Developing a running prototype of a bio-economic farm model for a trade-off analysis of different nutrient management options for maize cultivation in East-Africa (D1935 – Working document)

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Crop Nutrient Gap Project

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Short summary

Sustainable intensification of maize cultivation in East Africa will require increased inputs of nutrients. These nutrient can be applied using a range of nutrient management options, with possible trade-offs between yields, farmers' income and greenhouse gas emissions. Here, a running prototype is presented of a bio-economic farm model that enables systematic assessment of these trade-offs or synergies between yields, farmers' income and greenhouse gas emissions (for now only N2O emissions are included). The model is tested using data from Ethiopia. Despite fairly simple model assumptions, preliminary results show large variations in greenhouse gas emissions and farmers' income, depending on ecological conditions and nutrient management options used. In general, ecological conditions and nutrient management options that are beneficial for yield and farmers' income (such as the use of hybrid seeds and farming on in-fields) also seem to reduce effective N2O emissions (*i.e.* N2O emissions per tonne maize). In its current form, the model has a number of limitations, such as a lack of requirements for balanced nutrition (P and K) or inclusion of greenhouse gas emissions from fertiliser production. In a next step, these limitations will be addressed. In addition, the model will be expanded to include a wider set of nutrient management options (such as rotation or intercropping with legumes, or the use of organic inputs) and spatial variation in climate and soil types or market access.

Keywords

trade-off analysis; maize production; greenhouse gas emissions; East Africa; soil organic carbon; yields; economic incentives; climate smart agriculture

1. Introduction

Considering projected population trends, food requirements in East Africa will drastically increase in the coming decades (van Ittersum et al., 2016). One way to ensure supply will meet demand is by raising crop yields in the region. In East Africa, agricultural yields still have large potential to increase due to the large gaps between actual and potential yields. A recent study has shown that intensification of agriculture in regions with low current yields (such as in East Africa) is an option to reduce greenhouse gas emissions by avoiding or reducing agricultural land expansion into forests and/or grasslands, thus preserving carbon stocks (Van Loon, Hijbeek, ten Berge and Van Ittersum 2018, in prep). This is however only valid if higher yields are obtained with highly efficient use of fertilisers. For a successful implementation of such climate smart agricultural intensification, improved nutrient management options need to be economically viable for farmers in East Africa. It is however often unclear under which conditions agricultural intensification is beneficial for farmers' income in sub saharan Africa (Marenya and Barrett, 2009; Place et al., 2003; Sheahan et al., 2013).

Besides a number of good agricultural practices (such as improving planting densities and sound crop protection measures), farmers need to apply more nutrients to intensify production. The amounts of additional nutrients required represents the 'nutrient gap' between current nutrient applications and the total amount of nutrients removed from fields with increased yields (de Vries et al., 2017).

Farmers can use several nutrient management options to close the nutrient gap (*e.g.* use mineral or organic fertilisers, split application of fertilisers, combine with local or hybrid seeds). The nutrient management option a farmer chooses not only affects his or her nutrient use efficiency (how much of the applied nutrients are recovered by the crop), but also his or her income generation and the contribution to greenhouse gas emissions. Some practices might be most beneficial for farmers' income, but have a larger contribution to greenhouse gas emissions. Others might have the reversed effect.

So far, trade-offs and/or synergies between farmers' income and greenhouse gas mitigation as a function of nutrient management options have not been systematically assessed. Additionally, it is uncertain how such trade-offs or synergies might evolve over time, in cases where soil carbon and nutrient pools respond over longer time frames to the management exposed. We therefore address the following question: Can certain nutrient management practices be identified which are beneficial for both climate change mitigation and for farmers' income in East Africa? The aim of this report is to develop a running prototype of a bio-economic model which can be used to assess trade-offs between yields, farmers 'income and greenhouse gas emissions in function of different nutrient management options, both on the short and the long term.

The proposed model will focus on nitrogen (N) as the main limiting nutrient, which is also highly relevant for greenhouse gas emissions (*i.e.* N2O). The model will be useful for R&D investors, agri-business (including fertiliser companies) and government agencies for ex ante assessment of specific nutrient management options.

2. Methodology

One of the main constraints for raising maize yields in Sub Sahara Africa is the often (very) low agronomic nitrogen use efficiency (N-AE) of mineral fertilisers. A recent meta-analysis shows that for every kg N applied on farmers' fields, 19 kg additional maize grain is produced (Vanlauwe et al., 2011). As input prices are relatively high in East Africa compared to land or labour prices, the value cost ratio (VCR) of fertilisers (as affected by N-AE) is a key factor, especially in higher risk production environments (Morris, 2007). In addition, the N-AE of nutrient inputs also determines N2O emissions, as with less N inputs needed to achieve similar yields, less N2O will be emitted. Finally, a higher N-AE will result in more crop residues which can be potentially returned to the field (built-up of soil organic carbon (SOC) and a higher overall nutrient use efficiency (NUE). Our model is therefore based on documented effects of different nutrient management practices on the apparent N recovery, based on N-AE values, which then in turn affect maize yields, costs, income, N2O emissions and amounts of soil organic carbon (SOC) built up over time (Figure 1).

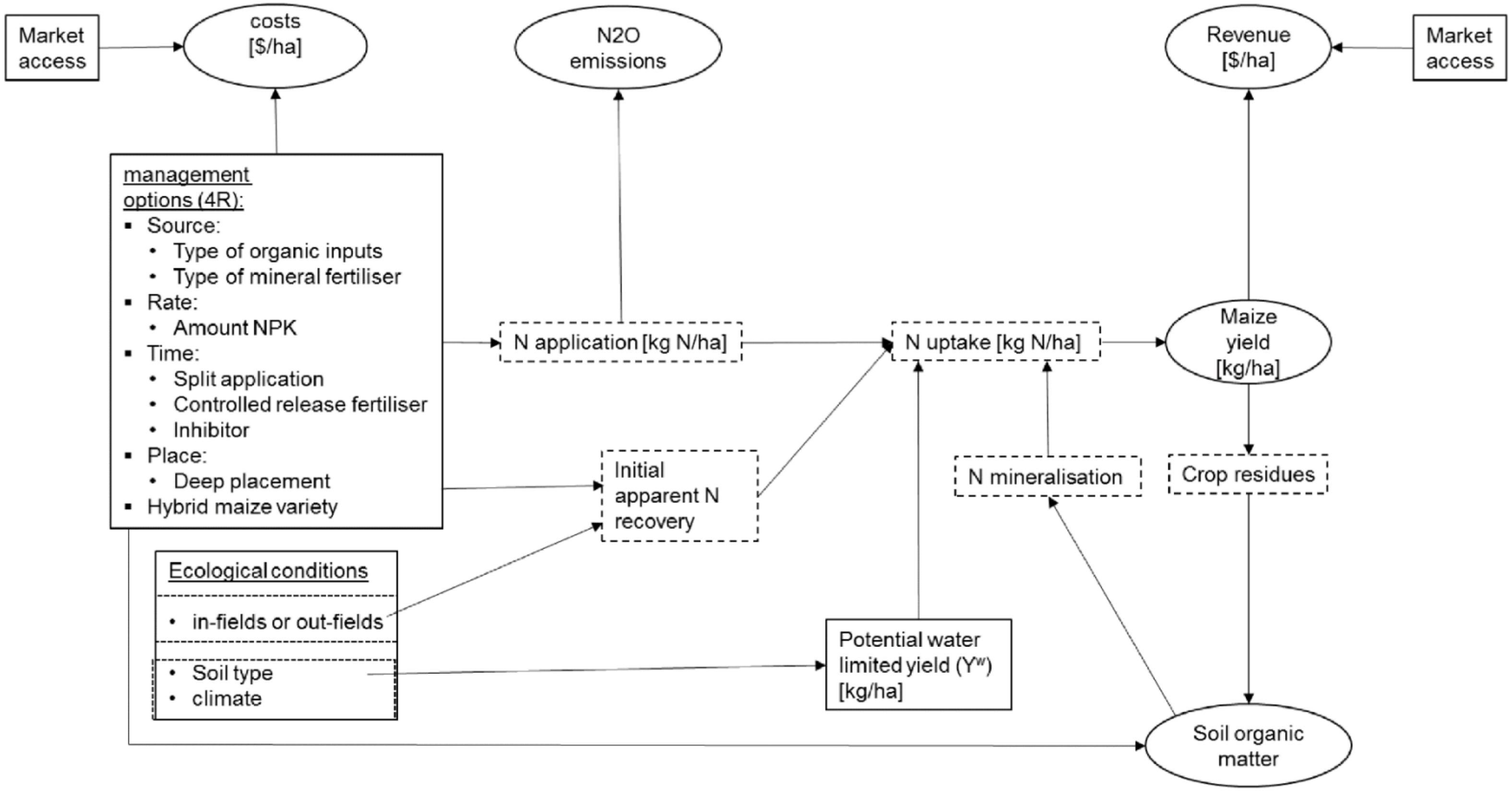

Figure 1: Simple schematic overview of model set-up. For readability, some relations are shown in general form and more specific relations between sub-components have been omitted. For complete model set-up including all model relations, see appendices. Solid squares are input variables. Dashed squares are intermediate model variables. Solid circles are model outputs.

Nutrient management options which can be included in the model are based on the 4R nutrient stewardship: right source, at the right rate, at the right time, in the right place (Snyder et al., 2014). Each nutrient management option has an associated cost (*e.g.* input costs or labour requirements) and effect on apparent N recovery, built up of SOC and/or N2O-emissions.

2.1. Estimating yield responses

In the running prototype model, yield response curves to N application are constructed by using the potential water limited yield (Y^w, based on local climate and soil type) as a yield ceiling (Global Yield Gap Atlas – GYGA; www.yieldgap.org). Nitrogen (N) applied is transformed into N uptake by the maize crop, depending on the control maize yield (yield without N application), the initial apparent N recovery (the apparent N recovery in the linear part of the response curve) and a response model called QUADMOD (Ten Berge et al., 2000). N uptake is transformed into maize yields using QUEFTS (Janssen et al., 1990).

Maize yields achieved with only the soil N supply (*i.e.* without N application at N=0) are estimated using national average maize yields (GYGA), and subtracting the yield component due to current fertiliser N applications (FAO, 2015) based on a mean estimate for N-AE (see appendix page 17 for formula used).

2.2. Estimating N2O emissions

N2O emissions from fertiliser application are estimated on the basis of total N application (IPCC, 2006). In a further model expansion, N2O emission will be differentiated for fertiliser type (Albanito et al., 2017; Xiao et al., 2017) and greenhouse gas emissions from fertiliser production will be included.

2.3. Selected case study to test the running prototype

In the running prototype, Ethiopia is taken as a case study. Two different nutrient management options and one ecological condition are being used to test the model: 1) type of mineral fertiliser (urea, DAP or NPS); 2) use of local or hybrid maize seeds; 3) cultivation on in or out fields. Additionally, in the running prototype, maize prices differ depending on market access (poor or good). Extension to other geographical regions, with other nutrient management options (such as organic inputs), a more continuous differentiation in market access and ecological conditions are foreseen in further model expansions (Section 4).

Average water limited yield potential in Ethiopia (12.5 tonne/ha) is taken as the current yield ceiling. In a later stage, this yield ceiling might be differentiated according to climate zone or type of seed use (hybrid or local). As a starting point for the initial apparent N recovery, 0.29 kg N uptake in maize per kg N application is used (Vanlauwe et al., 2011). Initial apparent N recovery is adjusted for cultivation on in- or out-fields (lower for out-fields and higher for in-fields, following Vanlauwe et al., 2011).

2.4. Estimating farmers' income

Maize yields produced are transformed into farmers‘ income based costs and revenue. Maize prices are based on the 2015 Living Standards Measurement Study (LSMS) data (CSA and Worldbank, 2015) and differentiated for poor or good market access. Labour requirements, costs of labour, fertilisers and seeds (local or hybrid) are based on expert knowledge (E. Woldemeskel and T. Amanu, personal communication).

3. Preliminary results for Ethiopia

To test the running prototype, Ethiopia was taken as a case study. The model is run with a first set of limited model options and input data, results should therefore not be taken as conclusive. This is only meant to test the methodology proposed and enable expansion of the model with additional nutrient management options and geographical and economical regions. Currently included management options in the running prototype are: choice of fertiliser (urea, DAP or NPS), use of seed type (local or hybrid seeds). Included external factors are market access (good or poor market access) and field location within the farm (in-field or out-field).

3.1. Comparing effects of nutrient management options along a wide range of N applications

Taking a wide range of N application (from 0 to 400 kg N/ha), effects of different nutrient management options on yield, N2O emissions and income are shown in Figure 2.

3.1.1. Yields

In the running prototype model, yield response curves to N application only differ regarding type of seed used (local or hybrid) and cultivation on in- or out-fields, resulting in four distinct response curves (Figure 2a). Yields almost double between the lowest and highest response curve (depending on N application level).

3.1.2. Income

Depending on the type of fertiliser used (cost) and maize price received (market access), incomes differ widely per maize yield achieved (Figure 2b). This effect is even more pronounced when relating income to N application (Figure 2c). For a certain level of N application (*e.g.* 100 kg N/ha), achieved income per ha differs between being around zero to around 40,000 TBE/ha/year (in 2015, 10,000 TBE ≈ 500 US dollar). Below 100 kg N/ha, all estimations of achieved incomes are positive.

3.1.3. N2O emissions

As less N application is translated into less N2O emissions, a similar effect of effective N2O emissions (kg N2O-N/kg maize) related to total N application is shown in Figure 2d as in Figure 2a. Effective N2O emission becomes more varied when related to maize yields achieved. Achieving a yield of 7 tons/ha, N2O emissions vary between 0.2 to 0.6 N2O-N/tonne maize (Figure 2e). Interestingly, when using the most positive combination (hybrid maize seeds on an in-field location), effective N2O emissions remain almost similar between 5 to 8 tonnes/ha (Figure 2e). A similar effect is observed for increased income associated with increased N application using hybrid seeds on in-fields. More in general, a certain income obtained from maize cultivation can be associated with a wide range of N2O emissions (Figure 2f).

3.1.4. Trade-offs and synergies

When considering N2O-emissions of maize cultivation on a hectare-basis (without including indirect land use changes and related loss of carbon stocks at lower yields), N application leads to more N2O emissions per ha, of which the size differs per nutrient management option and ecological condition (Figure 2g). To simultaneously stimulate economic development (farmers' income) and mitigate climate change, as little N2O should be emitted per TBE earned. Or, differently phrased, as much TBE should be earned for each N2O-N emitted per kg maize produced. When omitting the low N application rates (< 25 kg N/ha) as these can be deemed unsustainable on the long-run, an optimum seems to exist with most income generated with the least N2O emitted at around 170 kg N/ha using a hybrid maize variety on an in-field (Figure 2h). This would correspond with a farmers' income of 50,000 TBE/ha with around 0.2 N2O-N/tonne maize (Figure 2f).

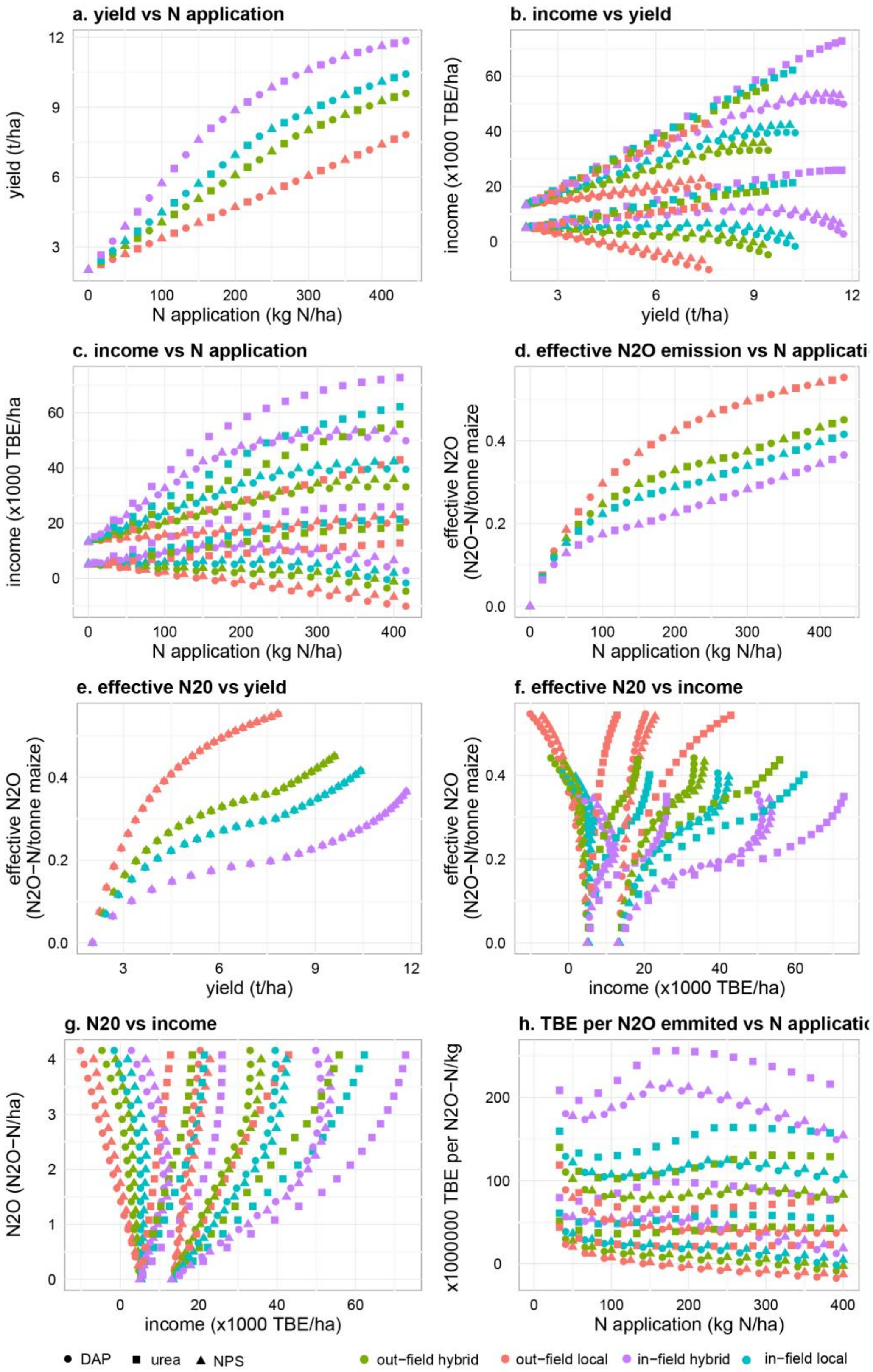

Figure 2: Overview of prototype model outcomes (with limited operation ability) for Ethiopia along a wide array of N application levels (o to 400 kg N/ha)

3.2. Comparing trade-offs at two levels of N application

When looking at a fixed N application level, do the nutrient management options which reduce N2O emissions also increase farmers' income? A first preliminary exploration is illustrated in Figure 3 on the use of hybrid maize seeds. The effects of using hybrid maize seeds is shown for maize yields, farmers' income and N2O emissions in different ecological conditions, at different market access and at two levels of N application. It can be seen from the figure that using hybrid maize seeds on in-fields not only increases yields, but also reduces effective N2O emissions and increases farmers' income. This should and could be explored further for other nutrient management options in more detail.

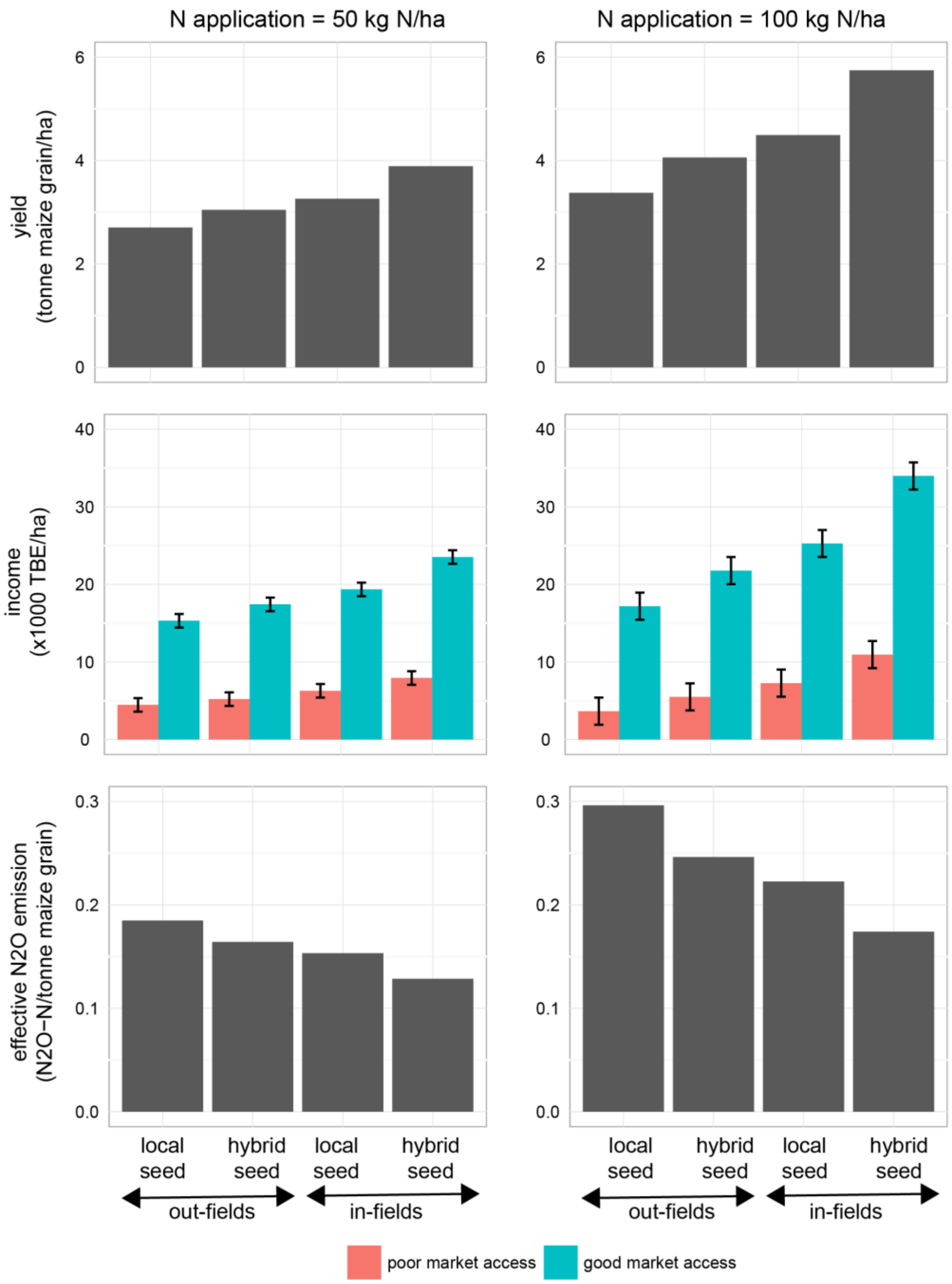

Figure 3: Overview of prototype model outcomes (with limited operation ability) for Ethiopia for two distinct levels of N application (N = 50 kg N/ha and N=100 kg N/ha)

4. Limitations of the running prototype

The current running prototype has a number of limitations, which will be shortly discussed here and which will be addressed in the coming months (Section 5).

Currently, N uptake is not yet limited by uptake of P, K or other nutrients (balanced nutrition is not yet set as a condition). Therefore, only urea can be used in the model to fulfil N demands, and costs to buy additional P and K (either in mineral or organic form) are not yet included. If balanced nutrients would be set as a condition for crop growth, model outcomes are expected to differ strongly depending on fertiliser type used, especially for the longer term. As an illustration, deficits or surplus of using either urea, NPS or DAP to fulfil N demands in the current prototype in shown if Figure 4.

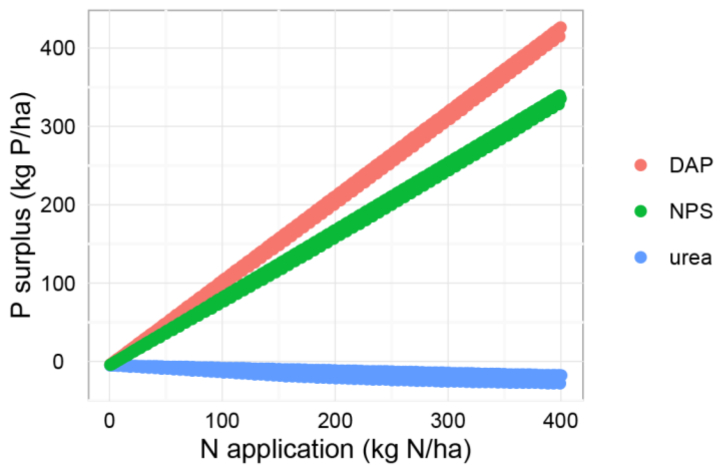

Figure 4: P deficit or surplus when using either urea, NPS or DAP to fulfil N demands of maize.

To test the running prototype, maize cultivation in Ethiopia was taken as a case-study using the average water limited potential yield (Yw) as a yield ceiling. In practice, potential yields vary strongly, depending on soil types and climates, but also on types of seeds use (local or hybrid). Different levels of Yw will affect the relation between N application, yields, farmers 'income and greenhouse gas emissions.

More in general, long-term effects of different nutrient management options are not yet included in the model. Long-term effects might relate to SOC built up or soil nutrient mining, but also to increased N2O emissions from residual N effects or soil acidification. Especially at lower N application levels, the current running prototype gives positive results for N2O emissions compared to maize yields, but most probably these maize yields cannot be achieved over the longer term without replenishing nutrients and thereby degrading soil fertility.

5. Further model expansion and applications

Starting from the running prototype, the model will be expanded to include a number of additional nutrient management options (*e.g.* alternative mineral fertilisers, liming, intercropping with legumes, use of organic inputs) and a dynamic element (assessment of short-term versus long-term effects through built up of SOC and mineralisation). Balanced nutrition will be included as a prerequisite for N uptake, or negative effects of unbalanced nutrition on maize yields will be incorporated.

In addition, the model will be linked to the Technological Extrapolation Domains (TEDs) developed within the crop nutrient gap project to enable spatial exploration (Table 1). Spatial variation relevant for the model can be differences in climates or soil types (linked to Yw or apparent N recovery) or access to markets (linked to input, labour prices or maize prices). Finally, a number of missing elements (such as GHG emissions from fertiliser production) will also be added.

Table 1: Planned expansion of the prototype trade-off model

Planned model addition	**Category**
Other fertiliser types (CAN, NPK)	Management
Use of organic inputs (compost, animal manure)	Management
Residue management	Management
Use of lime	Management, possibly linkage to soil maps
Use of N inhibitor	Management
Use of herbicides/pesticides	Management
Intercropping or rotation with legumes	Management
Use of micro-nutrients	Management, possibly linkage to soil maps
Improved utility of market access (now only included as maize price, also differentiation in input prices)	Market access, possibly spatial variation
P and K requirements	Management, yield limiting factors
Long –term dynamics (SOC sequestration, soil nutrient mineralisation, residual effects on N2O emissions)	Biophysical dynamics

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Appendices: Model formulation

A. Building blocks

The set-up of the model contains the following building blocks:

1. From N application to N uptake
2. From N uptake to yield
3. From yield to profit
4. From N application to N_2O emissions
5. From N application & yield to SOC change

B. General syntax

S *soil supply is net mineralisation (not uptake) (kg N/ha)*
A *Nutrient application rate (kg /ha)*
U *uptake by crop in total aboveground biomass*
R *N recovery from fertiliser (R1) or soil (R2)*
Y *grain yield*

C. From application to uptake

Potential yield

Symbol	Value	unit	meaning	comment	Reference
Y^W	variable	[kg /ha]	water limited yield	this will be the only yield ceiling until we start working with P or K limitation	GYGA

Amounts of nutrient inputs applied

Symbol	Value	unit			
A_{urea}	variable	[kg/ha]			
A_{DAP}	variable	[kg/ha]			
A_{NPS}	variable	[kg/ha]			

Nutrient contents of inputs

input	N [kg N/kg]	P [kg P/kg]	K [kg K/kg]	S [kg S/kg]	Ca (kg Ca/kg]	Reference
urea	0.46	0	0	0	0	Price 2006
DAP	0.18	0.20	0	0.01	0	Price 2006
NPS 19-38-7	0.19	0.17	0	0.07	0	Jemberie 2017

NFRV organic inputs

Symbol	Value	unit	meaning	comment	Reference
$NFRV_{animal\ manure}$		[kg N/ kg N]	N content in animal manure expressed as N in mineral fertiliser	Check if short-term or long-term	
$NFRV_{compost}$		[kg N/ kg N]	N content in compost expressed as N in mineral fertiliser	Check if short-term or long-term	
$NFRV_{straw}$		[kg N/ kg N]	N content in straw expressed as N in mineral fertiliser	Check if short-term or long-term	

Total nutrients applied.

N application.

Combining N application from mineral fertiliser and organic inputs into one variable

symbol	equation	unit	Meaning & comments
$A_{N,\ mineral}$	$A_{\mathrm{N,mineral}} = \sum_{input=i} A_{input} * N_{input}$	[kg N/ha]	N applied as mineral fertiliser
$A_{N,\ organic}$	$A_{\mathrm{N,organic}} = \sum_{input=i} A_{input} * N_{input} * NFRV$	[kg N/ha]	All N applied as organic input, expressed as mineral N application (Nitrogen Fertiliser Replacement Value)
A_N	$A_N = A_{N,\ mineral} + A_{N,\ organic}$	[kg N/ha]	

P and K application

symbol	equation	unit
A_P	$A_P = \sum_{input=i} A_{input} * P_{input}$	[kg P/ha]
A_K	$A_K = \sum_{input=i} A_{input} * K_{input}$	[kg K/ha]

Physiological parameters

symbol	Value	unit	Meaning & comments	Reference
γ (gamma)	0.624	[kg/kg] =[-]	relative yield Y/Y^W that marks the end of the linear uptake-yield domain. Coincides with the end of the constant physiological efficiency domain $\varepsilon = \varepsilon^M$	Janssen 1990
ε^M	52	[kg/kg N]	physiological efficiency (kg grain yield per kg N uptake in crop biomass) in linear domain, i.e. where constant	Janssen 1990
ε^A	31	[kg/kg N]	physiological efficiency (kg grain yield per kg N uptake in crop biomass) at saturation	Janssen 1990
ρ_{ini}	0.29	[kg N/kg N] =[-]	initial value of R_1 (apparent N recovery). Initial refers to the domain of constant recovery of mineral fertiliser N at low N availability; this ρ_{ini} is an average for SSA and can be adjusted for environment (E), given properties of fertiliser (F), or management-other-than-N-rate (M). When, expressed in kg yield/kg N it represents the agronomic N recovery	Vanlauwe 2010. Value for on-farm trials (19 kg add yield per kg N app).
$\varepsilon^{M,P}$	416	[kg/kg P]	physiological efficiency (kg grain yield per kg P uptake in crop biomass) in linear domain, i.e. where constant	
$\varepsilon^{M,K}$	78	[kg/kg K]	physiological efficiency (kg grain yield per kg K uptake in crop biomass) in linear domain, i.e. where constant	

Soil N supply

The control yield (without any N application) is based on soil N supply ($U_{N, soil}$). $U_{N, soil}$ is estimated using current yields in SSA per country and subtract the N uptake form fertiliser use.

Symbol	Value	unit	Meaning & comments	Reference
NAE_{ini}	19	[kg/kg N]	Initial agronomic N use efficiency. Initial refers to the linear domain of the yield response curve to N	Vanlauwe 2010
$Y_{current}$	variable	[kg/ha]		GYGA, others where applicable
$A_{N, current}$	variable	[kg N/ha]]		FAOSTAT, others where applicable

Symbol	equation	unit	Meaning & comments
$U_{N,\ soil\ short}$	$U_{N,soil} = \frac{Y_{current} - NAE_{ini} * A_{N,current}}{\varepsilon M}$	[kg N/ha]	N uptake from soil (from mineralisation).

$U_{N,\ soil}$ changes between short-term and long-term, depending on the amounts of crop residues returned or organic inputs used. This additional N supply can be adjusted for by increasing the NFRV values of organic inputs (using a long-term instead of short-term value) or adding a parameter called $U_{N,\ soil\ long}$

Environmental and management effects on N recovery

symbol	Value	unit	Meaning	comment	Reference
E	Default=1	[-]	effect of environment on ρ_{ini}	Possibly related to TEDs	
F	Default=1	[-]	effect of fertiliser type on ρ_{ini}		
M	Default=1	[-]	effect of management (other than N rate) on ρ_{ini}		

Variables on environmental effects:

Environmental characteristic	Effect on ANR (ρ_{ini})	comment	Reference
In-field	1.63		Vanlauwe 2010
Out-field	0.89		Vanlauwe 2010

Variables on management effects:

Management practice	Effect on ANR (ρ_{ini})	comment	Reference
Use of hybrid maize variety	1.51		Vanlauwe 2010, Heisey and Mwangi 1996
Non-N effect class I or III organic inputs	0.87		Vanlauwe 2010. Not certain if these are P and K effects
Non-N effect manure or compost	1.52		Vanlauwe 2010. Not certain if these are P and K effects
deep placement (>5 cm) of mineral fertiliser	1.43		Xia et al 2017
split fertiliser application	1.32		Xia et al 2017

use of controlled release fertiliser	1.37		Xia et al 2017
use of nitrification inhibitor	1.24		Xia et al 2017
use of urease inhibitor	1.39		Xia et al 2017

N-agronomic use efficiency at low N rates for a given environment and management

symbol	**equation**	**unit**	**Meaning & comments**
ρ	$\rho = E * F * M * \rho_{ini}$	[kg N/kg N] =[-]	Constant N recovery at low N availability for a given environment, fertiliser type and management (other than N rate). It is uncertain if these can be considered additional

N uptake response curve

symbol	**equation**	**unit**	**Meaning & comments**
U_{crit}	$U_{crit} = \gamma * Y^W / \varepsilon^M$	[kg N/ha]	N uptake at end of linear domain
U_{max}	$U_{max} = Y^W / \varepsilon^A$	[kg N/ha]	N uptake at full saturation (end of curved domain)
A_{crit}	$A_{crit} = (U_{crit} - U_s) / \rho$	[kg N/ha]	N application rate at end of linear domain
A_{max}	$A_{max} = A_{crit} + \frac{2}{\rho_{ini}}(U_{max} - U_{crit})$	[kg N/ha]	N application rate at full saturation (at end of curved domain where Umax is reached)

Nutrient uptake

symbol	**equation**	**unit**	**Meaning & comments**
U	For $A \le A_{crit}$: $U = U_S + \rho * A$ For $A > A_{crit}$: $U = U_{crit} + \rho(A - A_{crit}) - \frac{\rho}{2(A_{max} - A_{crit})}(A - A_{crit})^2$	[kg N/ha]	N uptake by crop in total above biomass
U_f	$U_f = U - U_S$	[kg N/ha]	N uptake from fertiliser in year of application. Not needed in calculations, but useful for assessment of practices

R_1	$R_1 = (U - U_s) / A$	[kg N/kg N] =[-]	apparent fertiliser N recovery in crop biomass (not needed etc. as above)
	$U = U_s + U_f$	[kg N/ha]	To confirm
U_P	$U_P = Y / \varepsilon^{M,P}$	Kg P/ha	Required P uptake[1]
U_K	$U_K = Y / \varepsilon^{M,K}$	Kg K/ha	Required K uptake
A_P	$A_P = U_P$	Kg P/ha	Simple assumption. Could be made more elaborate
A_K	$A_K = U_P$	Kg K/ha	

D. From uptake to yield

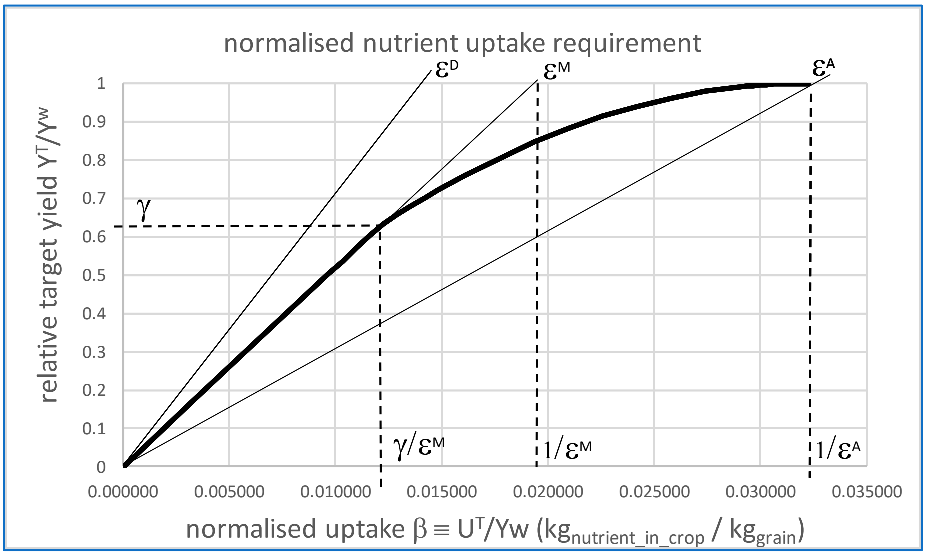

Figure 2: N uptake to yield in a normalised scheme

Normalised values for relation between N uptake and maize yield [2]

[1] This means we retain the balanced nutrition ratios adopted in WP1, but will deviate from those where N rate exceeds the critical N rate. At later stage, we may wish to deal with P or K limitation; this will be done by setting yield ceilings according to QUEFTS by multiplying available P or K with the phys efficiency parameters $\varepsilon^{D,K}$ and $\varepsilon^{D,K}$, respectively, denoting efficiency at 'maximum dilution'.

[2] Note Hein: I have kept here the scaled formulation for easy reference to WP1, although this introduces some redundancy: scaling and unscaling again

symbol	equation	unit	Meaning & comments
β_{crit}	$\beta_{crit} = \gamma / \varepsilon^M$	[kg N/kg]	Normalised N uptake at end of linear domain
Z	$Z = \frac{2(1-\gamma)\varepsilon^A}{\varepsilon^M - \gamma * \varepsilon^A}$	[(kg/kg N)]	
Q	$Q = \frac{\varepsilon^A(\varepsilon^M)^2}{2(\varepsilon^M - \gamma * \varepsilon^A)}$		

Maize yield

symbol	equation	Unit	Meaning & comments
β	$\beta = U / Y^W$		Normalised N uptake
β'	$\beta' = \beta - \beta_{crit}$		Meaning not very clear. Hein?
Y_{rel}	For $\beta \leq \beta_{crit}$: $\mathrm{Yrel} = \beta * \varepsilon M$ For $\beta > \beta_{crit}$: $Y_{rel} = \gamma + Z(\varepsilon^M * \beta' - Q * \beta'^2)$		Normalised yield (Y/ Y^W). The switch could have been A vs Acrit, instead of β vs β_{crit}, but the latter is more secure in case of extreme soil fertility
Y	$Y = Y^W * Y_{rel}$	[kg/ha]	yield

P and K requirements

symbol	equation	unit	Meaning & comments
U_P	$U_P = Y / \varepsilon^{M,P}$	Kg P/ha	Required P uptake[3]
U_K	$U_K = Y / \varepsilon^{M,K}$	Kg K/ha	Required K uptake
A_P	$A_P = U_P$	Kg P/ha	Simple assumption. Could be made more elaborate. Would need to take into account P and K from organic inputs also
A_K	$A_K = U_P$	Kg K/ha	

[3] This means we retain the balanced nutrition ratios adopted in WP1, but will deviate from those where N rate exceeds the critical N rate. At later stage, we may wish to deal with P or K limitation; this will be done by setting yield ceilings according to QUEFTS by multiplying available P or K with the phys efficiency parameters $\varepsilon^{D,K}$ and $\varepsilon^{D,K}$, respectively, denoting efficiency at 'maximum dilution'.

E. From yield to profit

Costs

Seeds

Amounts applied

Symbol	Value	unit	meaning	comment	Reference
$A_{local\ seed}$	25 kg/ha	[kg/ha]	Amounts of local maize seeds applied per ha		Marloes
$A_{hybrid\ seed}$	25 kg/ha	[kg/ha]	Amounts of hybrid maize seeds applied per ha		Marloes

Costs seeds

Symbol	Value	unit	meaning	comment	Reference
$C_{local\ seed}$	4	[ETB/kg]	Costs local seeds	Ethiopia	N2Africa country agronomist
$C_{hybrid\ seed}$	18.8	[ETB/kg]	Costs hybrid seeds	Ethiopia	N2Africa country agronomist

Total costs seeds

symbol	equation	unit	Meaning & comments
C_{seeds}	$C_{Seeds} = \sum_{seed=i} A_{seed} * C_{seed}$	ETB/ha	

Nutrients

For amounts of nutrients inputs applied, see sections 2.2 and 2.3

Costs nutrients per unit

Symbol	Value	Unit	meaning	comment	Reference
C_{urea}	11.5	[ETB/kg]		Ethiopia 2017	N2Africa country agronomist
C_{DAP}	14.5	[ETB/kg]		Ethiopia 2015	LSMS data
C_{NPS}	14	[ETB/kg]		Ethiopia 2017	N2Africa country agronomist

Total costs of nutrients

symbol	equation	unit	Meaning & comments
$C_{nutrients}$	$C_{nutrients} = \sum_{nutrient=i} A_{nutrient} * C_{nutrient}$	ETB/ha	

Labour

Labour requirements

Symbol	Value	Unit	meaning	com ment	Reference
$L_{land\ preparation}$	12	[days/ha]			N2Africa country agronomist
L_{sowing}	4	[days/ha]			N2Africa country agronomist
$L_{fertiliser\ application}$	6	[days/ha]			N2Africa country agronomist
$L_{weeding}$	12	[days/ha]			N2Africa country agronomist
$L_{pesticide\ application}$		[days/ha]			
$L_{harvesting}$	9*(Y/1000)	[days/ha]			(Ojiem et al., 2014)

Labour costs per day

Symbol	Value	Unit	meaning	comment	Reference
C_{day}	35	[ETB/day]			N2Africa country agronomist

Total labour costs

symbol	equation	unit	Meaning & comments
C_{labour}	$C_{labour} = \sum_{seed=i} L_{activity} * C_{day}$	ETB/ha	

Pesticides

Symbol	Value	Unit	meaning	comment	Reference
Pesticide					

Revenue

Price maize

Symbol	Value	unit	meaning	comment	Reference
P_{maize}	7.56	[ETB/kg]	Farm gate – good access	Ethiopia 2015	LSMS data
P_{maize}	3.55	[ETB/kg]	Farm gate – poor access	Ethiopia 2015	LSMS data

Revenue per hectare

symbol	equation	Unit	Meaning & comments
R	$R = P_{maize} * Y$	[ETB/ha]	

Income

symbol	equation	Unit	Meaning & comments
I	$I = R - C_{seeds} - C_{nutrients} - C_{labour}$	[ETB/ha]	

F. From N application to N_2O emissions

Set values for fixed parameters

symbol	Value	unit	meaning	comment	Reference
τ_{ini}	0.01	[N2O-N/N applied]			IPCC

Environmental and management effects on N_2O emissions

Some variables type of fertiliser used (F):

Type of fertiliser	Effect on N2O emission	comment	Reference
use of AN (ammonium nitrate)	2.1 (*τ)		Albanito et al 2017
use of urea with N inhibitor	0.7 (*τ)		Albanito et al 2017
use of other N fertilisers	1.1 (*τ)		Albanito et al 2017

Some variables on management effects (M):

Management practice	Effect on N2O emission	comment	Reference
use of controlled release fertiliser	0.75 (*τ)		Xia et al 2017
use of nitrification inhibitor	0.61 (*τ)		Xia et al 2017
use of urease inhibitor	0.63 (*τ)		Xia et al 2017

symbol	equation	Unit	Meaning & comments
N2O	$N2O = F * M * \tau_{ini} * A_N$	[N2O-N/ha]	

G. From N application & yield to SOC change

To be added in further model development

Partners involved in the Crop Nutrient Gap Project

- Wageningen University and Research
- International Fertilizer Association
- University of Nebraska Lincoln
- Yara
- CIMMYT