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Short Communication

CCAFS-MOT - A tool for farmers, extension services and policy-advisors to identify mitigation options for agriculture

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ABSTRACT

CCAFS-MOT is a tool to support farmers, policy advisors and agricultural extension services on the choice of management practices that reduce greenhouse gas emissions (GHG) without risking food security. It is an Excel-based tool which brings together several empirical models to estimate GHG emissions in rice, cropland and livestock systems, and provides information about the most effective mitigation options. Greenhouse gas emissions are estimated in terms of carbon dioxide equivalent per hectare (kg CO_2eq ha^{-1}) and carbon dioxide equivalent per unit of product (kg CO_2eq kg^{-1}). Baseline management practices are chosen by the user and a set of mitigation options are ranked according to their mitigation potential. The tool allows different levels of input to be specified from an introductory to detailed level, depending on objectives and issues like to accommodate users with different backgrounds and details concerning input data. As such it allows for product and region specific assessments of GHGs and mitigation potentials to be made without the need for expert knowledge or for lengthy model set-up and calibration.

1. Introduction

Limiting climate change will require substantial and sustained reductions of greenhouse gas (GHG) emissions (IPCC, 2013). Tackling the adaptive and mitigation challenges associated to climate change requires close consideration of the rural land use sector because this sector has the unique capacity of delivering zero and negative carbon emissions since it can act as a sink and reservoir for carbon (C) (Feliciano et al., 2013). Effective mitigation in agriculture and hence global climate change mitigation requires identification of GHG sources or hotspots in agricultural production systems (Adewale et al., 2016).

Several methods exist to estimate GHG emissions and carbon sequestration in the agricultural and forestry sector. The IPCC classifies methods available for agricultural GHG emission quantifications as Tier 1 when it uses default emission factors, Tier 2 which are hybrid approaches using process or empirical models to develop region-specific empirical equations with emission factors and Tier 3 which may include process-based models or direct measurement. In parallel to IPCC guidelines, many software tools have been developed recently to assess GHG emissions from agriculture and forestry practices, also at the smaller scale (Colomb et al., 2013; Hillier et al., 2012; Whittaker et al., 2013). Greenhouse gas emission calculators have been developed following different approaches, with different target and objectives, and for different geographic coverage (Colomb et al., 2013). Some examples of GHG accounting tools are the Cool Farm Tool[1], EX-ACT[2], USAID FCC[3], Holos[4] or ClimAgri®[5]. The main aim of a GHG accounting tools is to act as a user friendly interface to bridge input data with GHG emission calculations (Whittaker et al., 2013). According to Aylott et al. (2011), GHG accounting tools have been increasingly used for decision making and it is important they are suitable for that purpose. They should create awareness about the problem and stimulate learning between stakeholders (Schut et al., 2015).

The Climate Change, Agriculture and Food Security (CCAFS) research programme of the CGIAR supports the development of user-friendly science based decision-making tools that support policy advisers to design policies that maximise GHG emission mitigation in agriculture. To fulfil this objective, an advice-oriented tool that estimates GHG emissions and provides information on mitigation

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[1] http://www.coolfarmtool.org/ (Accessed 21/09/2016)
[2] http://www.fao.org/tc/exact/ex-act-home/en/ (Accessed 21/09/2016)
[3] http://www.afolucarbon.org/ (Accessed 21/09/2016)
[4] http://www.agr.gc.ca/eng/science-and-innovation/science-publications-and-resources/holos/?id=1349181297838 (Accessed 21/09/2016)
[5] http://www.ademe.fr/expertises/produire-autrement/production-agricole/passer-a-laction/dossier/levaluation-environnementale-agriculture/loutil-climagri (Accessed 21/09/2016)

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options according to a baseline management practices has been built. This tool has been named CCAFS-MOT (i.e. CCAFS-Mitigation Option Tool). The CCAFS-MOT differs from other tools in that it estimates GHG emissions for a given baseline of management practices and it ranks the most effective mitigation options to reduce GHG emissions.

This article describes the characteristics of CCAFS-MOT as well as the methods used in the tool to estimate GHG emission from agricultural sources and the methods used to quantify the effect of mitigation practices and their potential. It also illustrates the use of the model and discusses model validation.

2. Methods used in the model

The development of recommendations for various mitigation options requires several types of information. According to Kulshreshtha et al. (2000) these include:

1) The development of emission estimates from agricultural production for the base period;
2) The identification of mitigation strategies that can be implemented and which would lead to reductions in agricultural induced GHG emissions; and
3) A comparative analysis of the effectiveness of each strategy and/or measures in reducing emissions of GHGs from the agriculture.

The CCAFS-MOT tool takes into account regional and local contexts (e.g. land management, climate, geography and technology) as these affect GHG emissions and decision makers need to be aware of these specificities in the design of effective policies. The country is the input that provides regional sensitivity to CCAFS-MOT. It is required in the General Input section of CCAFS-MOT and it is the proxy used to allocate a world region factor to several GHG emission estimates. For example, the emission factors used to estimate GHG emissions from livestock are associated to 29 different world regions (see Herrero et al., 2013). The carbon emission factors for land use change are associated to ecological zones which in turn are associated to climate and continent. Finally, the yield default values are provided by FAOSTAT[6] on a country basis, and the impact of mitigation options on yield take is estimated according to the default values when real input data is not available. Therefore, each country inserted in the General Input section of the CCAFS-MOT is allocated to one world region, namely Latin America and Caribbean, Eastern and South-eastern Asia, Eastern and Western Europe, Middle East and North Africa, North America, Oceania, Russia and Sub-Saharan Africa.

The CCAFS-MOT groups several models to estimate the overall GHG emissions in different agricultural production systems as a function of management practice, and suggests mitigation options to reduce GHG emissions. Given the intended user group, the model does not include emissions from machinery or other primary energy use since this information is not generally available to policy makers, and it also does not include emissions from the usage of crop protection chemicals such as herbicides or pesticides. Greenhouse gas emissions from the production of synthetic fertiliser are, however, considered as this is a significant source of emissions globally which is directly driven by the use of the fertiliser in agriculture.

Greenhouse gas emissions from the production of synthetic fertiliser are, however, considered as this is a significant source of emissions globally which is directly driven by the use of the fertiliser in agriculture. The main production systems considered in this tool are upland crops (including upland rice), flooded rice and livestock systems (including grassland). Thirty one upland crops, grassland (including grass and cover mix), and 8 non-specified upland crops (e.g. tree crops, other grain, other N-fixing forage) were considered in this tool (see Supplementary material no 1). The main source of emissions from upland agricultural systems is nitrous oxide (N_2O) due to synthetic and organic nitrogen (N) application or residue incorporation (e.g. straw).

Flooded rice systems are substantial sources of both CH_4 and N_2O (Linquist et al., 2012) and are subdivided into several categories in the tool. Firstly rice systems can be divided into upland and lowland. Upland rice grows on dry soil in a similar way to most cereal crops whereas lowland rice is generally flooded for a significant period of time and can be divided into 1) irrigated; 2) rainfed; and 3) deep water rice systems. Irrigated systems can be 1) continuously flooded and 2) intermittently flooded with intermittently flooded rice including single and multiple drainage types. Continuously flooded fields have standing water throughout the rice growing season and may only be dried in preparation for harvest and seeding (pre-water regime). In rainfed rice systems, the water regime only depends on rainfall, and rainfed systems can thus be subdivided into 1) wet rainfed rice systems (flood prone) and 2) dry rainfed rice systems (drought prone). In wet rainfed systems, the water level may rise up to 50 cm during the cropping season whereas in dry rainfed systems drought periods occur during every cropping season. Deep-water rice is subdivided into 1) fields inundated with water depths between 50 and 100 cm and 2) fields with water depths > 100 cm. In rice production, water management influences the production of CH_4 and N_2O emissions by changing water content and consequently soil aerobic and anaerobic conditions (Jiao et al., 2006). Methane is produced in anaerobic conditions by methanogens (Takai, 1970; Conrad and Rothfuss, 1991). Therefore, upland rice systems are not a source of CH_4 emissions, since rice is grown in aerated soils. Nitrous oxide is formed primarily from nitrification and denitrification in soil, depending on the aerobic and anaerobic conditions of soil (Mosier et al., 1998). Water management is one of the most important agricultural activities that directly affect N_2O emissions in rice production (Liu et al., 2010). Nitrous oxide emissions were found negligible in continuously flooded rice paddies, while midseason drainage and dry-wet occurrences can trigger substantial N_2O emissions (Zou et al., 2005).

The tool also provides the users information about GHG emissions from livestock production (enteric fermentation and manure management) for different livestock animals (diary, non-dairy, pigs and poultry) and grassland. The main sources and types of GHGs from livestock systems are enteric fermentation (emit CH_4) and manure management (emit CH_4, N_2O). In addition, greenhouse gas emissions from feed production are also provided. The source of this data is Herrero et al. (2013). This tool also considers land use change, and consequent carbon dioxide (CO_2) emissions caused by the replacement of forests by agricultural production systems.

Regarding the impact of mitigation practices on CH_4 and N_2O emissions and soil organic carbon (SOC), the preferred mitigation potentials and emission factors were those published meta-analyses or quantitative reviews. If these were not available published field study analyses were used. For agroforestry a quantitative review was undertaken because the data required was not available. There is an extensive catalogue of potential individual mitigation practices for upland crops, grassland and livestock systems, and these were grouped for convenience in soil and above-ground carbon sequestration practices, and mitigation practices to reduce or avoid GHG emissions (Supplementary material no 2). Soil carbon sequestration practices are based on the premise that most agricultural soils have not reached their carbon saturation point and so are potential sinks.

Since the target users are non-experts, this tool was built to be user-friendly, and not time consuming, with low input data requirements and with scope limited to the production stage and land use management.

2.1. Models to estimate GHG emissions

2.1.1. Carbon dioxide emissions from land use change (deforestation of native vegetation)

Carbon dioxide (CO_2), CH_4, N_2O emissions resulting from the

[6] Food and agriculture data (http://www.fao.org/faostat/en/#home)

conversion of one hectare of forest into arable land or grassland, and grassland into arable, were estimated by multiplying the above-ground biomass in forests ton·dm·ha^{-1}) from Table 4.7, Volume 4, Chapter 4 (Forest Land) by the emission factors of CO_2, CH_4, N_2O in g kg^{-1} dry matter burnt for tropical and extra tropical forests from Table 2.5, Volume 4, Chapter 2 (Cropland) of the 2006 IPCC guidelines (IPCC, 2006).

The conversion of forests into cropland and grassland also leads to losses of SOC (soil organic carbon) due to soil disturbance and increasing decomposition (Freibauer et al., 2004; Six et al., 2002). The base factors of Ogle et al. (2005) were used to estimate annual changes in SOC due to a change in land use from forests (native systems) to long term cultivation (land cultivated for at least 20 years) or set-aside which were assumed to be similar to grassland (Supplementary material no 3).

2.1.2. Nitrous oxide (N2O) emissions from synthetic fertiliser application in cropland

The application of synthetic and organic fertiliser (e.g. manure, compost and residues) in agricultural fields (cropland, grassland, rice) increases nitrous oxide (N_2O), nitric oxide (NO) and ammonia (NH_3) emissions due to nitrification and denitrification processes that occur in the soil (IPCC, 2006). For nitrous oxide (N_2O), nitric oxide (NO) emissions related to synthetic and organic fertiliser application, the multivariate empirical model Stehfest and Bouwman (2006) was used:

$$log(N2O - N) = A + \sum_{i=1}^{n} E_i + E_f \times N_{applied} \quad (1)$$

where N_2O-N is the amount of N_2O and NO expressed in kg ha^{-1} of N over the time period covered by the measurements, A is a constant and E_i is the effect value for factors i (SOC, soil pH, soil texture, climate, crop type and length of experiment). Ef is the factor for N fertiliser input (0.0038 for N_2O and 0.0061 for NO). NO-N is converted to N2O-N using the indirect emission factor of 0.01 from IPCC, 2006) This simple Tier 3 model acknowledges that emissions vary as a function of the variables described above while only requiring broad characteristics of those variables (e.g. soil or climate classes) as inputs. It provides some refinement over Tier 1 methods but has the potential to reach a wider user base than process-based or measurement methods. To estimate nitrogen loss due to ammonia (NH_3) volatilization, the Bouwman et al. (2002) model was used:

$$ln(NH_3\ volatilisation\ factor) = \sum_{i=1}^{n} E_i \quad (2)$$

$$NH_3 = N_{applied} \times NH_3 volatilisation\ factor$$

Ammonia (NH_3) volatilization is expressed as N in kg ha^{-1}, and E_i is the effect value for factor i. The controlling factors for NH_3 volatilization from agriculture fields were crop type, fertiliser type, application mode, soil pH, soil CEC and climate NO and NH_3 emissions are then converted to N_2O by the factor 0.01 as given in IPCC (2006). Leaching is assumed to occur at a rate of 0.3 × N applied for moist climate zones with conversion to N_2O using the IPCC conversion factor of 0.0075 from IPCC, 2006 is also employed). The factors for N_2O, NO and NH_3 emissions are presented in Supplementary material (Supplementary material no 4).

2.1.3. Carbon dioxide (CO_2) emissions from synthetic fertiliser production

The production of synthetic nitrogen (N) fertiliser incurs on significant GHG emissions, mainly as CO_2 from the use of fossil fuels in the production of ammonia and N_2O emissions during the production of nitric acid. Several factors will impact on the GHG emissions from fertiliser production, namely the type of fertiliser, the technology and feedstock used and the presence or absence of N_2O abatement technologies (Brentrup et al., 2004). There has been considerable reduction over time in GHG emissions from fertiliser production, with current best available technologies close to the theoretical minimum emissions. This has resulted in regional differences in fertiliser production emission factors. The tool has average "world" emission factors as well as distinct emission factors for China and Europe. Emission factors for fertiliser production in China were collected from Zhang et al. (2013). Emission factors for fertiliser production in Europe were collected from Ecofys (2015). World average emission factors for fertiliser production were obtained from the International Fertiliser Industry Association (IFA, 2009). World data from IFA were complemented with information about the energy used to extract the raw material as well as emissions associated with the transport of raw materials to the processing plant. The estimates of GHG emissions were thus include GHG emissions from all relevant activities occurring during fertiliser production. The Fertilisers Europe Carbon Footprint Calculator for Fertiliser Products Specification (Version 1.0.1, 06 Feb 2014) was used to estimate GHG emissions from fertiliser production in Europe and in the World. Transport of fertilisers from the factory to the farm is excluded from the tool. Greenhouse gas emissions from the production and distribution of a range of fertiliser types GHG emissions are presented in Supplementary material (Supplementary material no 5).

2.1.4. Greenhouse gas emissions from burning cropland residues

Open field burning of crop and rice residues is a practice used by land users to clean agricultural land after crop harvest and this contributes to GHG emissions (IPCC, 2006; Johnson et al., 2007). The emission factors for CH_4 and N_2O emissions from burning of agricultural residues were taken from the IPCC (2006) (Supplementary material no 6). The amount of residues (in tonnes) burnt on site can be inserted manually by the user otherwise the tool assumes 50% of the residue is burnt. The straw from crop residues is estimated with the equations provided by the 2006 IPCC guidelines (Table 11.2, Volume 4, Chapter 11):

$$AG_{DM\,(T)} = \left(\frac{crop_{(T)}}{1000}\right) * slope_{(T)} + intercept_{(T)} \quad (3)$$

where $AG_{DM\ (T)}$ is the above-ground residue dry matter for crop (T) in Mg/ha and

$$crop_{(T)} = yield\,fresh_{(T)} \bullet DRY$$

The default factors slope (T), intercept (T) and DRY are from IPCC, 2006 (Supplementary material no 7).

2.1.5. Methane (CH_4) emissions from flooded rice fields

Rice fields are a major source of methane emissions (CH_4) during the flooded season, and an important source of nitrous oxide emissions (N_2O) during the non-flooded season (Yu et al., 2004; Jiao et al., 2006). Methane is produced in anaerobic conditions by methanogens (Takai, 1970; Conrad and Rothfuss, 1991). Nitrous oxide is formed primarily from nitrification and denitrification in soil, depending on the aerobic and anaerobic conditions of soil (Mosier et al., 1998). According to the IPCC (2007), about 30% and 11% of global agricultural CH_4 and N_2O emissions were from rice fields, respectively. The empirical equation provided by Yan et al. (2005) was used to estimate CH_4 emissions from rice production. Yan et al. (2005) developed a linear mixed model and showed that the controlling variables for CH_4 emission from wetland rice ecosystems were soil properties, water regime in the rice-growing season and in the previous season, organic amendments and climate. The Tier 1 IPCC default factors for the CH_4 emissions were also estimated with Yan et al. (2005) model (Eq. (4)). The values for these factors are presented in the Supplementary material no 8.

$$\ln(flux) = constant + a \times \ln(SOC) + pH_m + PWi + WTj + CL_k + OM_l \times \ln(1 + AOM_l) \quad (4)$$

where:

flux is the average CH_4 flux during rice growing season (mg CH_4 m^{-2} h^{-1})[++], *SOC* is the soil organic carbon content (%), pH_m is the effect of soil pH, *PWi* is the effect of preseason water status, *WTj* is the effect of water regime in growing season, CL_k is the effect of climate, OM_l is the effect of added organic material, and AOM_l the amount of organic amendment in (t ha^{-1}).

2.1.6. Nitrous oxide (N_2O) emissions from rice fields

Nitrous oxide emissions from upland fields and from wetland rice fields (continuously flooded) are estimated with Stehfest and Bouwman (2006) equations using the factor for cereals in the case of upland rice (Supplementary material no 4). Nitrous oxide emissions due organic fertiliser inputs (manure, straw, compost) in irrigated fields which are intermittently flooded with single and multiple-drainage were estimated using with Eqs. (5) and (6), respectively. This equation was derived by Zou et al. (2005) who statistically analysed 71 N_2O emission measurements from 17 field studies during the rice growing season.

$$y = 0.0042N \text{ (single drainage)} \tag{5}$$

$$y = 0.073N + 0.79 \text{ (multiple drainage)} \tag{6}$$

where *N* is the amount of N applied.

2.1.7. GHG emissions from burning rice straw

The amount of CH_4 and N_2O emissions from burning of rice straw was estimated by multiplying the amount of dry-matter of residues burnt (tonnes dry matter per hectare) by the emission factors (grams of CH_4, N_2O per kilogram of dry matter burnt) for agricultural residues (Supplementary material no 7). Once more, CO_2 emissions from burnt straw are not estimated as it is considered the next crop rotation will sequestered these emissions. The amount of straw (in tonnes) burnt on site can be inserted manually by the user otherwise the tool assumes 50% of the residue is burnt. The straw from rice is obtained with Eq. (7), provided by Yan et al. (2009):

$$Rice\ Straw = 3.43 \times Rice\ Yield + 1.36 \tag{7}$$

2.1.8. Greenhouse gas emissions from livestock and grassland

Livestock production is an important source of GHG emissions worldwide (Gerber et al., 2013). The tool evaluates methane (CH_4) emissions from enteric fermentation and manure management and nitrous oxide emissions (N_2O) from manure management and from feed production. Methane and N_2O emission factors were provided by Herrero et al. (2013). These authors present a spatially disaggregated global livestock dataset containing information on GHG emissions for 4 animal types (cattle, small ruminants, pigs, and poultry), 8 production systems and 28 regions. Emission factors for CH_4 emissions from enteric fermentation and manure management, and N_2O from manure management, are multiplied by the body weight (BW) of the animal chosen by the user to obtain kg CO_2eq per animal per year) (Supplementary material no 8). Nitrous oxide emissions from feed production (in g CO_2-eq/kg DM product) in the EU27, Africa and Latin America were taken from Mogensen et al. (2013). The feed composition (% of barley, corn, pulses, rice, sorghum, soybeans, wheat, other cereals, other root crops and other crops per head) was provided by Herrero et al. (2013). Greenhouse gas emissions from grassland management were estimated with the models used to estimate GHG emissions in cropland management.

[++] To obtain the flux of methane per hectare and per day the figure was multiplied by 24h and by 10,000m^2.

2.2. Mitigation options and potentials

2.2.1. Optimum N application in upland crops

In some regions, farmers apply fertiliser in excess. According to Moran et al. (2011), a reduction across the board in the rate at which fertiliser is applied could reduce the amount of N in the system and the associated N_2O emissions. For example, if fertiliser is applied twice instead of three times a year, a reduction in N_2O emissions could be achieved (Moran et al., 2011). Because optimum fertiliser, i.e. optimum N, application can vary from region to region, we are not able to determine the optimum N for each region. Therefore, we adapted the nitrogen use efficiency (NUE) method from Bentrup et al. (2004), which considers the optimal synthetic N application rate for a specific crop. The method was adapted to consider also the contribution of manure application to the N input. The NUE, expressed in percentage (%) is the ratio between the amount of N removed with the crop when this is harvested and the amount of N input through synthetic and organic fertiliser (Eqs. (8), (9) and (10)):

$$NUE\ (\%) = \frac{KgN\ removed\ with\ harvest}{Kg\ of\ N\ input} \times 100 \tag{8}$$

Based on NUE values from Bentrup et al. (2004) experiment on fertiliser application in winter wheat (Supplementary material no 9), it was assumed that optimum N would be that corresponding to a NUE of 85%.

$$Optium\ N\ input\ (kg\ N/ha) = \frac{Kg\ of\ N\ removed\ with\ harvest}{NUE\,(85\%)} \tag{9}$$

where kg N removed with harvest is estimated as follow:

$$Kg\ N\ removal\ with\ harvest\ (kg) = \\ = Crop\ yield\ \left(\frac{kg}{ha}\right) \times crop\ moisture\ content\ (\%) \times average\ N\ content\,(kg) \tag{10}$$

Crop yield is inserted by the user and average N content per crop was set as a default in the tool. Crop yield values were provided by Jate (2014) (Supplementary material no 10). If the calculation from the tool indicates that soil mining is occurring, i.e., inputs of N from synthetic fertilisers, and organic amendments such as compost, straw, and manure are not enough to meet the N requirements of the crop for the yield, the tool estimates GHG emissions from soil in a factor of 8 kg CO_2 emissions per kg of N needed to meet crop requirements.

2.2.2. Tillage practices in upland crops

Tillage regimes can be classified as conventional tillage, reduced tillage and no-till (IPCC, 2006). In conventional tillage there is substantial soil disturbance (e.g. full inversion and/or frequent tillage operations). Reduced tillage consists of shallow cultivation or ploughing, reduced number of tillage operations, lower depth of harrowing but no ploughing, use of the chisel coulter drill or zone tillage (van Kessel et al., 2013). No-till is the direct seeding without primary tillage. No-tillage and reduced tillage have been promoted in agroecosystems to sequester additional soil C (van Kessel et al., 2013). To estimate the potential soil C sequestration in crops and grassland we used Ogle et al. (2005) tillage factors for different climate zones to estimate annual SOC storage due to changing from conventional tillage to reduced or no-till management (Supplementary material no 11).

2.2.3. Incorporation of organic fertiliser (manure, compost, residues) to upland crops

According to Lal (1997) there is the potential for C sequestration during the conversion of residues incorporated in the soil into humus fraction. Smith et al. (1997) demonstrated that the addition of animal manure contributes to the increase in soil carbon stocks. To estimate SOC sequestration potential of manure, residue and compost incorpora-

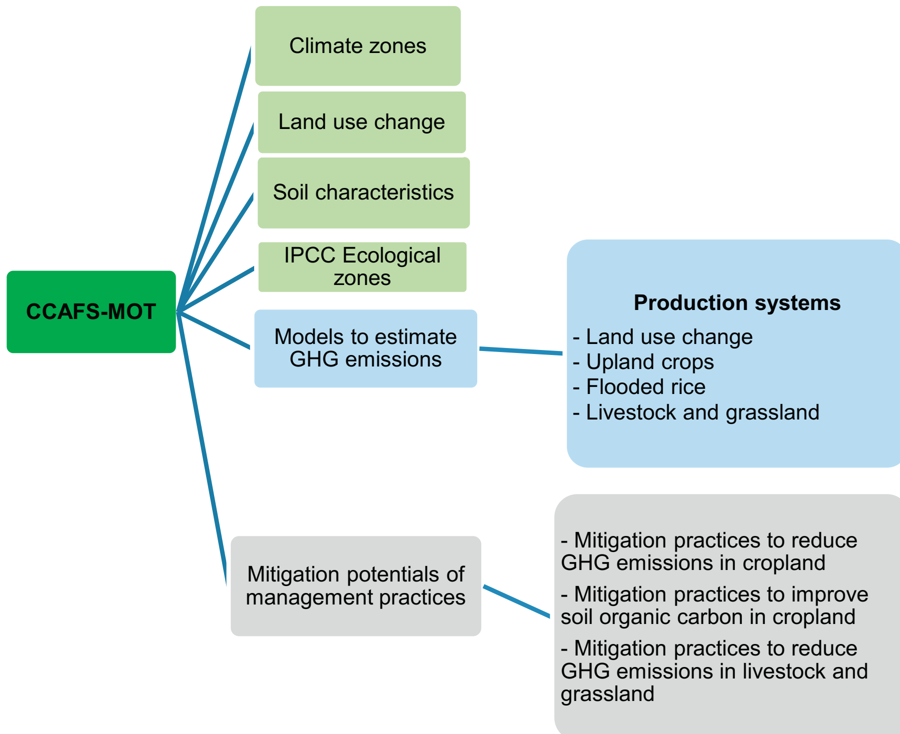

Fig. 1. Structure of the CCAFS-MOT.

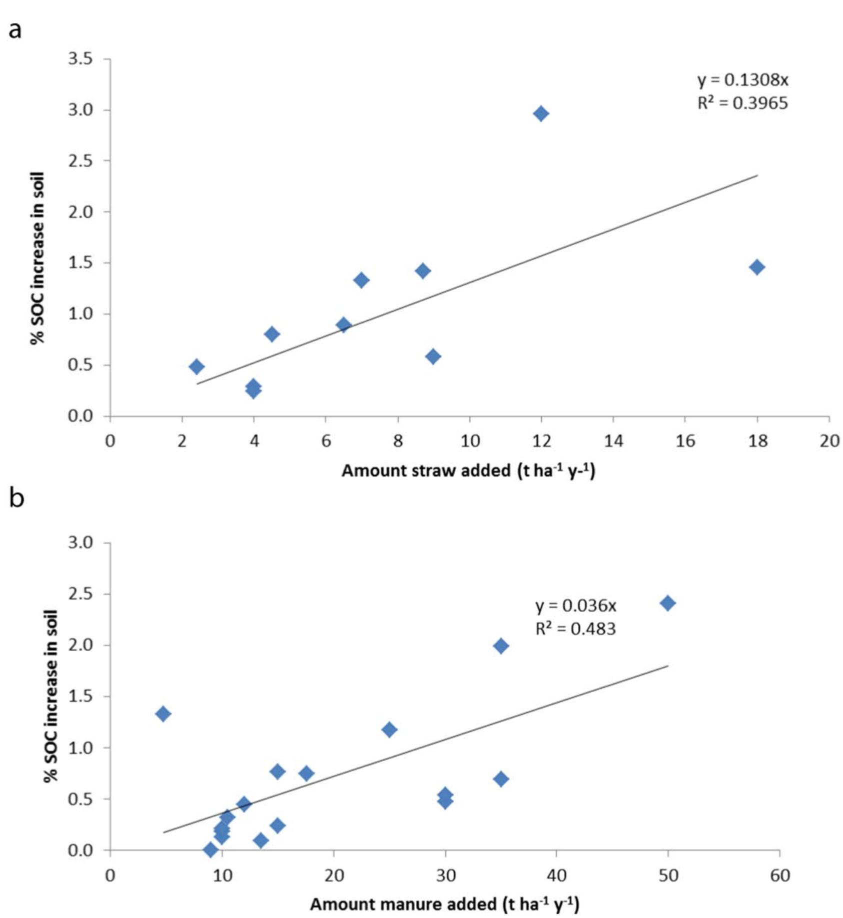

Fig. 2. a. Percentage of soil organic carbon (SOC) increase due to an addition of straw.b. Percentage of soil organic carbon (SOC) increase due to an addition of manure.

tion in soil, equations were derived from the data presented by Smith et al. (1997) on SOC changes between incorporation and non-incorporation of straw and manure on soils. The factors are, therefore, 0.1308 for residue and 0.036 for manure and compost (Fig. 2a and b). As a baseline option, the user inserts the amount or straw and/or manure inserted and the %SOC increase 0.1308% per each tonne of straw inserted by the user (Fig. 1a) and 0.036% per each tonne of manure inserted by the user (Fig. 1b). If no crop residues or manure were inserted in the baseline management, the tool suggests the incorporation of 50% of the residues produced by the crop and an incorporation of 10,000 kg (10 t) of manure as potential mitigation options. The amount of residue produced by the crop is calculated with using Eq. (3).

As the incorporation of residues increases the source of mineralisable N and consequently N_2O emissions, these were considered in the calculation of the overall mitigation potential of this management practice. Shan and Yan (2013) factors were used to estimate the increase in total N_2O emissions due to residue incorporation in upland crops: +23.5% N_2O emissions (factor used = 1.235). Stehfest and Bouwman (2006) equations were used to estimate N_2O emissions due to addition of manure and compost considering an incorporation rate of 10 t which is the same amount used for SOC estimates above.

2.2.4. Cover crops in upland crops

According to (Olson et al., 2014), the use of cover crops in intensive row crop rotations with different tillage treatments has been found to sequester SOC. Examples of cover crops are hairy vetch (*Vicia villosa* Roth), cereal rye (*Secale cereale L.*), crimson clover (*Trifolium incarnatum* L.), subterranean clover (*Trifolium subterraneum* L.), squarrosum clover (*Trifolium squarrosum* L.) or brown mustard (*Brassica juncea* L.). Ogle et al. (2005) found out that enhancing residue production by planting cover crops increases SOC storage relative to medium input rotations. Ogle et al. (2005) was used to estimate annual SOC change from low input (no incorporation of residues, no cover crops, no organic amendments) to medium input (30% and 60% residue incorporation), to high input (100% residue incorporation, cover crops), to high input with amendments (100% residue incorporation, cover crops, organic manure/compost incorporation) (Supplementary material no 12).

2.2.5. Application of nitrification inhibitors and polymer-coated fertilisers in upland crops and grassland

Agricultural fields are an important anthropogenic source of atmospheric nitrous oxide (N_2O) and nitric oxide (NO). Enhanced-efficiency fertilisers such as those with nitrification inhibitors (NIs), polymer-coatings (PCFs), and urease inhibitors (UIs) have been developed to increase the efficiency of fertiliser use by crops. Nitrification inhibitors are compounds that delay bacterial oxidation of NH_4 by depressing the activities of nitrifiers in soil, whereas UIs are compounds that delay the hydrolysis of urea. Slow-release fertilisers (e.g. PCFs) slow the rate of nutrient release through coating or chemical modification of the fertilisers. In CCAFS-MOT these effect are incorporated using Akiyama et al. (2010) - a meta-analysis of experimental field data (113 data points from 35 studies) which concluded that nitrification inhibitors significantly reduced N_2O and NO emissions in uplands and grassland, but that there was no significant difference between UIs, PCFs and conventional fertilisers (Supplementary material no 13).

2.2.6. Best fertiliser production technology

It is considered that best production technology (in terms of GHG per unit fertiliser production) currently exists in Europe. China and other world regions therefore have the potential to reduce emissions from fertiliser production to Europe levels (Fertilisers Europe, 2014). The difference between European figures and those outside Europe (Supplementary material no 5) were used to estimate the mitigation factor for fertiliser production when outside Europe.

2.2.7. Mitigation practices to reduce or avoid GHG emissions in flooded rice

Yagi et al. (1997) grouped mitigation practices to reduce CH_4 emissions in rice systems in four broad categories, namely 1) water management; 2) organic matter management 3) soil amendments and synthetic fertilisers 4) others (e.g. tillage). These mitigation measures were included in this tool to consider both impacts in CH_4 emissions and N_2O emissions.

Water management influences the production of CH_4 and N_2O emissions by changing water content and consequently soil aerobic and anaerobic conditions (Jiao et al., 2006). The mitigation potentials of different water regimes (Supplementary material 14) were taken from Nayak et al. (2015) who compiled a database for CH_4 emissions (267 data points) and N_2O emissions (204 data points) from rice production China. These authors classify irrigated water regimes in rice production in continuous flooding (F), mid-season aeration with single drainage (IS) and intermittent irrigation with multiple-drainage (IM). Intermittent irrigation has been further classified as IM-F, when the field is kept waterlogged after drainage, and IM-M, when the field is kept moist after drainage.

Organic matter such as livestock manure, compost, green manure (fresh biomass) or straw from previous crop, applied in rice cultivation decomposes in soils and acts as a substrate of fermentation reactions, significantly increasing CH_4 emissions in rice paddy soils (Feng et al., 2013; Yan et al., 2005; Yagi et al., 1997). It has been reported that combining the addition of organic matter with water management practices such intermittent irrigated with single drainage (IS) or with multiple drainage (IM) instead of continuously flooded can reduce CH_4 emissions (Yan et al., 2005; Nayak et al., 2015). Nayak et al. (2015) found that implementing intermittent irrigation (IS or IM) with livestock manure decreased CH_4 emissions by 22%, on average, when compared to continuous flooding (CF) with livestock manure. However, this also may increase N_2O emissions since improved soil aeration may increase nitrogen loss as a result of stronger nitrification, and later denitrification when the soils are flooded again (Yu et al., 2004). The addition of organic matter to rice systems also increases soil organic carbon (SOC). The impact of different water regimes combined with the addition of organic matter on N_2O and CH_4 emissions and SOC are presented in Supplementary material no 15. The estimates of the mitigation potentials and emission factors are described below.

For intermittent irrigation systems with livestock manure is application, we conducted a detailed analysis of the meta-data used by Nayak et al. (2015) to identify differences in CH_4 emissions between single (IS) and multiple (IM) drainage systems (Supplementary material no 15). Corresponding N_2O emissions related to livestock manure application and water regime were estimated using Eqs. (5) and (6) and estimating the N input from the amount of livestock manure inserted by the user in the baseline management section. It should be noticed that implementing single drainage (IS) together with livestock manure and multiple drainage (IM) with livestock manure are only mitigation options in relation to continuously flooded (CF) practices.

The application of straw increases CH_4 emissions by 108% compared to no organic matter addition while it decreased soil N_2O emissions by 21% (Nayak et al., 2015). The potential of combining straw addition with non-continuously (intermittently irrigated, rainfed) than continuous flooded rice systems (CF) to reduce CH_4 emissions was estimated using the regression Eqs. (11) and (12) provided by Sanchis et al. (2012) to predict CH_4 emissions for a straw incorporation rate of 0 to 10 t/ha. The mitigation potential (0.452) was estimated by taken the average of the abated emissions due to non-continuously flooded water regimes per tonne of straw added.

$$EF_{continuously\ flooded} = 160.0 + 103.3\ \text{Straw} – 6.70\ \text{Straw}^2 \quad (11)$$

$$EF_{non-continuoulsy\ flooded} = 82.9 + 69.1\ \text{Straw} – 6.70\ \text{Straw}^2 \quad (12)$$

The analysis of the meta-data used by Nayak et al. (2015) provided the N_2O emissions from straw added to rice systems, depending on the water regime. Incorporating straw during the off-season drained period and improving organic matter management by promoting aerobic degradation through composting are also possible mitigation options for reducing CH_4 emissions in rice systems (Yagi et al., 1997). The effect of straw application off-season on CH_4 emissions was taken from Miura cited by Yagi et al. (1997). Regarding compost addition, the effect of adding this type of organic manner to rice systems was taken from Nayak et al. (2015) for continuous flooded (CF) in relation to no organic matter addition, and the same percentages from livestock were assumed for the other water regimes (IS and IM) in relation to continuous flooding (CF). Finally, SOC increase due to addition of organic matter inputs (straw, livestock manure) were provided by Nayak et al. (2015). It should be noticed that compost was assumed to have the same impact than livestock manure and that the impact on SOC was the same across all water regimes apart from off-season water regime where it was assumed the same impact as for upland crop systems.

Finally, the replacement of urea by ammonium sulphate and the application of enhanced-efficiency N fertilisers (e.g. nitrification and urease inhibitors) have different effects on CH_4 and N_2O emissions. The impact on CH_4 emissions by replacing urea by ammonium sulphate is represented by Eq. (13) taken from Linquist et al. (2012). According to these authors, the same mitigation option increases N_2O by 24% (Supplementary material no 16).

$$CH_4\text{emissions}(\%) = 3\text{E-}05\ x^2 – 0.0794x – 8.1401$$
$$R^2 = 0.79 \quad (13)$$

The utilisation of enhanced-efficiency nitrogen fertilisers decreases both CH_4 and N_2O emissions. No-tillage practices reduce CH_4 emissions by 17% (factor used = 0.83) and increase N_2O emissions by 48% (factor used = 1.48) when compared to conventional tillage (Nayak et al., 2015). The meta-data compiled by Nayak et al. (2015) also provided the impact of no-tillage practices on SOC, i.e., 0.59% per year until a maximum of 20 years since the practice is applied (factor used = 0.0059).

2.2.8. Mitigation practices for livestock and grassland

To select mitigation options for livestock systems Tables A1 to A5 from FAO report (Hristov et al., 2013) were used (Supplementary material no 17). These tables provide information on the potential of different practices to reduce CH_4, N_2O, NH_3 emissions, whether practices are recommended or not, and applicability of the mitigation practices in different regions. Only the recommended practices were used. These are related to enteric fermentation and manure management emission reduction practices, and consequently, methane (CH_4) and nitrous oxide (N_2O) emissions.

2.2.9. Agroforestry

A meta-analysis (Feliciano et al., unpublished) was used to estimate the sequestration effect of different agroforestry systems in different climate zones.

$$AGCS = AF + AF_{climate} + AF_{AF\ system} + AF_{time} \quad (14)$$

where $AGCS$ is aboveground carbon sequestration in t C ha^{-1} yr^{-1}, and $AF_{climate}$, AF_{system}, and AF_{time} are the factors for climate, type of agroforestry system implemented, and time of implementation of the agroforestry system, respectively. The factor classes and coefficients for $AGCS$ are presented in Table 1.

The equation created by this model to estimate soil carbon sequestration (SCS) is:

$$SCS = BF + BF_{LU\ before} + BF_{AF\ system} + BF_{time} \quad (15)$$

where SCS represents the soil carbon sequestration in t C ha^{-1} yr^{-1}, and $BF_{LU\text{-}before}$, BF_{AF_system} and BF_{time} the factors for land use type before the implementation of agroforestry, the type of agroforestry system implemented, and time of implementation of the agroforestry system, respectively. The factor classes and coefficients for SCS are presented in Table 2:

Table 1
Factor classes and coefficients for above ground carbon sequestration.

Factor/factor class	Coefficient
Constant	1.212
Climate	$AF_{climate}$
Semiarid	− 3.336
Other	0
Agroforestry type	AF_{AF_system}
Alley Cropping	− 3.495
Other	0
Time since transition (years)	AF_{time}
≤ 10	5.277
10–15	1.206
15–20	1.705
≥ 20	0

Table 2
Factor classes and coefficients for soil carbon sequestration.

Factor/Factor class	Estimate
Constant	− 8.252
Landuse_before	BF_{LU_before}
Cropland	8.464
Fallow	5.522
Other	0
Agroforestry type	BF_{AF_system}
Homegarden	5.768
Boundary planting	6.482
Silvopastoral	7.230
Others	0
Time since transition	BF_{time}
≤ 5	− 1.310
5–25	0.791
≥ 25	0

3. Results - model case study and evaluation

The CCAFS-MOT tool is freely available for download.[7] To obtain GHG emissions, advice on mitigation options and the impacts of mitigation options on crop yields, users insert values in corresponding worksheet cells.

The CCAFS-MOT essentially consists of a compilation of empirical models for the various sources of GHG emissions across a range of farm production systems. Since many of the underlying models are empirical and data driven the need for validation is not as great as for process or mechanistic models (they are fully informed by the available data and therefore do not need to be tested against it further than was done in the initial publications of those models. In such models, which apply across a range of agricultural systems and locations and include various interacting sources of GHG emission a comprehensive model validation requires testing across a wide range of systems and settings. However, according to Oreskes et al. (1994), verification and validation of numerical models of natural systems (e.g. soil, grassland, agroforests and livestock systems) is impossible because natural systems are not closed systems and the input parameters required are incompletely known. In addition, the scale of the model elements is usually small (results obtained by the CCAFS-MOT are presented in hectares), and the relation between these results and larger scale model parameters is always uncertain and generally unknown (Oreskes et al., 1994). In addition the observation and measurement of both independent and dependent variables require several inferences and assumptions. The main objective of the CCAFS-MOT is to enable farmers, extension

[7] https://ccafs.cgiar.org/mitigation-option-tool-agriculture (Accessed 21/09/16).

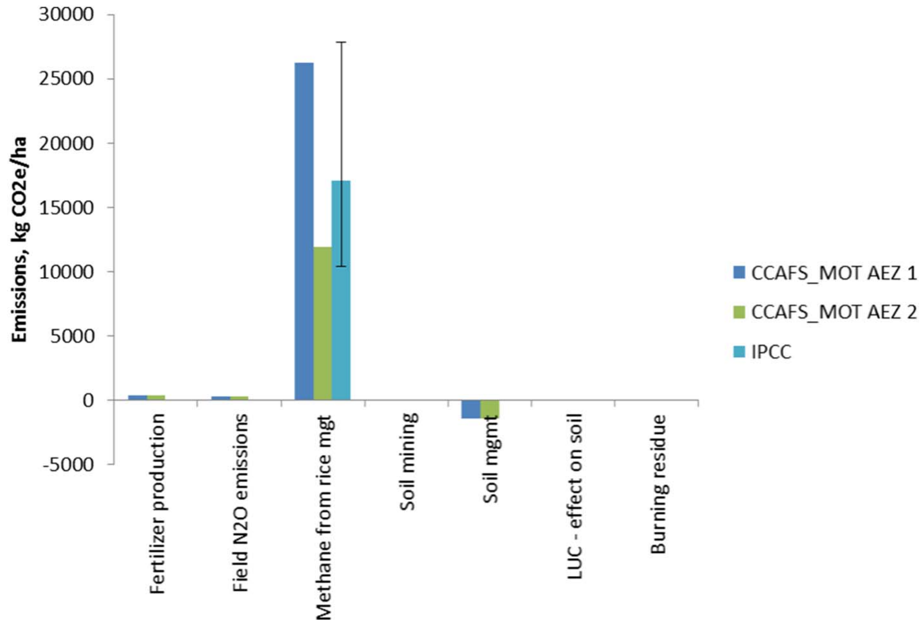

Fig. 3. GHG emissions profile for rice suggested by CCAFS-MOT for AEZ1 and AEZ2 scenarios.

services and policy-advisors to discover or learn about effective mitigation options in agricultural systems. We consider that the main value of models is heuristic, i. e., that models are illustrations, useful for guiding further study but not susceptible to proof (Oreskes et al., 1994).

Nevertheless, we present an example of a paddy rice production system in order to illustrate the inputs needed and the estimates obtained (GHG emissions and ranking of mitigation options) by the CCAFS-MOT. In this case, more than one model (Yan et al., 2005, Sanchis et al., 2012, and Nayak et al., 2015) have been combined to predict GHG emissions and the case study illustrates that the combination of the underlying models is sensible. The baseline is set up as follows on the *Rice* tab of CCAFS-MOT. The same management practices have been tested in two different climate zones – AEZ1 (Warm arid and semi-arid tropics) and AEZ2 (Warm sub-humid tropics) – to illustrate how the GHG emissions from rice are dependent on location with predicted emissions in AEZ approximately twice those in AEZ2 (Table 3).

Table 3
Input data for the rice section in the CCAFS-MOT.

Yield	3000 kg/ha
Crop duration	120 days
Water regime	Flooded
Pre-season water	Flooded
Organic fertiliser	5000 kg/ha (straw off-season, < 20 years)
Tillage	Conventional
N	119 kg/ha Urea
P	59.5 kg/ha TSP (triple super phosphate)
K	59.5 kg/ha MoP (Monoammonium phosphate)

Fig. 3 shows that in both cases the majority of emissions are from methane in the field. For comparison Fig. 3 also shows CH_4 emissions as predicted by the IPCC Tier 1 method. It can be seen that the predictions from CCAFS-MOT lie within the confidence interval given by the IPCC Tier 1 and illustrates the added granularity given by the Yan et al., 2005 model (used in CCAFS-MOT) over the disaggregated IPCC Tier 1 method.

Figs. 4 and 5 shows the mitigation options returned by CCAFS-MOT for the AEZ1 and AEZ2 scenarios. The potential of the multiple drainage option is highest. The value provided by CCAFS-MOT is consistent with that which is obtained by exploring the same scenario via the Yan et al. and IPCC Tier 1 methods (for the IPCC scenario we used the high and low confidence intervals from the above example respectively for AEZ1 and AEZ2. It is also noteworthy that the net effect of the increase in N_2O emissions is much smaller than the saving resulting from reductions in CH_4 emissions (Yan et al., 2009) (in fact the model predicts similar findings for residue incorporation from upland cropping systems where the net increase in N_2O emissions from increased mineralization is much smaller than the saving from soil sequestration). Other effective mitigation options concern the replacement of Urea with Ammonium Sulphate (AS) or the use of nitrification inhibitors. The NI option appears to have promise although since Linquist et al. (2012) and others have found a consistent reduction in CH_4 emissions when using NIs even though the mechanism is unclear. In addition Linquist et al. (2012) could find no significance relationship to the quantity of NI applied. This surprising finding does not negate the significance of the findings but does mean that further research would be need to better quantify the impact of NIs before the option is widely deployed. In this example there is no difference between the no-till and reduced till options since the models employed do not differentiate the practices. In other upland cropping systems where the dataset of Ogle et al. (2005) is used this would not be the case. Other options related to fertiliser technologies are relatively unimportant in the paddy rice example but have greater importance for other upland crops.

4. Discussion

This tool is essentially a simple systems model to predict the GHG emissions from farming and the effectiveness of a common suite of mitigation options. It estimates GHG emissions from the production of specific crops or livestock types. It also suggests the potential mitigation practices that could be implemented to reduce GHG emissions and the mitigation potential for reduction given a certain management baseline. The tool does not allow a full Life Cycle Analysis (LCA) but it does allow the estimation of GHG emissions from fertiliser production, according to its origin, because this is directly associated to the amount of fertiliser applied in cropland and rice and it is important for users to be aware of this source of emissions and about the variation in those emissions according to the region where the fertiliser is produced. This allows evaluation of policies to support and promote the implementation of cleaner technologies for fertiliser production.

In the calculation of GHG emissions the tool uses both IPCC (2006)

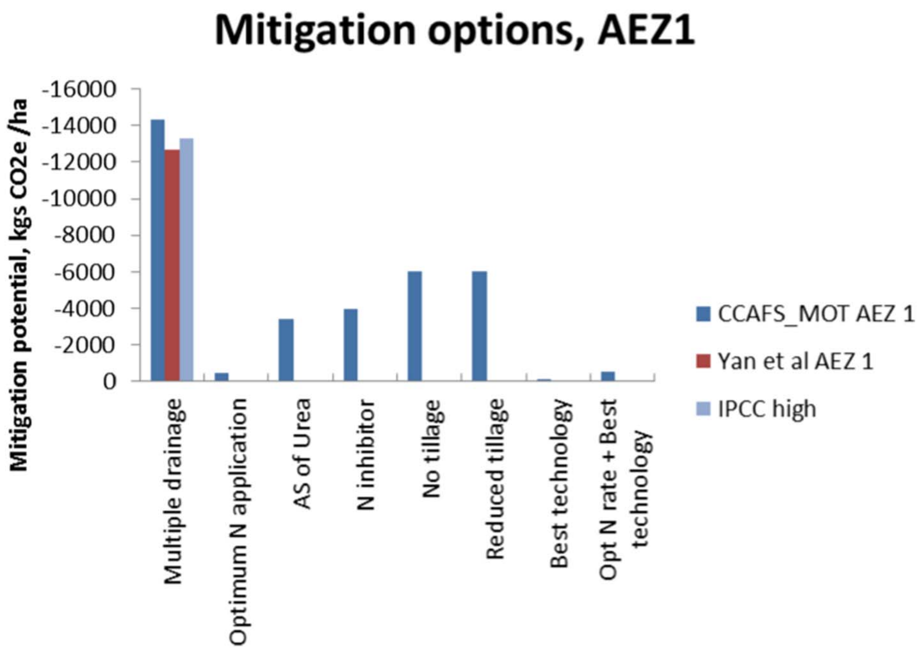

Fig. 4. Mitigation options for rice suggested by CCAFS-MOT for theAEZ1 scenario.

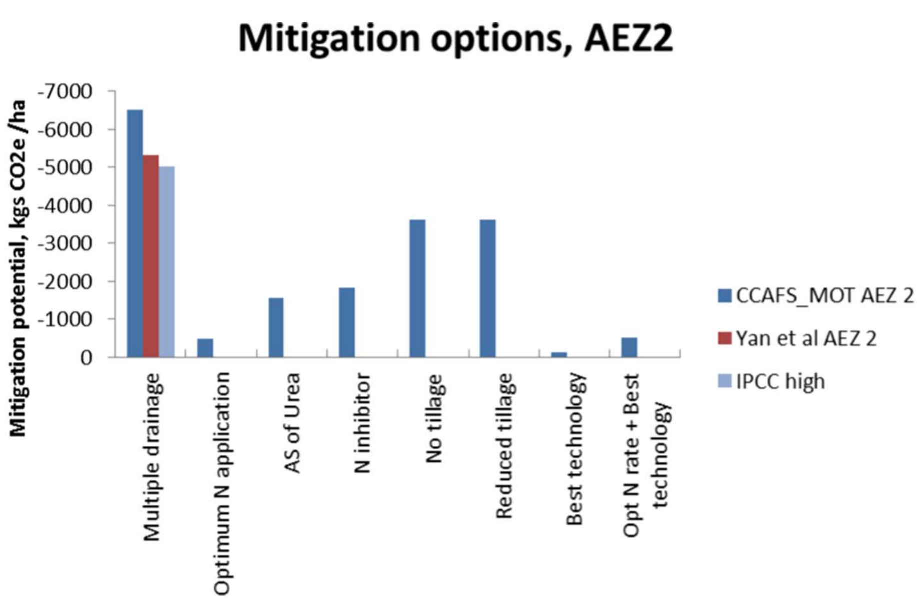

Fig. 5. Mitigation options for rice suggested by CCAFS-MOT for the AEZ2 scenario.

emission factors and factors from other published empirical models. For example, the tool uses the IPCC (2006) factors to estimate CO_2 emissions from urea and liming application and burning of residues in cropland, but uses Stehfest and Bouwman (2006) to estimate N_2O emissions from fertiliser, manure, compost and residue incorporation. It also uses a recently published GHG emissions database published by Herrero et al. (2013) to estimate GHG emissions from livestock production. The mitigation potentials of different management practices were mainly collected from published meta-analysis (e.g. Akiyama et al., 2010; Feng et al., 2013; Ogle et al., 2005) or from existing methods (e.g. Bentrup & Palliere method to estimate optimum N application). Although the IPCC (2006) methodology allows comparability of farm agricultural GHG emissions across countries and sectors, review undertaken of available empirical models identified several which we feel are more appropriate given their sensitivity to location and to management options for mitigation. Eventually these models and their application may inform later revisions of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Although the models used were based on existing or new extensive reviews, and designed to have a wide geographic range of applicability there remains the issue of geographic bias in the data underlying the models. In, for example, the model of Stehfest and Bouwman (2006) around 10% of the data is from tropical regions, and although there have been efforts to conduct further controlled studies in tropical regions in recent years the issue remains (see for example Albanito et al., 2017). The uncertainty in applying such models in data poor regions or circumstances will essentially always be greater than in data rich areas. In addition, for certain processes such as field N_2O emissions it should be recognised that uncertainty is always large when making field level predictions regardless of the model employed. Tools such as CCAFS-MOT should thus be used as decision support rather than as a precise and definitive predictor of GHG emissions and mitigation potential. Other potential sources of model uncertainty relate to potential propagation within the model due to interactions between driving variables. Sources of such error are limited in the CCAFS-MOT and we believe we have addressed the two most likely sources in the case studies above. In future revisions of the tool it would be possible to integrate a measure of uncertainty. Hardaker and Lien (2010) argue that is essential to present decision makers with uncertainty associated to the variables used to describe agricultural systems. Bezlepkina et al. (2011) also consider that sustainability assessment tools have to deal with uncertainty. Large uncertainty associated to mitigation practices could suggest areas for further research or utilisation of regional emission factors whenever they exist. Rosenstock et al. (2014) believes that the results from uncertainty analysis can be easily explained to decision makers however this view is not universally shared. Mastrandrea et al. (2010) provide guidance of how uncertainty should be communicated. One option to report uncertainty might be to replace the word ‘uncertainty’ by the word ‘risk’ (assessment) because it is believed policy-makers understand this concept better. The best method to transmit uncertainty to decision makers remains unclear and should be done in a way that is informed by the needs of decision makers. This information is being collected during the presentation of the CCAFS-MOT to a wide range of stakeholders via workshops and webinars, and will be used to inform the development of a subsequent version that will deal with uncertainty.

To increase usability, two options for inserting input in the CCAFS-MOT were developed. These options are ‘simplified’ and ‘detailed input’ and they apply to soil characteristics (soil texture, SOC, pH, bulk density) and management practices (fertiliser type, fertiliser amount, fertiliser composition in terms of N, P and K). For livestock systems, the only necessary input is body weight (BW) of the animal in kg with default values are suggested according to livestock type, production system and world region. The CCAFS-MOT only provides an estimate of the biophysical mitigation potentials of mitigation practices. As such it addresses one of the knowledge gaps essentially for informed decision making for mitigation, however it does not consider implementation barriers such as, for example, physical, biological, economic, social, political, institutional, educational, and market barriers (Feliciano et al., 2013). The barriers to the implementation of mitigation practices are highly site and context-specific, and practices that may act positively in one context may have adverse effects in another. According to Proctor et al. (2011), advisors to land managers, will take into consideration factors such as local geography and ecology, the social context and motivations of the land managers, as well as the technical capabilities and commercial objectives of the farm business. Ultimately, land managers (e.g. farmers, estate owners, foresters, land owners) are those who decide whether a mitigation practice will be implemented or not, and several variables influence their behaviour and consequent decision. In California, Jackson et al. (2012) found out that farmers are more likely to adopt mitigation practices that reduce energy inputs or increase efficiency than practices with high upfront costs such as anaerobic manure digesters. In Scotland, Feliciano et al. (2014) found that farmers were mainly willing to expand the uptake of mitigation practices they were already implementing because they consider these are the most cost-effective. According to Ajzen (1991), some key variables that influence decisions about the implementation of mitigation practices are behavioural beliefs and attitudes, normative beliefs and subjective norms, control beliefs and perceived behavioural control or behavioural intention and behaviour. These can act as barriers or opportunities for implementation.

The process of identifying barriers is essential to the design of effective policy mechanisms for driving change. The fact that reduction targets have been missed suggests that there are important barriers which need to be assessed – some can be social (e.g. peer pressure), some economic (e.g. capital costs), some environmental (e.g. climate change adaptation). The preferred approach of governments is to use persuasive approaches such as incentives rather than imposed measures (e.g. penalties). An example of a voluntary initiative is the “Farming for a Better Climate” implemented in Scotland, UK, which was created to promote the adoption of efficient measures that also reduce emissions, particularly those having an overall positive impact on business performance (SRUC, 2017). The CCAFS-MOT can be used in parallel with similar initiatives, as a platform to support by extension services to identify, together with farmers, the practices with the highest mitigation potential.

The CCAFS-MOT also has the role of facilitating informed management decisions in order to develop site specific mitigation plans as for example the Nationally Appropriate Mitigation Actions (NAMAs), which are set of policies and actions undertaken as part of the countries commitment to decrease GHG emissions. The assessment of Climate Smart Agricultural (CSA) practices could also benefit from the information provided by the CCAFS-MOT. Climate Smart Agricultural practices aim at supporting the society's potential to sustainably increase agricultural productivity, the resilience of food systems and the adaptive capacity of farmers to climate change, and the reduction of the impact of food, fuel and fiber production on the climate system (FAO, 2013). Currently the CCAFS-MOT can provide the information on the contribution of food production on GHG emissions and how to mitigate these, partly contributing to the assessment of CSA practices. Including information on the impact of the highly ranked mitigation practices on crop yields would be of additional value. In Africa, smallholder farmers depend on farm production for food and income and both are linked (Rosenstock et al., 2013). Finally, using the CCAFS-MOT as a platform to identify synergies between mitigation and adaptation would potentially support advisors to policy makers to design mechanisms to support both mitigation and adaptation and consequently, field advisors to help farmers taking advantage of these mechanisms. Tubiello and van der Velde (n.d) suggest that some adaptation activities, which increase resilience of systems and improve rural incomes, may be attractive to carbon markets because of their associated mitigation potential. Previous studies have identified potential synergies between mitigation and adaptation in coffee production systems while simultaneously improving farmers' incomes (Rahn et al., 2013; Matocha et al., 2012; Lin, 2011; Schroth et al., 2009). Rahn et al. (2013) defends that the generation of carbon credits for mitigation practices could, in parallel, generate funding for adaptation practices. Therefore, mitigation practices that would benefit crop yields and increase farmer's resilience would potentially be more accepted and widely implemented. This is in line with the objective of this CCAFS-MOT, which is to support advisors to policy makers and extension services to identify promising management options on specific crops, rice and livestock systems that reduce GHG emissions, without jeopardizing food security. Therefore, current development of the tool includes the analysis of the impact of mitigation practices on crop yields and integration of this information in the tool.

An evaluation of the climate smartness of practices has been already undertaken by the Mitigation of Climate Change in Agriculture (MICCA) in East African sites (Rosenstock et al., 2014). This evaluation could be expanded to other sites, with the support of the CCAFS-MOT since this remains flexible regarding the list of mitigation practices that can be added to it. The flexibility to include other mitigation practices and methods to estimate mitigation potentials is, therefore, an essential characteristic of this tool. Future work includes analysing the results of workshops and webinars with scientists and target users to decide on which regional practices need to be added and which mitigation potentials are available. This will be especially for the rice and livestock sections which are among the biggest contributors to GHG emissions within the agricultural sector. According to Bezlepkina et al. (2011), including stakeholders and qualitative knowledge in sustainability assessment in agriculture, improves the development of comprehensive and transparent scenarios that are useful for targeting strategies and policies, and that it builds up scientific and political credibility of assessment models.

5. Conclusion

Climate change is one of the major challenges facing the planet. In order to avoid dangerous climate change, countries need to take action to limit overall net GHG emissions and to enhance sinks of CO_2. There are international and national targets for GHG emissions, including in agriculture. There is an extensive catalogue of potential individual mitigation practices for the agricultural sector, and these are often grouped for convenience. The CCAFS-MOT estimates GHG emissions from several upland crops, rice and livestock systems in different geographic regions and it ranks the most effective mitigation options for these different crops according based on current management practices, climate and soil characteristics. The tool joins several empirical models to estimate GHG emissions and consider mitigation practices that are compatible with food production. The tool was built with the objective of providing policy-makers across the globe access to reliable information needed about how to reduce GHG emissions in the agricultural sector. This tool is different from other tools since it estimates mitigation options according to a baseline management practices, taking into account mitigation options that are already being implemented. This helps further understanding those systems which are already contributing to GHG emissions mitigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.03.006.

References

Adewale, C., Higgins, S., Granatstein, D., Stöckle, C.O., Carlson, B.R., Zaher, U.E., Carpenter-Boggs, L., 2016. Identifying hotspots in the carbon footprint of a small scale organic vegetable farm. Agric. Syst. 149, 112–121.

Akiyama, H., Yan, X., Yagi, K., 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis. Glob. Chang. Biol. 16, 1837–1846.

Albanito, F., Lebender, U., Cornulier, T., Sapkota, T.B., Brentrup, F., Stirling, C., Hillier, J., 2017. Direct Nitrous Oxide Emissions From Tropical And Sub-Tropical Agricultural Systems: A Review and Modelling of Emission Factors. Sci. Rep. 7, 44235.

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process. 50 (2), 179–211.

Aylott, M., Higson, A., Evans, G., Hamer, A., Mortimer, N., 2011. What is the most appropriate LCA method for measuring greenhouse gas emissions from bioenergy? Biofuels Bioprod. Biorefin. 5 (2), 122–124.

Bezlepkina, I., Reidsma, P., Sieber, S., Helming, K., 2011. Integrated assessment of sustainability of agricultural systems and land use: methods, tools and applications. Agric. Syst. 104 (2), 105–109.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Estimation of global NH3 volatilization loss from synthetic fertilisers and animal manure applied to arable lands and grasslands. Glob. Biogeochem. Cycles 16 (2), 8-1-8-14.

Colomb, V., Touchemoulin, O., Bockel, L., Chotte, J.L., Martin, S., Tinlot, M., Bernoux, M., 2013. Selection of appropriate calculators for landscape-scale greenhouse gas assessment for agriculture and forestry. Environ. Res. Lett. 8, 015029.

Brentrup, F., Küsters, J., Lammel, J., Barraclough, P., Kuhlmann, H., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems. Europ. J. Agron. 20, 265–279.

Conrad, R., Rothfuss, F., 1991. Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. Biol. Fertil. Soils 12, 28–32.

Ecofys, 2015. Fertilizers and Climate Change. Looking to 2050. Final. Ecofys 2015 by order of Fertilizer Europe.

FAO, 2013. Climate-Smart Agriculture Sourcebook. Food and Agriculture Organization of United Nations 2013. Available at http://www.fao.org/docrep/018/i3325e/i3325e.pdf (Accessed 21/09/2016).

Feliciano, D., Nayak, D., Smith, P., Wollenberg, E., Neufeldt, H., Hillier, J., 2017. Carbon Dioxide Sequestration Potential of Different Agroforestry Systems in Different World Regions - A Systematic Analysis.Carbon Dioxide Sequestration Potential of Different Agroforestry Systems in Different World Regions - A Systematic Analysis .

Feliciano, D., Hunter, C., Slee, B., Smith, P., 2013. Selecting land-based mitigation practices to reduce GHG emissions from the rural land use sector: a case study of North East Scotland. J. Environ. Manag. 120, 93–104.

Feliciano, D., Hunter, C., Slee, B., Smith, P., 2014. Climate change mitigation options in the rural land use sector: stakeholders' perspectives on barriers, enablers and the role of policy in North East Scotland. Environ. Sci. Pol. 44, 26–38.

Feng, J.F., Chena, C., Zhanga, Y., Songb, Z., Dengb, A., Zhengb, C., Zhang, W., 2013. Impacts of cropping practice on yield-scale greenhouse gas emission from rice fields in China: a meta-analysis. Agric. Water Manage. 164, 220–228.

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling Climate Change Through Livestock – A Global Assessment of Emissions and Mitigation Opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Hardaker, J.B., Lien, G., 2010. Stochastic efficiency analysis with risk aversion bounds: a comment. Aust. J. Agric. Resour. Econ. 54 (3), 379–383.

Herrero, M., et al., 2013. Biomass use, production, feed efficiencies and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. U. S. A. 110 (52), 20888–20893.

Hillier, J., Brentrup, F., Wattenbach, M., Walter, C., Garcia-Suarez, T., Mila-i-Canals, L., Smith, P., 2012. Which cropland greenhouse gas mitigation options give the greatest benefits in different world regions? Climate and soil-specific predictions from integrated empirical models. Glob. Chang. Biol. 18 (6), 1880–1894.

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013. Mitigation of greenhouse gas emissions in livestock production – a review of technical options for non-CO2 emissions. In: Gerber, Pierre J., Henderson, Benjamin, Makkar, Harinder P.S. (Eds.), FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy.

IFA, 2009. Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainably. In: International Fertilizer Industry Association, First edition. IFA, Paris, France (July 2009).

IPCC, 2006. 2006 IPCC guidelines for national greenhouse gas inventories, prepared by the national greenhouse gas inventories programme. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Institute for Global Environmental Strategies, Tokyo, Japan, Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (Accessed 21/09/2016).

IPCC, 2007. Climate Change 2007: Synthesis Report. In: Writing Team, Core, Pachauri, R.K, Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland 104 pp.

IPCC, 2013. Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson, L.E., Haden, V.R., Hollander, A.D., Lee, H., Lubell, M., Mehta, V.K., O'Geen, A.T., Niles, M., Perlman, J., Purkey, D., Salas, W., Sumner, D., Tomuta, M., Dempsey, M., Whee-ler, S.M., 2012. Adaptation strategies for agricultural sustainability in Yolo County, California. 2012, Report to the California Climate Change Center. Available at http://www.energy.ca.gov/2012publications/CEC-500-2012-032/CEC-500-2012-032.pdf (Accessed 21/09/2016).

Jate, M., 2014. Review of Nutrient Removal Data of Crop Yield. (Unpublished Document) Research Centre Hanninghof, Yara International, Hanninghof, Duelmen, Germany.

Jiao, Z., Hou, A., Shi, Y., Huang, G., Wang, Y., Chen, X., 2006. Water management influencing methane and nitrous oxide emissions from rice field in relation to soil redox and microbial community. Commun. Soil Sci. Plant Anal. 37, 1889–1903.

Johnson, J.M., Franzluebbers, A.J., Weyers, S.L., Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150 (1), 107–124.

Kulshreshtha, S.N., Junkins, B., Desjardins, R., 2000. Prioritizing greenhouse gas emission mitigation measures for agriculture. Agric. Syst. 66 (3), 145–166.

Lal, R., 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effects by CO2 enrichment. Soil Tillage Res. 43, 81–107.

Lin, B., 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61 (3), 183–193.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K.J., 2012. Fertiliser management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crop Res. 135, 10–21.

Liu, S., Qin, Y., Zou, J., Liu, Q., 2010. Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice-winter wheat rotation system in southeast China. Sci. Total Environ. 408 (4), 906–913.

Matocha, J., Schroth, G., Hills, T., Hole, D., 2012. Integrating climate change adaptation and mitigation through agroforestry and ecosystem conservation. In: Nair, P., Garrity, D. (Eds.), Agroforestry—The Future of Global Land Use. Springer, Berlin, pp. 105–126.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., Zwiers, F.W.,

2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Available at http://www.ipcc.ch (Accessed 21/09/2016).
Mogensen, L., Lesschen, J.P., Klumpp, K., Hutchings, N., Stienezen, M., Eory, V., Lecomte, P., Olesen, J., 2013. Compiled database on LCA (Life Cycle Assessment) coefficients for including pre-chain emissions in LCA of animal products. In: Deliverable 10.2. Animal Change Project. Theme 2: Food, Agriculture and Fisheries, and Biotechnologies. Seventh Framework Programme, Available at http://www.animalchange.eu/Content/deliverables.html (Accessed 21/09/2016).
Moran, D., MacLeod, M., Wall, E., Eory, V., McVittie, A., Barnes, A., Rees, B., Pajot, G., Matthews, R., Smith, P., Moxey, A., 2011. Developing carbon budgets for UK agriculture, land-use, land-use change and forestry out to 2022. Climate Change 105, 529–553.
Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., Minami, K., 1998. Assessing and mitigating N2O emissions from agricultural soils. Clim. Chang. 40, 7–38.
Nayak, D., Saetnan, E., Cheng, K., Wang, W., Koslowski, F., Cheng, Y.-F., Zhu, W.Y., Wang, J.-K., Liu, J.-X., Moran, D., Yan, X., Cardenas, L., Newbold, J., Pan, G., Lu, Y., Smith, P., 2015. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. Sustainable intensification of China's agriculture: the key role of nutrient management and climate change mitigation and adaptation. Agric. Ecosyst. Environ. 209, 108–124.
Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72 (1), 87–121.
Olson, K., Ebelhar, S., Lang, J., 2014. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open J. Soil Sci. 4, 284–292. Available at http://www.scirp.org/journal/PaperInformation.aspx?paperID=48993 (Accessed 21/09/2016).
Oreskes, N., Shrader-Frechette, K., Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the earth sciences. Science 263 (5147), 641–646. Available at http://science.sciencemag.org/content/263/5147/641 (Accessed 24/02/2017).
Proctor, A., Phillipson, J., Lowe, P., Donaldson, A., 2011. Field advisors as agents of knowledge exchange. A Rural Economy and Land Use project investigating the field expertise of specialist advisors and their role as knowledge brokers between scientific research and land management. In: Policy and Practice Notes. Note No. 30. July 2011.
Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., Van Rikxoort, H., Shriver, J., 2013. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitig. Adapt. Strateg. Glob. Chang. 19 (8), 1119–1137.
Rosenstock, T.S., Mpanda, M., Kimaro, A., Luedeling, E., Kuyah, S., Anyekulu, E., Freeman, O.E., Thiong'o, M., Abwanda, S., Mutuo, P., Mativo, J., Shaba, S., Kirui, J., Franzel, S., Neufeldt, H., Shepherd, K., Neely, C., 2014. Science to Support Climate-smart Agricultural Development. Concepts and Results From the MICCA Pilot Projects in East Africa. 2014 Food and Agriculture Organization of the United Nations (FAO), Rome.
Rosenstock, T.S., Rufino, M.C., Butterbach-Bahl, K., Wollenberg, E., 2013. Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems. Environ. Res. Lett. 8, 021003.
Sanchis, E., Ferrer, M., Torres, A.G., Cambra-Lopez, M., Calvet, S., 2012. Effect of water and straw management practices on methane emissions from rice fields: a review through a meta-analysis. Environ. Eng. Sci. 12 (29), 1053–1062.
Schroth, G., Läderach, P., Dempewolf, J., Philpott, S., Haggar, J., Eakin, H., Castillejos, R., Garcia, M.J., Soto, P.L., Hernandez, R., Eitzinger, A., Ramirez-Villegas, J., 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. Mitig. Adapt. Strateg. Glob. Chang. 14, 605–625.
Schut, M., Klerkx, L., Rodenburg, J., Kayeke, J., Hinnou, L.C., Raboanarielina, C.M., Adegbola, P.Y., van Ast, A., Bastiaans, L., 2015. RAAIS: Rapid Appraisal of Agricultural Innovation Systems (Part I). A diagnostic tool for integrated analysis of complex problems and innovation capacity. Agric. Syst. 132, 1–11.
Shan, J., Yan, X., 2013. Effects of crop residue returning on nitrous oxide emissions in agricultural soils. Atmos. Environ. 71, 170–175.
Six, J., Feller, C., Denef, K., Ogle, S.M., Sa, J.C.M., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils - effects of no-tillage. Agronomie 22, 755–775.
Smith, P., Powlson, D., Glendining, M., Smith, J., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Glob. Chang. Biol. 3 (1), 67–79.
SRUC, 2017. Farming for a Better Climate. Online source: https://www.sruc.ac.uk/info/120175/farming_for_a_better_climate.
Stehfest, E., Bouwman, L., 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosyst. 74 (3), 207–228.
Takai, Y., 1970. The mechanism of methane fermentation in flooded paddy soil. Soil Sci. Plant Nutr. 16, 238–244.
Tubiello, F.N., and van der Velde, M. (n.d.) Land and water use options for climate change adaptation and mitigation in agriculture. SOLAW Background Thematic Report - TR04A. GET-Carbon, New York, USA.
van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N2O emissions in reduced tillage systems: a meta-analysis. Glob. Chang. Biol. 19 (1), 33–44.
Whittaker, C., McManus, M.C., Smith, P., 2013. A comparison of carbon accounting tools for arable crops in the United Kingdom. Environ. Model Softw. 46, 228–239.
Yagi, K., Tsuruta, H., Minami, K., 1997. Possible mitigation options from rice cultivation. Nutr. Cycl. Agroecosyst. 49, 213–220.
Yan, X., Akiyama, H., Yagi, K., Akimoto, H., 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Glob. Biogeochem. Cycles 23 (2) (n/a-n/a).
Yan, X., Yagi, K., Akiyama, H., Akimoto, H., 2005. Statistical analysis of the major variables controlling methane emission from rice fields. Glob. Chang. Biol. 11 (7), 1131–1141.
Yu, K., Chen, G., Patrick Jr, W.H., 2004. Reduction of global warming potential contribution from a rice field by irrigation, organic matter, and fertilizer management. Glob. Biogeochem. Cycles 18 GB3018.
Zhang, W., Dou, Z., He, P., Ju, X., Powlson, D., Chadwick, D., Norse, D., Lu, Y., Zhang, Y., Wu, L., Chen, X., Cassman, K.G., Zhang, F., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertiliser in China. Proc. Natl. Acad. Sci. 110 (21), 8375–8380.
Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Glob. Biogeochem. Cycles 19, GB2021.