rainy days	18	14	11	18	12	8	9	11	18	17	17	19

Outputs

Results for age 1 years

Expected yield	0	tFFB/ha
Soil N total variation	42	kgN/ha
Soil water initial: 210 final:	210	mm
N fixed by legume	0	kgN/ha
Fraction of soil covered	86	%
Fertiliser 25 kgN/ha; losses	149	kgN/ha

Recommendations

N may be in excess (yellow months)

1) For adapting inputs to plant needs, you may:
- decrease/postpone min/org fertilisers
- increase understorey biomass
- export palm residues

2) For mitigating losses, you may: (see "Risk of loss" graph below, for h

Red scores: losses higher than with standard practices; Yellow scores: 0 to 5

Loss pathways (kgN/ha):		Indigo® scores	
Leaching	23	9	
N_2	55	-	
N_2O	17	0	• apply fertiliser when soil moisture is low
NO_x	1	6	• ↘ mineral/organic fertilisers inputs
NH_3	51	0	• ↘ urea and/or organic fertilisers. Urea: bury or apply when rain frequenc
Runoff-Er	1	3	• ↗ soil cover, ↘ fertiliser rate, apply when rain intensity is low

Monthly dynamics for the selected year & Summary from 1 to 10 years

Monthly dynamics for age 1 years

Fixation rate9 (%)	0	0	0	0	0	0	0	0	0	0	0	0

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

Technical Report

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Download IN-Palm (Excel file)
(https://ur-systemes-de-perennes.cirad.fr/download-in-palm)

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1. User instructions

IN-Palm is an agri-environmental predictive indicator specific to oil palm plantations based on an operational model. It simulates the risk of nitrogen (N) losses from the field, through 6 loss pathways: ammonia (NH_3) volatilisation; N losses through runoff-erosion; nitrous oxide (N_2O), dinitrogen (N_2) and nitrogen oxides (NO_x) emissions; and N leaching. Simulations require 21 readily available input variables on crop factors, soil, weather and management practices. 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 (modules) 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 year’s management practices)
	> 10 years	**Input sheet for old palms** (results do not highly depend on previous year’s 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 module testing	Tool - For visualising the behaviour of each fuzzy module
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., 2002a), 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., 2002b), 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 mineral 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 weather and management practices, 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 shown in the top right-hand corner of the input variables column (Figure 1.1c). This representation is only illustrative, to help the user visualise the management choices, and calculations are not based on it. To complete this visual representation, some pictures of management options are given in the sheet 'Pictures' (Table A.1, in Appendices).

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.

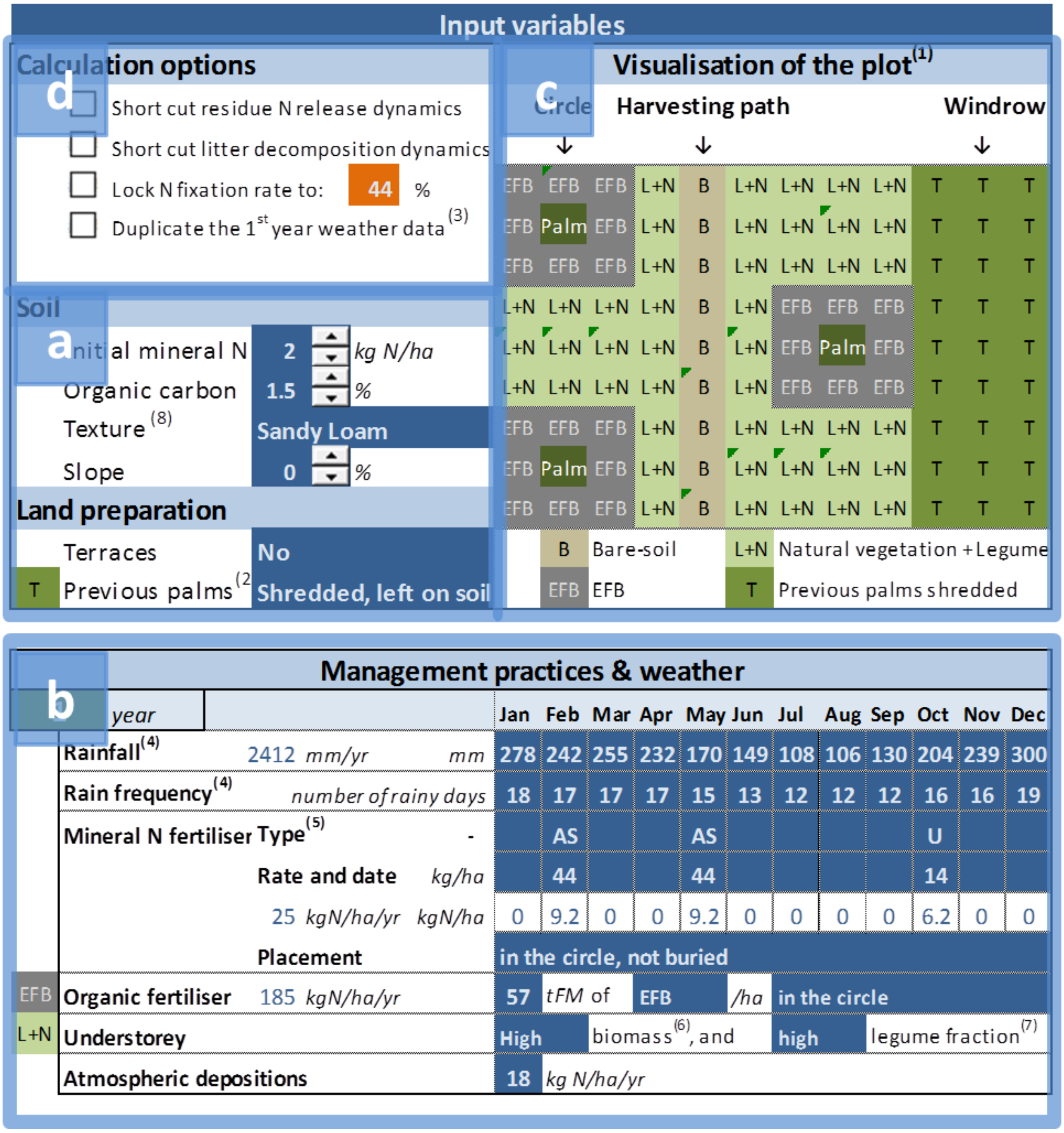
Other calculation options located in the top left-hand corner of the input column can be used for advanced testing of the modelling approach (Figure 1.1d). Their utility is described in the section 1.2 "How to dig into the structure and calculations".

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 type	Input variable	Units	Classes
Crop factors	Age of palms	years	Integer (min. 0, max. 30)
	Expected yield after 3 years	t FFB ha^{-1} yr^{-1}	Real number (min, 0, max. 40))
Soil and land	Soil initial mineral N	kg N ha^{-1}	Real number (min. 0)
	Soil initial water content	mm	Real number (min. 0)
	Soil organic C	%	Real number (min. 0, max. 10)
	Slope	%	Real number (min. 0, max. 30)
	Terraces	-	Yes No
	Soil texture	-	Sand Loamy Sand Sandy Loam Loam Silt Loam Silt Clay Loam Sandy Clay Loam Silty Clay Loam Silty Clay Clay Sandy Clay

Weather	Number of rainy days	month-1	Integer (min. 0, max. 31)
	Monthly rainfall	mm	Real number (min. 0)
	Atmospheric N deposition	kg N ha^{-1} yr^{-1}	Real number (min. 0)
Fertiliser management	Rate/Date of mineral fertiliser	kg ha^{-1}	Real number (min. 0)
	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 (1st 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)



Input variables

Calculation options

☐ Short cut residue N release dynamics
☐ Short cut litter decomposition dynamics
☐ Lock N fixation rate to: 44 %
☐ Duplicate the 1st year weather data (3)

Soil

Initial mineral N	2	kg N/ha
Organic carbon	1.5	%
Texture (8)	Sandy Loam	
Slope	0	%

Land preparation

Terraces	No
T	Previous palms (2)	Shredded, left on soil

Visualisation of the plot (1)

Circle ↓ Harvesting path ↓ Windrow ↓

EFB	EFB	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T
EFB	Palm	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T
EFB	EFB	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T
L+N	L+N	L+N	L+N	B	L+N	EFB	EFB	EFB	T	T	T
L+N	L+N	L+N	L+N	B	L+N	EFB	Palm	EFB	T	T	T
L+N	L+N	L+N	L+N	B	L+N	EFB	EFB	EFB	T	T	T
EFB	EFB	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T
EFB	Palm	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T
EFB	EFB	EFB	L+N	B	L+N	L+N	L+N	L+N	T	T	T

B	Bare-soil	L+N	Natural vegetation + Legume
EFB	EFB	T	Previous palms shredded

Management practices & weather

year			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (4)	2412 mm/yr	mm	278	242	255	232	170	149	108	106	130	204	239	300
Rain frequency (4)		number of rainy days	18	17	17	17	15	13	12	12	12	16	16	19
Mineral N fertiliser Type (5)		-		AS			AS					U		
	Rate and date	kg/ha		44			44					14		
	25 kgN/ha/yr	kgN/ha	0	9.2	0	0	9.2	0	0	0	0	6.2	0	0
	Placement		in the circle, not buried											
EFB Organic fertiliser	185 kgN/ha/yr		57	tFM of	EFB	/ha	in the circle							
L+N Understorey			High	biomass (6), and	high	legume fraction (7)								
Atmospheric depositions			18	kg N/ha/yr										

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) weather and management practices, (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

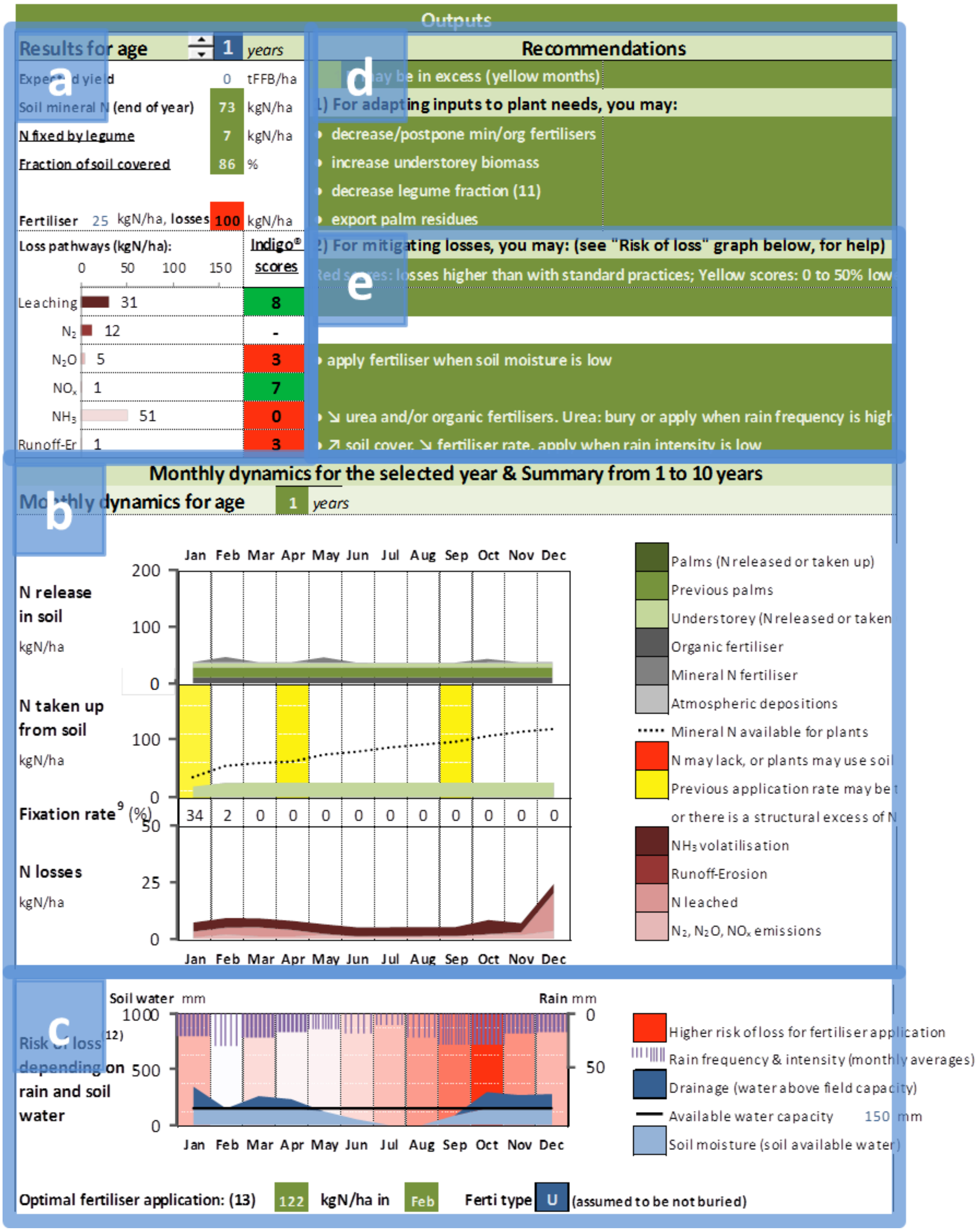
Nitrogen and water dynamics and N losses are presented by some general annual values, losses in kg N ha^{-1} yr^{-1}, scores between 0 and 10, and the details of N and water dynamics over the chosen year.

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 less than plant needs, a red bar is displayed in the graph, indicating that N may be lacking. When soil mineral N available for plants is more 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. 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-related 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 in a given month leads to high losses, a dark red bar is displayed on this month. When fertiliser application in 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 less than 10, the user need only consider results displayed for years below the actual age.



Results for age 1 *years*

Expe d yield 0 tFFB/ha

Soil mineral N (end of year) 73 kgN/ha

N fixed by legume 7 kgN/ha

Fraction of soil covered 86 %

Fertiliser 25 kgN/ha, losses 100 kgN/ha

Loss pathways (kgN/ha):		Indigo® scores
Leaching	31	8
N_2	12	-
N_2O	5	3
NO_x	1	7
NH_3	51	0
Runoff-Er	1	3

Recommendations

ay be in excess (yellow months)

1) For adapting inputs to plant needs, you may:
- decrease/postpone min/org fertilisers
- increase understorey biomass
- decrease legume fraction (11)
- export palm residues

2) For mitigating losses, you may: (see "Risk of loss" graph below, for help)

ed s es: losses higher than with standard practices; Yellow scores: 0 to 50% low

- apply fertiliser when soil moisture is low
- ↘ urea and/or organic fertilisers. Urea: bury or apply when rain frequency is high
- ↗ soil cover. ↘ fertiliser rate, apply when rain intensity is low

Monthly dynamics for the selected year & Summary from 1 to 10 years

Monthly dynamics for age 1 *years*

Fixation rate[9] (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	34	2	0	0	0	0	0	0	0	0	0	0

Optimal fertiliser application: (13) 122 kgN/ha in Feb Ferti type U (assumed to be not buried)

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	Losses up to 3 times higher than with standard practices
0	Losses 3 or more times higher than with standard practices

1.1.2.2. Recommendations for management changes

IN-Palm provides recommendations for management changes to help adapt N inputs to plant needs, reduce N losses, and find 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 be lacking or 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 match plant needs, within a range of ±5 kg N ha^{-1}.

Table 1.4. 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 is neither lacking, nor 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, it is proposed that the user increases soil cover or applies 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. 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 fertiliser 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 the optimal mineral fertiliser date (month) 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 into 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 summarised in the tables A.1, A.2 and A.3 in Appendices.

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 enables 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 in 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’ enables testing of the behaviour of a given fuzzy decision tree module (see section 2). For a given tree selected by the user, this tool gives a quick overview of the output space, to check the response of the output space to input value changes, and to identify unrealistic or undesirable behaviours. Moreover, this sheet illustrates how fuzzy logic improves the output space compared to standard decision trees.

Finally, for advanced testing of 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 Mineral N Budget module, can be short cut. When this module is short cut, calculations are done assuming that all of the N in plant residues is released into 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 module.

2. Advantages and computation of fuzzy decision tree models

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

2.1. The fuzzy decision tree modelling approach

Unlike process-based or regression models, which apply quantitative equations to derive output values from input values, decision tree models apply rules in form of 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). Each rule is 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 reached by applying the rules, 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, falling into 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 the 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 all rules. 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 quantitative outputs to be obtained, even when processes are not fully understood or when mathematical relationships between inputs and outputs are not available. This characteristic is particularly useful in contexts of knowledge scarcity, which is the case for N dynamics and losses in oil palm. However, due to their structure, decision trees can yield only 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, due to thresholds effects (Figure 2.1e).

Fuzzy logic (Zadeh, 2008) applied to decision trees allows continuous output spaces to be obtained 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.

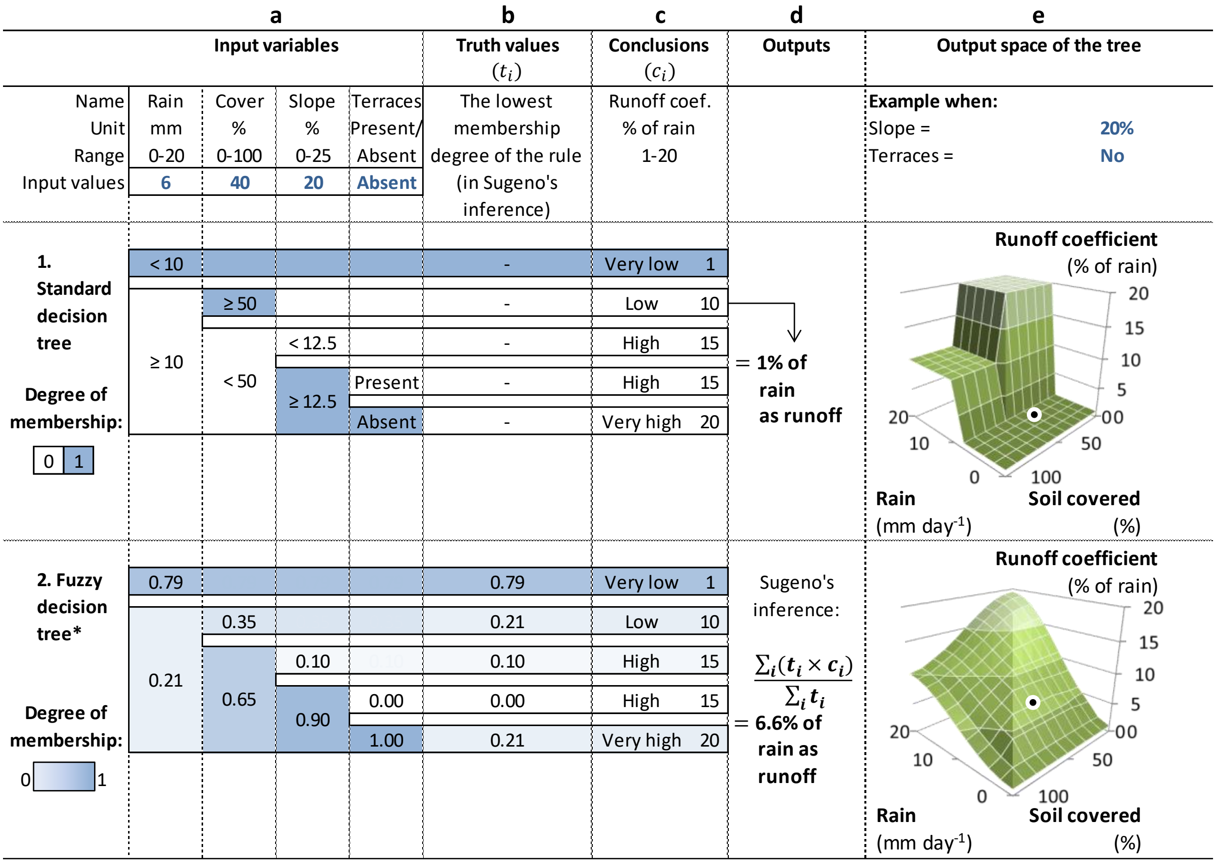


Figure 2.1. Standard decision tree vs. fuzzy decision tree: example for the Water Runoff module of IN-Palm.

For a given combination of input variables (a), truth values are calculated for all rules in the fuzzy tree (b) whereas 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): $Membership\ degree_{Unfavourable} = \frac{1}{2} \times [1\ +\ \cos\ (input\ value\ \times\ \pi)]$

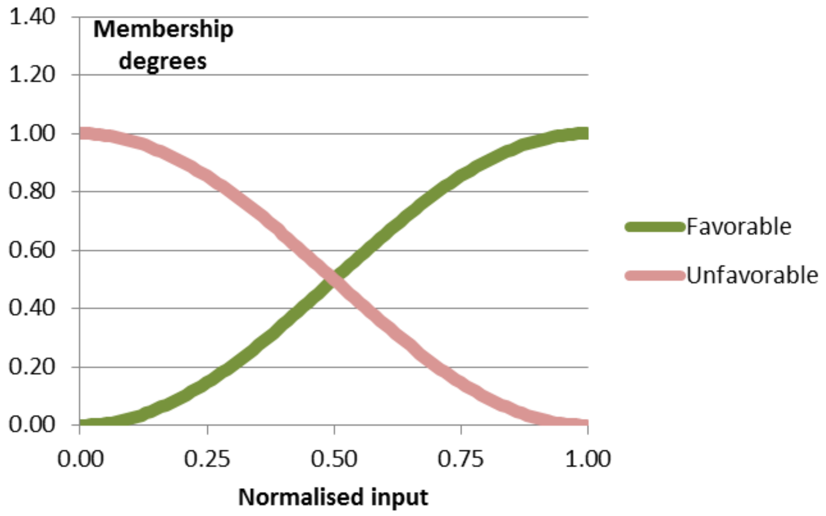


Figure 2.2. Representation of the two cosine membership functions associated with the classes Favourable and Unfavourable.

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.

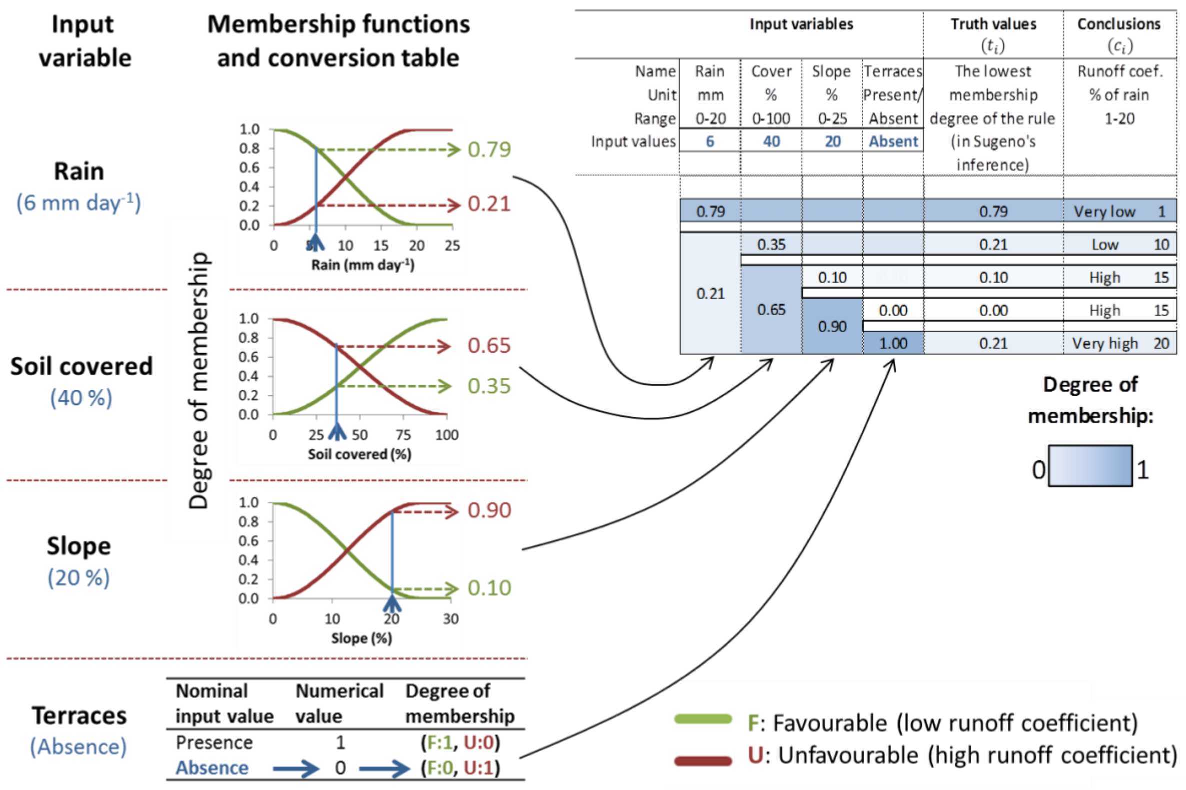


Figure 2.3. Calculation of membership degrees of input values to the Favourable and Unfavourable classes.

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

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 month 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, and net mineralization of soil organic N.

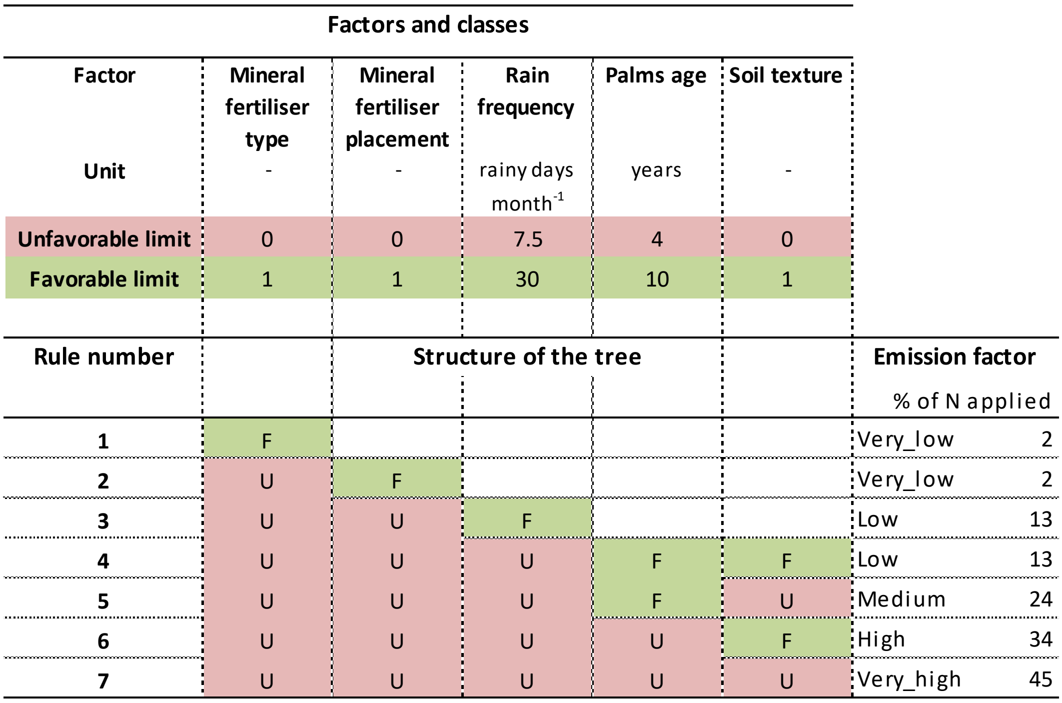
3.1. Ammonia volatilisation from mineral and organic fertiliser

Module 1.1 R-NH_3-Mineral

The volatilisation of NH_3 from mineral fertiliser application is estimated using a fuzzy decision tree (Figure 3.1). This decision tree has 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.2 and A.3 in Appendices.



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 of 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-NH_3-Organic

The volatilisation of NH_3 from organic fertiliser application is estimated using the regression model of Bouwman et al. (2002a) (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 fixed to fit oil palm conditions (see Table A.2 in Appendices 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 12.

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 tonnes 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 initial residues from the previous cycle, current palm and understorey residues, and organic fertiliser.

Two types of parameters were necessary to estimate inputs: the mass of initial residues from the previous cycle and the annual turnover rates of other plant residues (see references in Table A.4 in Appendices). $Decomposition$ is calculated for each residue type following the exponential equation of Moradi et al. (2014), which embeds a constant *k,* specific to oil each palm residues, and defining the decomposition speed. Moradi et al. (2014) provide *k* for empty fruit bunches, rachis, leaflets and the whole frond. But they do not provide *k* values for other potential oil palm residues, such as inflorescences, old trunks at replanting, dead roots from roots turnover, etc. However, using the *k* values of the four oil palm residues, from Moradi et al. (2014), and their respective C/N values from various authors (see Table A.4 in Appendices), we found a logarithmic relationship between *k* and C/N, with an R2 of 0.79 (equation 7).

Equation (7): $k = -0.074 \times \ln\left(\frac{C}{N}\right) + 0.4651$

Therefore, we considered three cases to determine *k* values used in the equation of Moradi et al. (2014): (a) when *k* values were provided by Moradi et al. (2014), such as for fronds, we used these values; (b) when *k* values were not provided but C/N ratios were available in the literature, such as for roots and trunks, we inferred approximate *k* values using the logarithmic relationship between *k* and C/N; and (c) when C/N ratios were not available in the literature, such as for inflorescences, we used the available *k* value from Moradi et al. (2014) for the oil palm residue likely to have the closest C/N, such as empty fruit bunches in the case of inflorescences (see *k* values in Table 3.2).

Table 3.2. Decomposition speed, i.e. *k* values, for oil palm residues and compost

Palm residues	*k* value (decomposition speed)	Carbon / Nitrogen (C/N)*
Trunk	0.14 (b)	82
Leaflets	0.26 (a)	18
Rachis	0.12 (a)	107
Spears	0.26 (c)	-
Cabbage	0.26 (c)	-
Frond bases	0.12 (c)	-
Inflorescences	0.20 (c)	-
Fronds	0.15 (a)	41
Roots	0.11 (b)	117
Compost	0.21 (b)	30
EFB	0.20 (a)	52

a: *k* value provided by Moradi et al. (2014)
b: *k* value inferred from C/N*
c: *k* value hypothesized from the closest oil palm residue
* see Table A.4 in Appendices for references for C/N

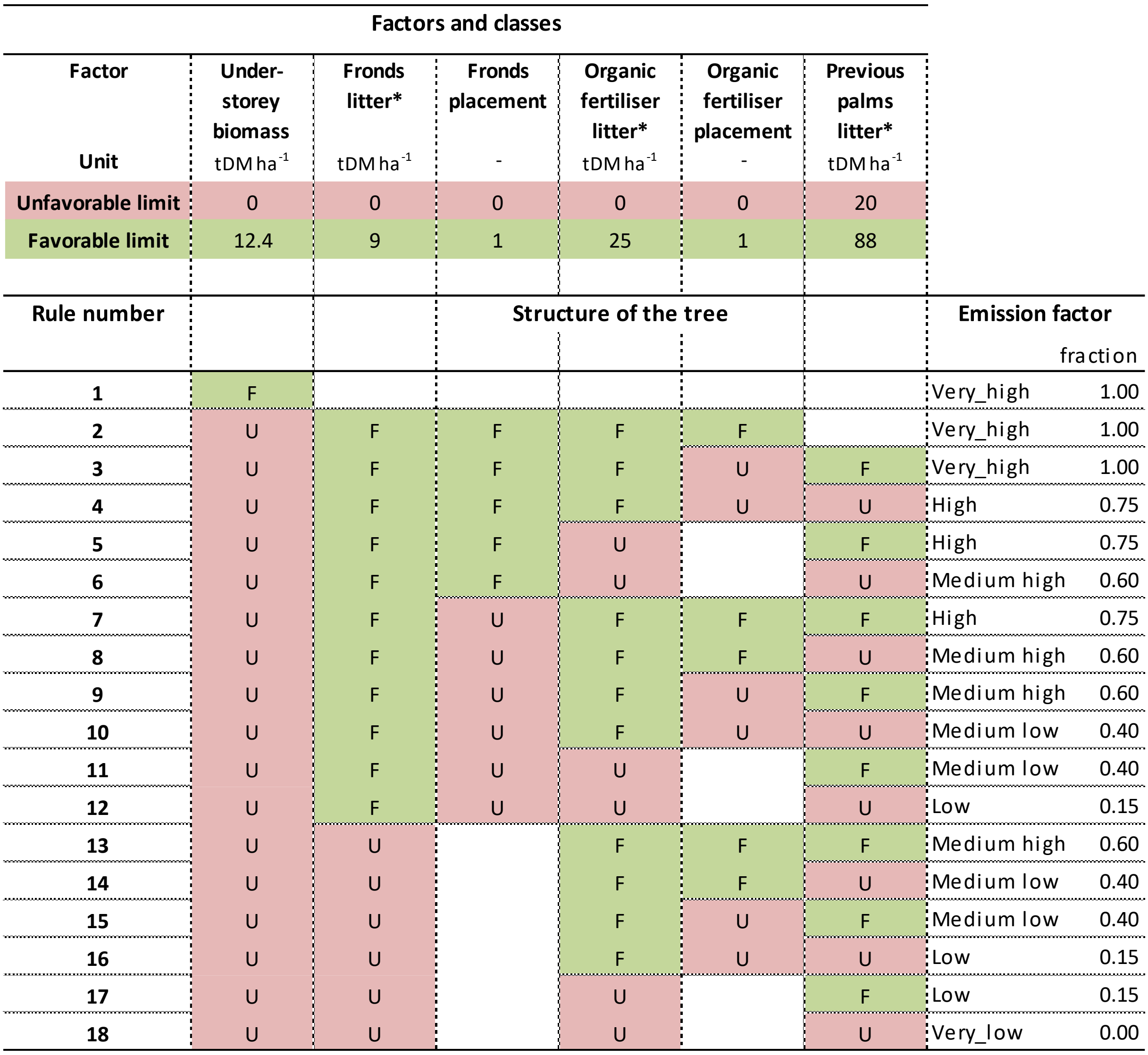
The output of this module is an annual value of litter amount, expressed in ton of dry matter ha^{-1}. References used for mass of initial residue, turnover rates and decomposition speed are detailed in Tables A.2 and A.4 in Appendices.

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 has 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}), frond 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, frond 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 3.3).

The output of the decision tree is a fraction of soil covered between 0 and 1, for that year. References used for tree structure, tree calibration and output range, are detailed in Tables A.2 and A.3 in Appendices.



Factor	Understorey biomass	Fronds litter*	Fronds placement	Organic fertiliser litter*	Organic fertiliser placement	Previous palms litter*	Emission factor	
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							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 of 18 rules and 6 factors. For each factor are defined two limits of classes: Favorable and Unfavorable. The output of the decision tree is a fraction of soil covered in that year. DM: dry matter, *Intermediate variable calculated by another module

Table 3.3. 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 has 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 3.4).

The output of the decision tree is a runoff coefficient for each month, ranging from 1 to 20 % of rain. References used for tree structure, tree calibration and output range, are detailed in Table A.2 and A.3 in Appendices.

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 3.4. 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 (8) adapted from Corley and Tinker (2003). This module uses, as input variables, all inputs to and outputs from the soil water pool.

Equation (8): $W\ (m+1) = W\ (m) +\ Rain\ (m+1) - Intercepted\ water\ (m+1) - Water\ runoff\ (m+1) - Evapotranspiration\ (m+1) - Drainage\ (m+1)$,

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 roots are located (1.5 m), plant available water holding capacity and soil saturation water content. 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 water 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 1.5 m depth, and hence lost to the palms.

The output values of this module are plant available water and drainage for that month. 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.2 and A.4 in Appendices.

3.3. Denitrification from fertilisers and runoff-erosion

Module 3.1 R-N_2O-Mineral

Emissions of N_2O from mineral fertiliser application are estimated using a fuzzy decision tree (Figure 3.4). This decision tree has 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 3.5).

The output of the decision tree is a monthly emission factor, ranging from 0.01 to 13.0 % of mineral fertiliser rate applied. References used for tree structure, tree calibration and output range are detailed in Table A.2 and A.3 in Appendices.

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 has 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

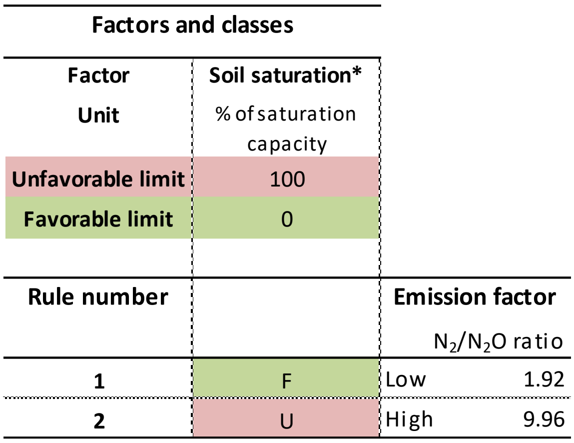
Table 3.5. Conversion of nominal input variables into numerical values for N_2O emissions from fertiliser

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 has 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.2 and A.3 in Appendices.



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 has 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. (2002b) (Equation 9).

Equation (9): $Annual\ NOx\ emission = e^{(-1.527\ +\ \sum_i correction\ factor_i)}$

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.2 in Appendices).

Following the method described by Bouwman et al. (2002b), 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.

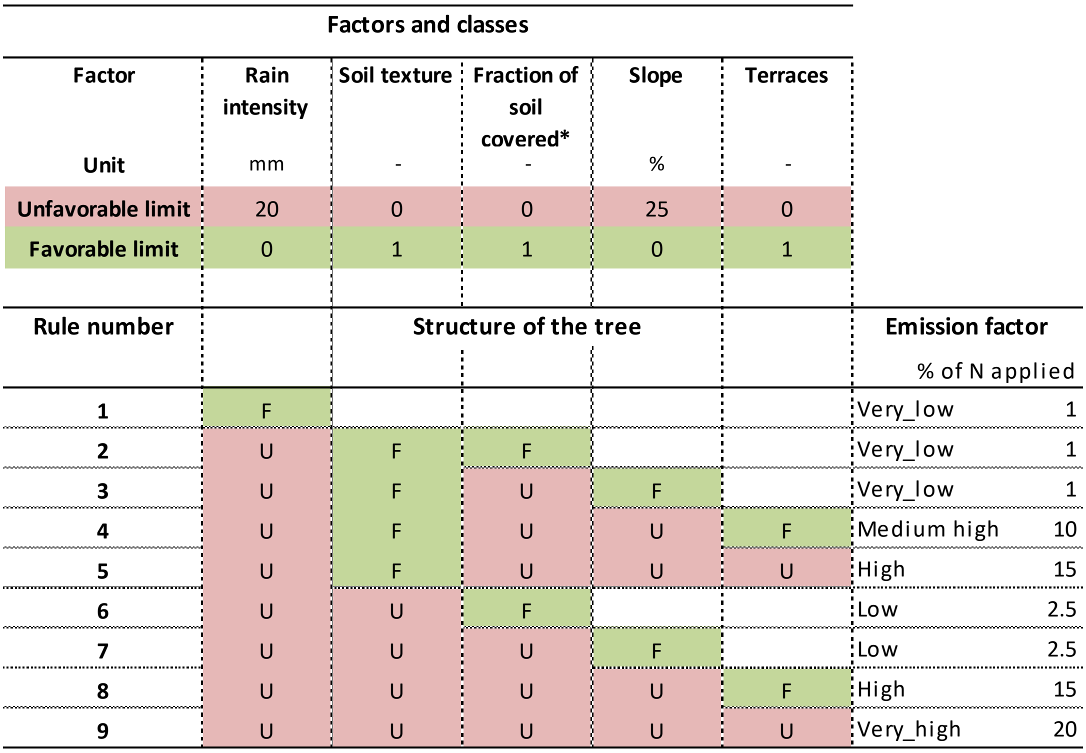
The output of this module is hence an annual emission of N losses from fertiliser and organic application, directly expressed in kg N ha$_{-1}$ year$_{-1}$. For monthly calculations of the N budget, this annual value is divided by 12.

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 has 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 3.6).

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.2 and A.3 in Appendices.



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 has 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 3.6. 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 % on 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 those for 20 year-old palms.

The output of the decision tree is an annual palm N uptake (kg N ha^{-1} yr^{-1}) depending on palm age and expected yield. References used for tree structure, tree calibration and output range, are detailed in Table A.2 and A.3 in Appendices.

		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

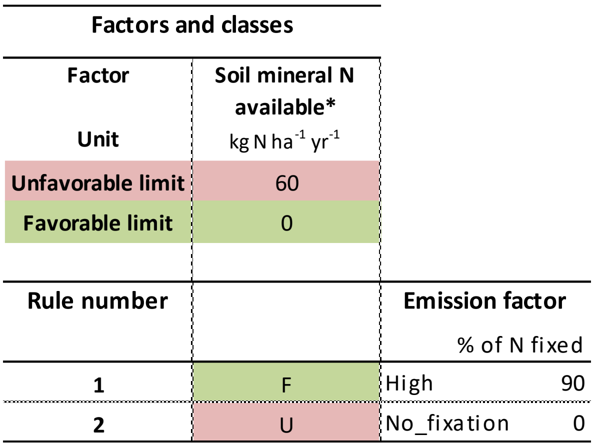
Figure 3.7. Decision tree for palm N uptake

The tree has 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 has 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 Mineral 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.2 and A.3 in Appendices.



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 has 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 that was fixed from the atmosphere. N: nitrogen, *Intermediate variable calculated by another module

Module 4.3 Soil Mineral N Budget

The Soil Mineral N budget module uses a mass budget approach applied to N flows in the plantation, following equation (10). This module uses, as input variables, all inputs to and outputs from the soil mineral N pool.

Equation (10): $Soil\ mineral\ N\ (m+1) = Soil\ mineral\ N\ (m) + Fertiliser\ N\ net\ release\ (m+1) + Atmospheric\ deposition\ N\ net\ release\ (m+1) + Litter\ N\ net\ release\ (m+1) -$

$$Palm\ N\ uptake\ (m+1) - Understorey\ N\ uptake\ (m+1) - N\ losses\ (m+1) + net\ soil\ organic\ N\ mineralization\ (m+1),$$

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 a parameter corresponding to the soil mineral N equilibrium for oil palm (Allen et al., 2015). Inputs from fertiliser, atmospheric deposition and litter are net release, after subtracting the initial 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 (e.g. from 0.23 to 3.12 % of dry matter for oil palm residues, see Table 3.7), the annual rate of turnover, and the rate of net N release through decomposition (from 1 to 3 years).

$Palm\ N\ uptake$ is estimated by the Palm N Uptake module, depending on palm age and the expected yield. $Understorey\ N\ uptake$ is calculated by the Understorey N Uptake/Fixation module, 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 lower than the soil mineral N equilibrium, 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 lower than this equilibrium, a net soil N mineralization is estimated, equal to the value missing to reach the equilibrium. At the end of the month, the soil mineral N is hence always equal or higher than the equilibrium.

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.2 and A.4 in Appendices.

Table 3.7. N content of palm residues used in IN-Palm for the calculation of *Litter N net release*

	N (% of DM)	References
Trunk	0.56	Khalid el al. (1999a, p. 29)
Leaflets	2.18	Khalid, et al. (1999a, p. 29)
Rachis	0.45	Khalid et al. (1999a, p. 29), in line with Moradi et al. (2014, p. 211)
Spears	2.14	Khalid el al. (1999a, p. 29)
Cabbage	3.12	Khalid el al. (1999a, p. 29)
Frond bases	0.23	Khalid el al. (1999a, p. 29)

Inflorescences	1.94	Khalid el al. (1999a, p. 29)
Roots	0.32	Khalid et al. (1999b), Ng et al. (1968)

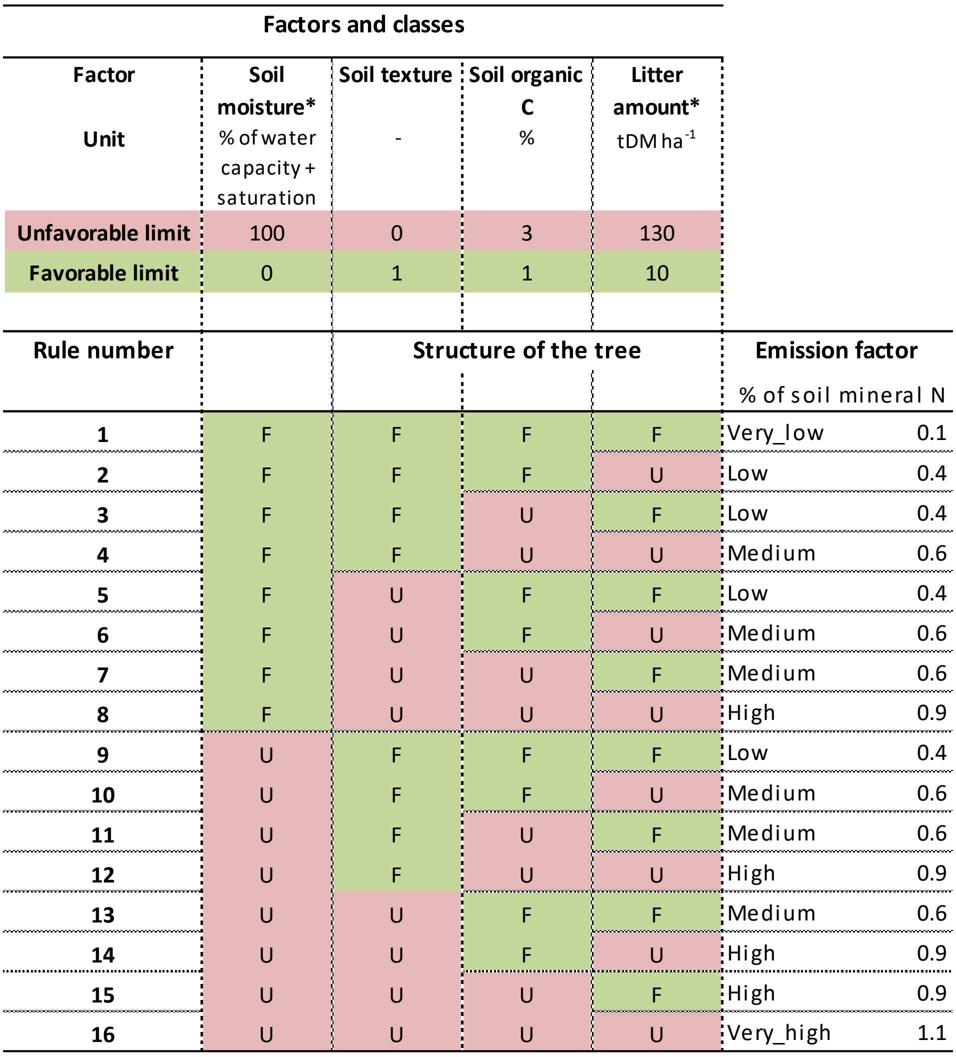
DM: Dry Matter

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 2.5 % of mineral N available in soil for losses. References used for the output range are detailed in Table A.2 and A.3 in Appendices.



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 has 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.

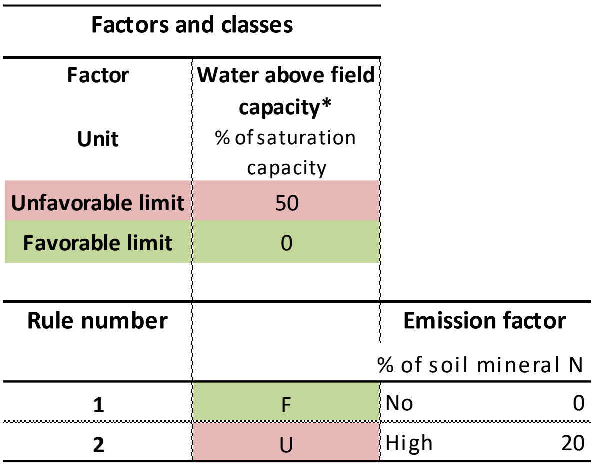
Module 5.3 R-NO_x-Baseline

Baseline emissions of NO_x from soil are estimated using the regression model of Bouwman et al. (2002a), which is also 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 has 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 5 % of soil mineral N available for losses. References used for tree structure, tree calibration and output range are detailed in Table A.2 and A.3 in Appendices.



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 has 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):

$$\text{Equation (11):} \begin{cases} if\ loss < 2R: & Score = -\frac{3 \times loss}{R} + 10 \\ if\ 2R < \ loss < 6R: & Score = -\frac{loss}{R} + 6 \\ if\ loss > 6R & Score = \ 0 \end{cases}$$

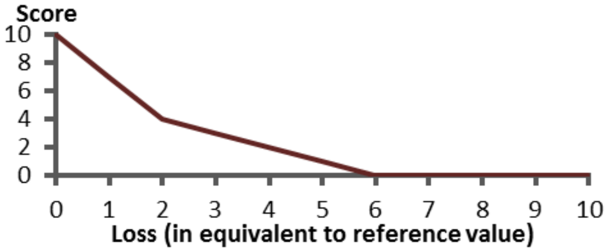


Figure 4.1. Representation of the function to convert a loss of nitrogen into a score.

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 to those for 25-year old palms.

Table 4.1. Reference value of N loss for each loss pathway, depending on palm age. Reference values are equal to 50 % of the N loss, measured or modelled, associated with standard management practices. Reference values are given in kg N ha^{-1}.

Age of palms	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
NH3	0	7	9	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	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	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	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	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	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	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	0	56	45	35	38	30	20	14	15	13	16	16	16	16	14	14	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 be lacking or 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 be lacking in a given month and 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 lack or excess 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 plant uptake < -5 kg N ha^{-1}	● N may lack (red months) Yield may not be achieved, or soil N may be mined.
Soil mineral N after plant 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 plant 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 better adapt N inputs to plant needs (Table 4.3) and reduce 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*

* In the case of an ex-post evaluation, the recommendation of exporting or not initial palm residues from the previous cycle cannot be applied and only intends to help the user quantify the role of initial residues in the excess of N in soil.

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

* In the case of an ex-post evaluation, the recommendation of exporting or not initial palm residues from the previous cycle cannot be applied and only intends to help the user quantify the role of initial residues in the excess of N in soil.

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 sufficient 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 in 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 loss when applying fertiliser in months with high rain intensity.

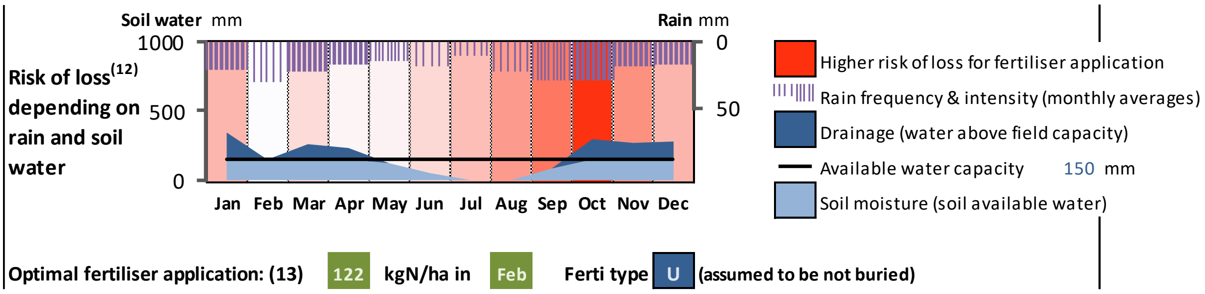


Figure 4.2. Visualisation of the risk of applying fertiliser, for each month of the year. The darkest red corresponds to the riskiest month to apply mineral fertiliser with respect to N loss, and the whitest shade corresponds to the safest month. N loss depends on the dynamics and interaction of weather, 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.

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Appendices

Table A.1. 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

Table A.2. 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}	Regression model of Bouwman et al. (2002a)
	Input	Organic fertilizer type	year	Animal manure	-	
	Input	Crop type	-	Upland crop	-	
	Input	Application mode	year	Broadcast	-	
	Input	Soil pH	-	≤ 5.5	-	
	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	
R-N_2O-Mineral and R-N_2O-Baseline (emissions from mineral fertilizer and soil mineral N)	Input	Mineral fertilizer rate and date	month	-	kg N ha^{-1} $month^{-1}$	-
	Input	*Soil mineral N available for losses	month	-	kg N ha^{-1}	-
	Input	*Soil moisture (% of available water capacity + saturation capacity)	month	0 to 100	%	-
	Input	Soil texture	-	c	-	-
	Input	Soil organic C content	-	0 to 10	%	
	Input	*Litter amount	year	-	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} $month^{-1}$	Regression model of Bouwman et al. (2002b)
	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	-	
	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 Mineral N Budget	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.3. 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} (in 30 cm depth)	≥ 56	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.4. 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 Mineral N Budget	Initial soil mineral N, i.e. equilibrium	kg N ha^{-1} m^{-1}	45 to 55.2, depending on soil texture	(Allen et al., 2015)
	Initial soil organic N, i.e. equilibrium	t N ha^{-1} m^{-1}	14.4 to 26, depending on soil texture	(Allen et al., 2015)
	N content of initial residue	kg N ha^{-1}	65 to 536	(Khalid et al., 1999a, p. 29, 1999b)
	N content of palm and understorey residues during the growth cycle	N in % of DM	0.23 to 3.12, depending on the residue type	Pruned fronds, inflorescences, roots turnover, frond bases: Khalid et al., (1999a, p. 29, 1999b), Moradi et al. (2014, p. 211), Ng et al. (1968) Understorey: Agamuthu and Broughton (1985, p. 120), ATP Neucapalm (2007, unpublished data)
	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)

DM : Dry Matter, N: Nitrogen, C: Carbon

References of appendices

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