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ORIGINAL ARTICLE

Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in Western Kenya

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Abstract Integrated soil fertility management (ISFM) is a concept that includes the management of organic matter in smallholder farming systems for sustainable intensification. To determine whether ISFM is also eco-efficient, we measured and simulated nitrogen (N)-dynamics and nitrous oxide (N_2O) emissions in an ISFM long-term maize trial in Western Kenya. The total annual N-balance averaged over 10.5 years was negative for all continuous maize treatments that received only inorganic N-fertilizer. The N-balance was zero or positive when maize was grown in rotation with the green manure cover crop, *Tephrosia candid*, and/or to which 4 Mg ha^{-1} season^{-1} farm yard manure (FYM) added. These results thus substantiate the importance of organic matter management in tropical ecosystems. They also underpin that mineral N-fertilizer application alone does not guarantee agro-ecosystem sustainability, which should be considered in fertilizer (subsidy) policies. Treatments that included Tephrosia and FYM application emitted the largest amounts of N_2O. Highest emissions (12.0 kg N_2O–N ha^{-1}) were simulated for the maize–Tephrosia rotation to which FYM and 30 kg ha^{-1} of mineral fertilizer N was added and 2 Mg ha^{-1} maize stovers retained. Such treatments had the highest N-emission intensity. The slope of the linear regression equation describing the N_2O emission–N-input relationship of all considered treatments (0.023) was twice as high as the IPCC-Tier-1 emission factor. Maize–Tephrosia treatments had the highest seasonal maize yields. These were, however, not high enough to compensate for the inclusion of Tephrosia into the system as compared to growing maize continuously, compromising adoption by smallholder farmers.

Keywords Eco-efficiency · Greenhouse gas emissions · IPCC Tier 1 · Long-term trials · CropSyst · Modeling · Sustainable intensification · ISFM

Introduction

Sustainable agricultural intensification is one of the major issues to meet the growing demand for food in the coming decades (Pretty et al. 2011; Vanlauwe et al. 2014a, b). This especially applies to sub-Saharan Africa (SSA) where agriculture directly sustains the livelihood of two-thirds of the population (IFDC 2006). Limitations in soil organic matter and other key nutrients hugely constrain agricultural productivity in many parts of Africa. The soil fertility of many

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African soils is inherently low, and cultivation without nutrient replenishment is the major driver of continued soil fertility degradation (Swift and Shepherd 2007).

Even though an increased use of chemical fertilizer seems the best way to feed Africa short-term (Nature 2012), soil scientists and agronomists tend to agree that mineral fertilizers alone will not solve the farmers' problems in the medium to long term. Sound management of soil health integrates the physical and biological fertility of the soil, which can only be achieved if soil organic matter levels can be maintained or increased. ISFM is a concept that acknowledges this principal. ISFM had been developed in the late 1990s, among others, by the Tropical Soil Biology and Fertility Institute of the International Center of Tropical Agriculture (CIAT) based in Nairobi. Besides addressing the management of organic matter, ISFM embraces social, cultural and economic processes regulating soil fertility management strategies (Bationo et al. 2012). ISFM may be considered as one of the best known, taught and tested agronomic practices in SSA. Numerous articles about ISFM have been published in journals and books throughout the last 15 years (see e.g. Bationo et al. 2007 for a comprehensive overview and Vanlauwe et al. 2014a, b for a more recent account). Besides addressing the sustainability of nutrient management, optimizing for agronomic resource use efficiency is the backbone of ISFM.

These are also two aspects of the paradigm of eco-efficiency. Besides, eco-efficiency embraces increasing productivity while decreasing negative impacts on natural resources (CIAT 2009). Similar to the World Commission on Environment and Development (WCED) delineation of the concept of sustainability (WCED 1987), approaches that merit the term *eco-efficient* must meet the economic, social, and environmental needs of the rural poor (Cassman and Daugherty 2012). Eco-efficiency seeks to strive toward solutions that are competitive, profitable, sustainable, and resilient in the face of a changing climate.

So, while ISFM focuses merely on efficiency as far as nutrient use is concerned, eco-efficiency also takes into account environmental pollution, such as through the release of greenhouse gases like methane, carbon dioxide (CO_2) and nitrous oxide (N_2O).

Agriculture is a major source of anthropogenic N_2O emissions into the atmosphere. Soils contribute about 75 % to these emissions (Scheehle and Kruger 2006). According to the Food and Agriculture Organization of the United Nations (FAO), in 2010 N_2O emissions contributed 19 % to the global total GHG emissions (expressed in CO_2 equivalents, CO_2e.) from agriculture *and* land use; the other contributors were carbon dioxide (57 %) and methane (24 %; FAOSTAT 2014). Globally, land use (change) was only a very minor emitter of N_2O emissions (3 %) while agriculture-based emissions contributed the bulk (97 %). Asia was by far the major contributor to the global N_2O emissions from agriculture and land use, with China alone contributing 468 Mt CO_2e, i.e. 20 % of the total. Africa ranked second, with SSA emitting 312 Mt CO_2e (13 % of the global total; Table 1). Hickman et al. (2011) projected that year-2000 level N_2O emissions of Africa could easily double by 2050 in response to intensification of agriculture.

However, the estimates of N_2O emissions from agriculture are subject to notable uncertainty (IPCC 2014), and as such are aforementioned figures and projections. In general, very few studies have been documented on N_2O emissions from agriculture in SSA—less than 15 in total according to Rosenstock et al 2013. To our knowledge N_2O emissions have never been systematically studied in ISFM trials. Thus, little is known about the environmental footprint of common smallholder agriculture in SSA, and even less about the impact of intensifying agriculture through ISFM, and whether ISFM qualifies as eco-efficient.

The unique circumstances of SSA—i.e. the large-scale and long-lasting depletion of nitrogen (N) in soils and agro-ecosystems in response to the absence of notable applications of mineral N fertilizer—make it very difficult to reliably estimate N_2O emissions by application of simple standard tools, such as by emission factors produced by IPCC (2006). Not surprisingly, these have been criticized for failing to properly represent the heterogeneity among local conditions, and repeated claims have been made to "increase the global coverage of direct and indirect N_2O flux measurements to encompass all major agricultural land-use types and climates, land-use changes and management practices" (Reay et al. 2012).

This study intended to shed more light on the issue. Therefore, we measured and simulated N-dynamics and N_2O fluxes in a CIAT ISFM long-term maize (*Zea mays*) trial in Western Kenya. The aim was, one the

Table 1 N_2O emissions from agriculture and land use by regions in 2010 (FAOSTAT 2014)

Region	N_2O emissions from land use and agriculture (Mt CO_2e)
Asia	1105
China	468
Africa	343
SSA	312
North Africa	30
South America	297
North America	281
Europe	233
Oceania	68
World	2325

one hand, to evaluate the various tested treatments for some indicators reflecting their eco-efficiency, taking advantage of the fact that only long-term trials are actually suited to provide a true insight into how intensification would affect emissions *long term*. On the other hand, the study aimed at laying the basis (i.e. model calibration and evaluation) for carrying out further model-based, *ex-ante* scenario analyses for fine-tuning and optimizing the in situ tested treatments and to develop best–best options for sustainable intensification rapidly and in comprehensive fashion.

Materials and methods

Study area

The study site is CIAT's long-term trial (INM3) located in Western Kenya near the village of Madeya, 50 km northwest of the city of Kisumu (0°8′38.30″N, 34°24′13.70″E, 1330 m.a.s.l.). The climate is subhumid, with a mean annual temperature of 22.5 °C and annual rainfall of between 1200 and 2206 mm (avg. 1727 mm; observation period 1997–2013) distributed over two rainy seasons: the long rainy season lasts from March until August and the short rainy season from September until January (Supplementary Figure 1).

Thus, two crops per year can be produced. Maize is the dominating crop in this region, followed by food legumes such as common beans or, more recently, soybean. The soil in the region has been classified as an Acric Ferralsol, with a clay content of between 55 % (topsoil) and 85 % (subsoil), low CEC and high aluminum saturation, a pH between 4.9 and 5.5, and a topsoil organic matter (SOM) content of about 34 g/kg. Major growth limiting nutrient are—in the order of importance—phosphate (P), nitrogen (N) and potassium (K; Kihara and Njoroge 2013).

Treatments

CIAT's INM3 long-term trial was implemented in 2004. The layout is a split–split–split plot design with four blocks/repetitions. The individual plot size is 4.5 m × 6 m. The aim of INM3 is to test the long-term performance of contrasting integrated soil fertility management practices, namely (1) application of farm yard manure (FYM; main plots), (2) maize (M) stover residue retention (sub-plots), and (3) various crop rotations, namely maize monocropping or intercropping with soybean (Soy) and maize planted in rotation with the perennial legume *Tephrosia candida* (T), as well as various levels of mineral N and P fertilizer application (sub–sub-plots).

In detail, FYM application comprised either an addition of 4 Mg ha^{-1} (FYM +) every season, or none (FYM−). Analogously, either 2 Mg ha^{-1} of maize stover were retained (R+), or all stovers were removed (R−) after harvest. Crop rotation was aliased with N and P mineral fertilizer application, and sub-plots split into:

(a) M–M:

   i. N0–P60
   ii. N30–P60
   iii. N60–P60
   iv. N90–P60

(b) T–M or M–T:

   i. T–M: N0–P60
   ii. T–M: N30–P60
   iii. M–T: N0–P60
   iv. M–T: N30–P60

(c) "Intercropping":

   i. Soy + M: NO–P60
   ii. Soy + M: NO–P60 (equal to i)
   iii. M–T (rotation!): N0–P0
   iv. T–M (rotation!): N0–P0

where the number following N and P indicates application of N and P-fertilizer in kg N or P per hectare per season. Throughout the 10 years of the trial, six different locally common hybrid maize cultivars were grown: starting with *HB513* in 2004 followed by *WS402, IR, WS502, WS403* the first 4 years and *DH4 for* the last 6 years.

M–T indicates the rotation treatment where maize was planted in the long-rain season and Tephrosia in the short-rain season, while T–M describes the opposite. The trial thus has 48 treatments.

This study did not consider any of the intercropping treatments, i.e. neither soybean intercropped with maize nor the M–T and T–M rotation without application of phosphate fertilizer, and thus these treatments are not further described.

Agronomic management

The plant spacing of maize and Tephrosia was 0.75 m × 0.25 m, with one plant per hill, whereas two (maize) or five (Tephrosia) seeds per hole were planted and then thinned. During the considered 10 years of the long-term trial—2004 to 2014—planting of maize and Tephrosia in the long-rain season took place between 29 March and 26 April, and between 8 September and 3 October in the short-rain season. Harvesting of the two crops was carried out between 15 August and 13 September and 4 February and 12 March in the long- and short-rain season, respectively.

All plots receive 60 kg ha^{-1} potassium chloride fertilizer per season. P (triple-super phosphate) and K fertilizer was applied at planting by broadcasting and then incorporated into soil by hand hoeing. N fertilizer (urea) was managed by split application, 1/3 at planting and 2/3 when maize reached knee height. At planting N-fertilizer was broadcasted together with the P and K fertilizer, while at topdressing stage it was banded.

The experiment was kept weed free by hand weeding at least twice a season. Maize stem borers were controlled by standard pesticides application (Beta-cyfluthrin) once early in the season.

Land preparation/tillage was done following common hand hoeing practice to maximum 30–35 cm depth, with soil disturbance and mixing diminishing with depth. FYM and chopped Tephrosia residues were left in the field, while maize stovers were removed after harvest and then 2 Mg ha^{-1} re-applied a few days before planting by broadcasting on the soil surface. All organic materials were subsequently manually incorporated into soil.

Measurements

Starting 1997, daily maximum and minimum temperature and daily rainfall were recorded manually a few kilometers away from the site. With the start of the trial, these parameters were recorded directly on site. An automatic weather station was installed on site in August 2013 recording air temperature, solar radiation, rainfall, wind speed and direction as well as relative humidity at hourly intervals.

Since the beginning of the trial, dates of all aforementioned management interventions were recorded. At each harvest, aboveground biomass of Tephrosia, and stover, cob and grain weight of maize was determined on each plot.

Measurements were intensified in the short-rain season in 2013 and the subsequent long-rain season in 2014 in three selected, contrasting treatments, namely:

(a) “mixed crop-livestock farmer”: FYM+ R− M–M, N0
(b) “intensive maize farmer”: FYM− R+ M–M N90
(c) “Integrated soil fertility management”: FYM+ R+ T–M (or M–T) N30

These encompassed the range of applied mineral N (0–90 kg ha^{-1}), as well as both FYM and residue retention levels. At the same time, they also included two management practices/farming systems (a and b) prevalent in Western Kenya.

A soil profile was excavated next to the site on a piece of fallow land, and major soil horizons identified (Jelinski et al. 2015). Soil texture, bulk density, organic carbon, total soil N, pH, CEC and Olsen-P was determined in samples from this profile to a depth of 2 m.

In the first three (of a total of four) replicates of the three selected treatments mineral soil N (ammonium and nitrate) was determined at depths of 0–10, 10–25 and 25–50 cm on 12 September and 5 October 2013 and 22 January, 22 April, 8 May, 17 June and 5 August 2014.

Automatic capacitance probes (*AquaCheck*) with a total length of 1.2 m were installed in mid-September in rep 1 of each selected treatment in the middle of the plot. Hourly probe readings down to 1.2 m (20 cm intervals) were converted into volumetric soil moisture data using the factory calibration curves provided by the manufacturer. Due to a malfunctioning readout unit soil moisture readings were rather patchy in the long-rain season in 2014, and therefore these were not used any further.

Total aboveground biomass (AGB, kg ha^{-1}) of maize in the three treatments was determined destructively in both seasons on 5 October and 19 November 2013 and at harvest 6 January 2014, as well as 23 April, 8 May and 17 June, and at harvest 4 August 2014. Green leaf area index (GAI, m^2/m^2) was also determined on these dates (but not at harvest), by measuring the length (L) and width (W) of the last fully developed leaf of five randomly selected plants. Single leaf area was determined using the empirical equation: Area (cm^2) = 0.687 * L (cm) * W (cm). The factor 0.687 is the result of simplifying the empirical double-log equation (LN(Area) = −0.99 + 1.231 * LN(L) + 0.854 * LN(W)) suggested by Mokhtarpour et al. (2010) yielding an R^2 of 0.995 comparing leaf areas determined with their and the simplified approach. The total green leaf area was calculated by multiplying single leaf areas with the number of green leaves of each plant. The GAI is this green area divided by the ground area covered by each plant (0.1875 m^2).

The AGB N-content was determined by analyzing the N-concentration of plant subsamples. The N uptake (kg N ha^{-1}) was calculated by multiplying N-concentration and AGB. Total N-uptake at harvest is the sum of stover-, cob- and grain-N-content.

Samples were taken from the applied manure in September 2013 and the harvested Tephrosia in January 2014 and forwarded for analysis of N P and K content.

Gas samples for the determination of soil nitrous oxide (N_2O) emissions from maize plots were taken 8–10 times during the season in the selected treatments and reps. Therefore, 1 day after planting, three plastic frames—37 cm wide, 55 cm long and 15 cm high—were pushed 10 cm deep into the soil. The three frames were arranged diagonally across the plots approximately 1.5 m away from each other. At time of sampling, plastic chambers with same length and width and 22.5 cm high were clamped air-tight on top of these frames. Chambers were equipped with a digital thermometer for measuring air-temperature inside the chamber, a battery-driven small fan for air-mixing and a little outlet to which a 1 m long tube (diameter 5 mm) was connected to avoid air-pressure build-up while preventing air-influx/contamination. Gas samples from the three chambers in a single plot were taken with a syringe through a septum-sealed valve and then pooled. Samples were taken 0, 15, 30 and 45 min after the chamber was mounted. Samples were analyzed for carbon dioxide, methane and N_2O with a gas chromatograph (SRI Institute, model 8610C) at the World Agroforestry Center (ICRAF) lab in Nairobi. The N_2O flux is calculated from the linear increase of concentration inside the chamber over time applying the ideal gas law:

$$F = \frac{\Delta c * M * p * h}{R * T} \tag{1}$$

where F is the gas flux (μg $N/m^2/min$), Δc (ppb/min) is the slope of the linear regression fitted to the increase in gas volumetric concentration measured over the 45 min, M is the molar weight of the gas (kg/kmol), p is the atmospheric air pressure (bar) measured with a barometer at day of sampling, h is the total chamber height (m), R is the ideal gas constant equal 0.08314 (m^3 bar/kmol/K) and T is the air temperature (K) inside the chamber.

Simulations

We used the cropping system simulation model, CropSyst version 4.19.01 (Stöckle et al. 2003, 2014), to simulate crop growth, yield, water and N-dynamics of the 32 treatments described above (=all but "intercropping"). CropSyst is a multi-year, multi-crop, daily time step, mechanistic simulation model. It has been applied successfully under a range of climatic conditions and for a variety of annual crops, such as maize, barley, rice, sorghum, potato, beans and alfalfa, to mention a few. Besides soil organic matter, water and N-dynamics and -uptake, CropSyst can simulate N_2-emissions, NH_3-volatilization losses, as well as N_2O emissions distinguishing nitrification and denitrification processes as a source of N_2O. Total denitrification and the fraction of N lost as N_2O are modeled as a function of nitrate concentration, soil respiration rate, and soil moisture.

The 2013–2014 detailed observations in the three selected treatments were used to calibrate CropSyst, which was then used to simulate 10 years of each of the treatments.

Maize crop cultivar parameters were adjusted using observed key phenological stages (growing degree days from planting until emergence, end of vegetative growth, flowering, grain filling and maturity), and fitting simulated to observed AGB accumulation, GAI and canopy N-concentrations by changing related CropSyst crop parameters (compare supplementary Table 1). Maximum accumulation of biomass was adjusted to observed values using CropSyst's Transpiration Use Efficiency (TUE) model. This uses a regression-based approach to determine TUE under given conditions of atmospheric vapor pressure deficit (VPD). TUE depends on the TUE (g biomass/kg H_2O) when VPD is 1 kPa (TUE@1 kPa) and the scaling coefficient for the TUE regression power function.

For the simulation of AGB accumulation, N-uptake and N-fixation of Tephrosia, the generic crop growth routine of CropSyst was used. As Tephrosia is a perennial plant that would continue growing if not harvested at one point in time, we chose an arbitrarily high value for growing degree days from emergence to begin senescence and disabled "maturity is significant". Canopy growth was described with the canopy coverage module of CropSyst's crop growth routine with a maximum canopy cover equal to 85 %; a value derived by visual estimation in the field, and in accordance with data derived for Tephrosia by Rutunga et al. (1999). Furthermore, the N-fixation routine of CropSyst was enabled to allow simulation of atmospheric N_2 fixation. The maximum aboveground N concentration at maturity was set to observed values (19.8 g/kg), while the remaining N-uptake parameters were left at default in the absence of data to calibrate them. Analogously to the calibration of maize, eventually total biomass accumulation was adjusted to observed values by changing TUE@1 kPa. A maximum rooting depth of 1.1 m was set for both, maize and Tephrosia, and it was assumed that the root mass of both crops would equal 40 % of the aboveground biomass.

The simulation of crop yield in CropSyst is governed by the unstressed harvest index as well as the biomass translocation to grain factor. To optimize the overall model performance, these two parameters were adjusted considering the entire data set, i.e. the observed biomass and yield of all considered treatments from 2004 to 2014.

A 1.1 m deep soil profile was defined in CropSyst and subdivided into 17 layers with a thickness of 5 cm (top 60 cm of the soil) or 10 cm (60–110 cm). Soil water dynamics were described using the hourly cascade routine of CropSyst. Runoff and thus water infiltration into the soil was described with the SCS curve number approach (USDA Soil Conservation Service 1988). The soil hydraulic parameters, field capacity and permanent wilting point, were derived with the pedotransfer functions developed by Minasny and Hartemink (2011). Furthermore, the layer bypass coefficient was used to adjust the (velocity of) downward movement of nitrate in the soil. This coefficient simplistically accounts for flow through cracks and macropores, and as such describes the fraction of water bypassing the more immobile water phase which governs the solute movement of nitrate and ammonium.

Soil organic matter (SOM) turnover was described with the multiple organic matter pool of CropSyst which lends its concept to the Century SOM model (Parton et al. 1994) that distinguishes various SOM pools with different turnover rates. In CropSyst the percent abundance of microbial biomass, active labile, active meta-stabile and passive SOM needs to be initialized for each soil layer. This was done by simulating a period of 50 years of past farmer's typical management of maize in the region with no application of fertilizer (as fertilizer application is a more recent trend), and using the final %-abundance of SOM pools as starting values for all subsequent simulations. Observed (soil profile description) SOM and mineral N contents were used as initial values, whereas individual values for the 17 defined soil layers were interpolated from observation by cubic splines, with fixed values at 0–10 cm equal to the observed values for 10 cm depth.

The Penman–Monteith method for estimating evapotranspiration was chosen. Required solar radiation, wind speed and relative humidity data, not measured on site until August 2013, were downloaded from the global NASA-POWER Agroclimatology database (http://power.larc.nasa.gov).

As outlined earlier, we did neither monitor in detail nor simulate any of the soybean-maize intercropping treatments or the M–T and T–M rotation without application of phosphate fertilizer, as CropSyst has no routines (yet) to handle intercropping or P-dynamics and P crop response.

Statistical analysis and efficiency parameters

For determining the fit between observed and simulated model results, the Pearson's correlation coefficient (R), the root mean squared error (RMSE), the relative root mean squared error (RRMSE), and the modified coefficient of efficiency (E) was calculated:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(observed_i - simulated_i)^2}{n}} \tag{2}$$

$$RRMSE = \frac{RMSE}{Average(observed)} * 100 \tag{3}$$

$$E = 1 - \frac{\sum_{i=1}^{n}|observed_i - simulated_i|}{\sum_{i=1}^{n}|observed_i - Average_{obs}|} \tag{4}$$

The coefficient of efficiency was originally defined by Nash and Sutcliffe (1970). In its modified version, the squared difference terms are replaced by the absolute differences. This avoids sensitivity to outliers as is the case for the original coefficient (Willmott et al. 1985). An E value of zero indicates that the model describe observations as good as the average value calculated across observations. A negative E shows that an average value would be a better predictor than model results. An E approaching 1 describes an increasingly improved fit of modeled and observed yields superior to simply assuming an average.

To describe the relationship between the various N-inputs and rainfall and corresponding N_2O-emissions we applied simple and multiple linear regression analysis.

Simulated N_2O emission results were tested for treatment difference by an analysis of variance (ANOVA with years as reps) using the GenStat (version14) software.

Simulated N_2O emissions were also expressed as emission intensities, which is the kg N_2O–N emitted per Mg of maize biomass exported (i.e. without stover that was retained in the R+ treatments).

Results

2013–2014 seasons: intensified sampling and model calibration

Soil moisture

Using decision criteria set up by USDA Soil Conservation Service (1988), the SCS curve number was estimated to be 86, which corresponded to a soil with a slow infiltration rate and poor hydraulic properties. Thus, annually between 12 and 23 % of the rainfall was simulated to run off, whereby annual runoff and rainfall correlated very strongly ($R > 0.9$) irrespectively of the treatment considered. Despite this significant amount of water not infiltrating into the soil, CropSyst tended to somewhat overestimate soil moisture dynamics at 20 cm in the three plots/treatments where continuous soil moisture data were recorded; increases in soil moisture were simulated to occur faster and more pronounced than measured (Fig. 1). Nevertheless, the overall accuracy of simulations was sufficient, especially taking into consideration that permanent wilting point and field capacity were derived merely by pedo-transfer functions. Simulated moisture contents deviated from observed moisture contents less than 5 Vol% (with a few exceptions), which is the usual measuring accuracy of factory calibrated capacitance probes. Under the treatment FYM+ R+ T–M N30 (Fig. 1) simulations overestimated root water extraction at 60 cm toward the end of the season. This was not the case in the other two treatments (data not shown). A close match existed between observed and simulated water contents at 100 cm, which is a strong sign that simulations did correctly capture the drainage of water below the maximum rooting depth of both crops.

Soil mineral N

After 10 years of seasonal addition of 4 Mg ha^{-1} FYM containing 70 kg N ha^{-1}, full maize stover removal and continuous maize cropping without any addition of mineral N-fertilizer (FYM+ R− M–M N0), the simulated ammonium and nitrate contents in

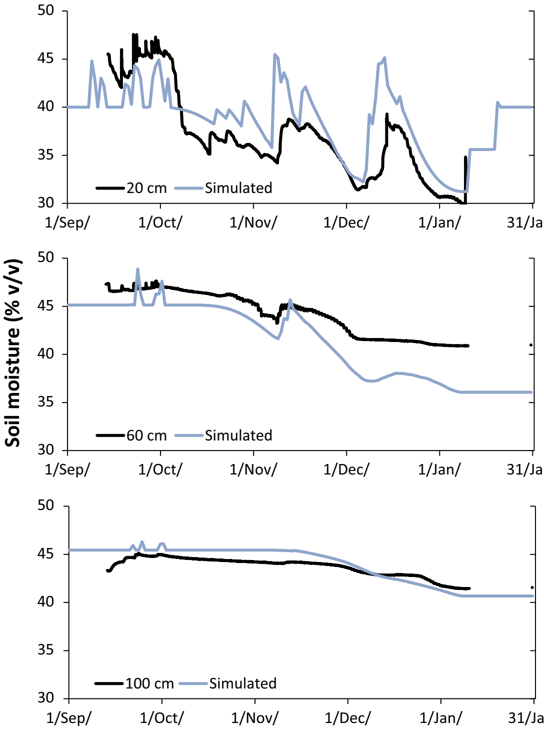

Fig. 1 Observed (*black*) and simulated (*blue*) soil moisture (%v/v) at 20, 60 and 100 cm depth under the treatment FYM+ R+ T–M N30 in the 2013 short-rain season. (Color figure online)

0–50 cm depth were notably lower than observed ones, especially 5 October 2013 (Fig. 2). Simulated and observed ammonium and nitrate contents, on the other hand, were close under the FYM+ R+ T–M or M–T N30 treatment, and reasonably close under the FYM− R+ M–M N90 treatment. The latter treatment had the highest standard deviation of observed mineral N contents indicating a notable spatial micro-heterogeneity in response to the (partly banded) mineral fertilizer-only application of N. The split application of mineral N was clearly visible in the simulated ammonium signal in both seasons.

The layer bypass coefficient was adjusted to 0.5 for the whole soil profile, meaning that only 50 % of the water moving through the soil actually contributed to transporting nitrate and ammonium. Increasing this value further had little impact on increasing mineral N-contents in 0–50 cm depth (and thus improving the model fit) in the long run. Underestimation of mineral N contents in FYM+ R− M–M N0 was rather related to the depletion of nitrogen in general in response to too little addition of organic or inorganic N in relationship to the withdrawn amounts.

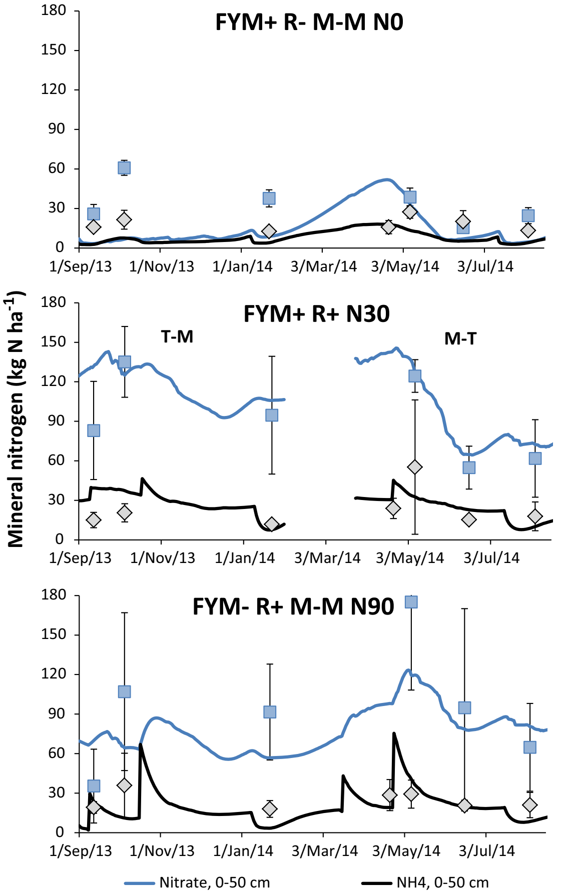

Fig. 2 Observed (*points*) and simulated (*lines*) ammonium and nitrate contents (kg N ha^{-1}) at 0–50 cm depth in the three treatments studied in detail; *bars* denote the standard deviation of the mean

Seasonal dynamics of aboveground biomass, green area index and canopy N-concentration

Simulated maize AGB at maturity of the three treatments studied in more detail over two seasons (2013–2014) was close to observed values, i.e. within the range of the standard deviations of the means (Fig. 3). In the middle of the short-rain season (19 Nov.) simulations underestimated AGB somewhat, while however predicting observed GAI quite precisely. The opposite was true for the subsequent long-rain season 2014 (data not shown).

For the sake of improving overall GAI simulations and thus AGB and yield predictions, we used different values for the initial green area index, the specific leaf area (SLA) and N-uptake related parameters for maize grown in rotation with Tephrosia and monocropped maize without manure application (supplementary Table 2). Values were slightly lower for the latter.

The maize canopy N-concentration was very well predicted in the short-rain season 2013 for the treatment FYM+ R+ T–M N30 (Fig. 3, middle). This was not surprising, as this was the treatment with the highest observed canopy N-concentrations, which were thus used for model calibration, i.e. adjustment of the critical as well as maximum N concentration of canopy at emergence, the maximum aboveground N concentration at maturity, the N concentration curve slope and the end of the dilution curve value. The canopy N-concentration early in the cropping season was slightly overestimated in both study seasons for the FYM− R+ M–M N90 and the FYM+ R− M–M N0 treatments. Regarding the latter, simulations also underestimated canopy N-concentrations later during both seasons; a direct response of underestimated mineral N-contents in the soil resulting in less N-uptake than actually occurring.

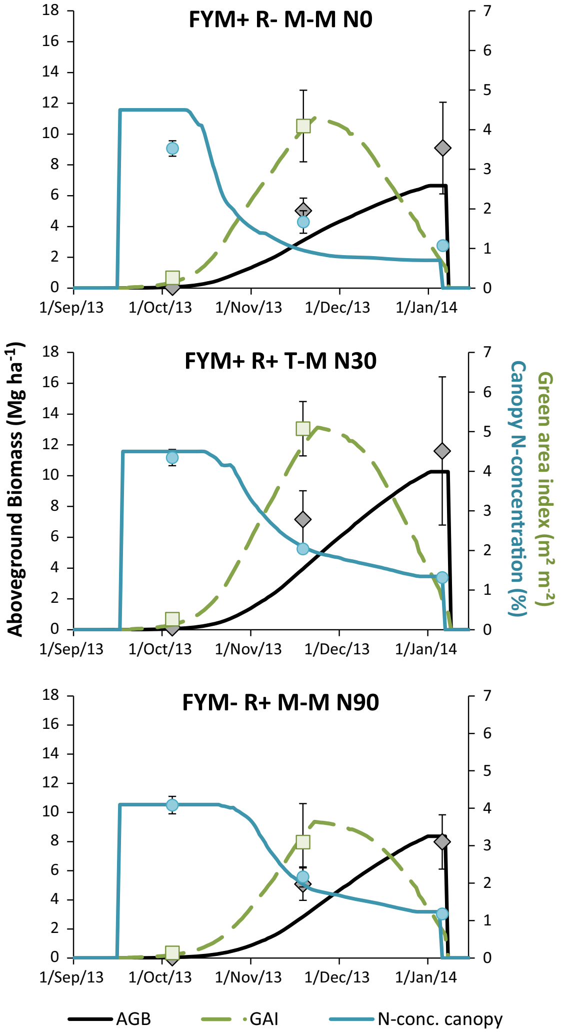

Fig. 3 Observed (*dots*) and simulated (*lines*) aboveground biomass (AGB; Mg ha^{-1}) *green* area index (GAI; m^2 m^{-2}) and canopy N-concentration (%) of the three treatments studied in detail; *bars* denote the standard deviation of the mean. (Color figure online)

Tephrosia aboveground biomass at harvest was well predicted with CropSyst's generic crop growth routine, which is exemplarily shown for the FYM+ R+ N30 maize–Tephrosia (M–T) and Tephrosia–maize (T–M) rotation in Fig. 4 (both treatments merged). The corresponding correlation coefficient, R, was 0.859, the RMSE equal 1.87 Mg ha^{-1}, the RRMSE equal 22 %, and the model efficiency, E, equal 0.63.

For the entire trial the harvested (observed) Tephrosia AGB ranged between 0.56 and 16.53 Mg ha^{-1} (5 %-percentile 1.72, 95 %-percentile 12.89 Mg ha^{-1}) with an average biomass of 7.09 Mg ha^{-1}. The Tephrosia AGB sampled in 2013–2014 had an average N-content of 1.98 %. This means that the average N-uptake of Tephrosia was equal to 140 kg N ha^{-1} season^{-1} (5–95 % percentile: 34–255 kg N ha^{-1} season^{-1}).

Nitrous oxide emissions

Average observed N_2O emissions never surpassed 50 g N ha^{-1} day^{-1}, and in the majority of case were below 5 g N ha^{-1} day^{-1} or close or equal to zero towards the end of the two seasons (Fig. 5). Highest emissions in both seasons were observed in the FYM+ R+ T–M or M–T N30 treatment. Simulations, on the other hand, produced daily emissions peak of at maximum up to 378 g N ha^{-1} day^{-1} (FYM+ R+ M–T N30, 26 March 2014). However, observed low emissions in the majority of cases (exception: 20 May 2014) also coincided with low simulated emissions. As such, the overall model fit was exceptionally good, even though the visual impression would suggest a significant overestimation of emissions by CropSyst. In accordance with observations, total seasonal

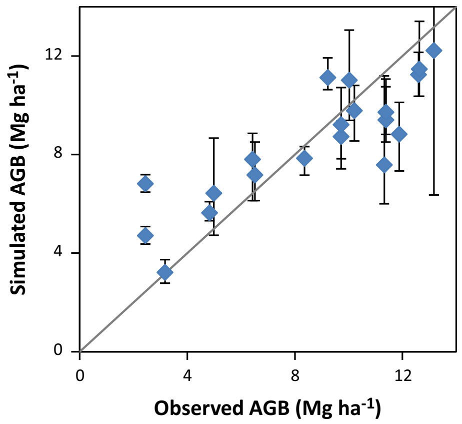

Fig. 4 Plotting simulated against observed Tephrosia above-ground biomass (AGB; Mg ha^{-1}) for the FYM+ R+ N30 maize–Tephrosia and Tephrosia–maize rotation from 2004 to 2014; *bars* denote the standard deviation of the mean

emissions (planting until maturity) with 5.3 and 8.7 kg N ha^{-1} were highest in the FYM+ R+ T–M or M–T N30 treatment followed by the FYM+ R− M–M N0 (3.0 and 4.0 kg N ha^{-1}) and the FYM− R+ M–M N90 treatments (3.4 and 3.3 kg N ha^{-1}) in the short- and long-rain season, respectively. Simulated emissions were highest when the soil moisture content was above field capacity approaching saturation.

Long-term trends

Maize biomass, yield and model performance

Treatments including either maize–Tephrosia (M–T) or Tephrosia–maize (T–M) rotation but otherwise the same (FYM, R and N) management did not significantly (paired *t* test) differ in terms of any of the considered simulation results, i.e. biomass, yield, or N-dynamics. Thus, these treatments were lumped together and the annual average yields, AGB and N-fluxes calculated.

Simulations in most cases reproduced the long-term dynamics of biomass and yield well (supplementary Table 3). The model efficiency (E) was positive in 16 and 21 out of the 24 simulated treatments for AGB and yield, respectively. Both E's were also positive if calculated across all treatments. Likewise, average observed and simulated yields, AGB and harvest index (observed = 0.427, simulated = 0.429) compared very well across all treatments. Even though 10.5-year average observed and simulated yields and AGBs were close, CropSyst simulations could not well predict the seasonal dynamics of the continuous maize treatments that did not receive any mineral N-fertilizer, yielding a low R, a high RMSE and RRMSE, and a negative E. Treatment FYM+ R− M–M N0 which was studied in detail in 2013–2014 was among these. Simulations underestimated AGB and yield in the short-rain season in 2004, 2006, 2007 and 2009 and subsequently overestimated both (Fig. 6). Seasonal dynamics of the M–T/T–M treatments were well predicted in general. Simulations were mostly within the range of observation (indicated by the bars in Fig. 6) or very close. This was also the case for the continuous maize treatments with 30, 60 or 90 kg N ha^{-1} applied as mineral fertilizer each season.

N-balance

Farm yard manure application of 4 Mg ha^{-1} season^{-1} provided for an annual input of 140 kg N ha^{-1} (Table 2). Maize stover retention (2 Mg ha^{-1}) added another 16 or 32 kg N ha^{-1} depending whether maize was monocropped or not. Atmospheric N-fixation by Tephrosia contributed a considerable amount of N to the T–M or M–T rotation, with on average between 99 and 135 kg N ha^{-1} season^{-1}. As expected, N derived from the atmosphere (NdfA) was highest in treatments that otherwise did not receive any/much further N, and dropped to on average 64 % in the FYM+ R+ T–M/M–T N30 treatment. The N-withdrawal by the harvested maize grain and, if applicable, stover ranged between 71 and 254 kg N ha^{-1} year^{-1}, and was highest for the continuous maize rotation with two maize crops per year when receiving some N-inputs. Annual leaching of N below 1.1 m soil depth on average was 13 kg N ha^{-1} year^{-1}.

Leaching was highest under treatments with high organic or inorganic N-input; at maximum 42.4 kg N ha^{-1} year^{-1} under FYM+ R+ T–M/MT N30 and at minimum 3.7 kg N ha^{-1} year^{-1} under FYM+ M–M N30 with or without residues retained. Total annual gaseous N-emissions ranged between 2 and 52 kg N ha^{-1} (average 19 kg N ha^{-1}).

The N-balance was negative for all continuous maize rotations that, besides mineral N, did not receive organic fertilizer in the form of FYM, irrespectively of whether or not 2 Mg ha^{-1} maize stover was retained. 4 Mg ha^{-1} FYM addition twice a year alone could sustain N-exports under continuous maize even if no

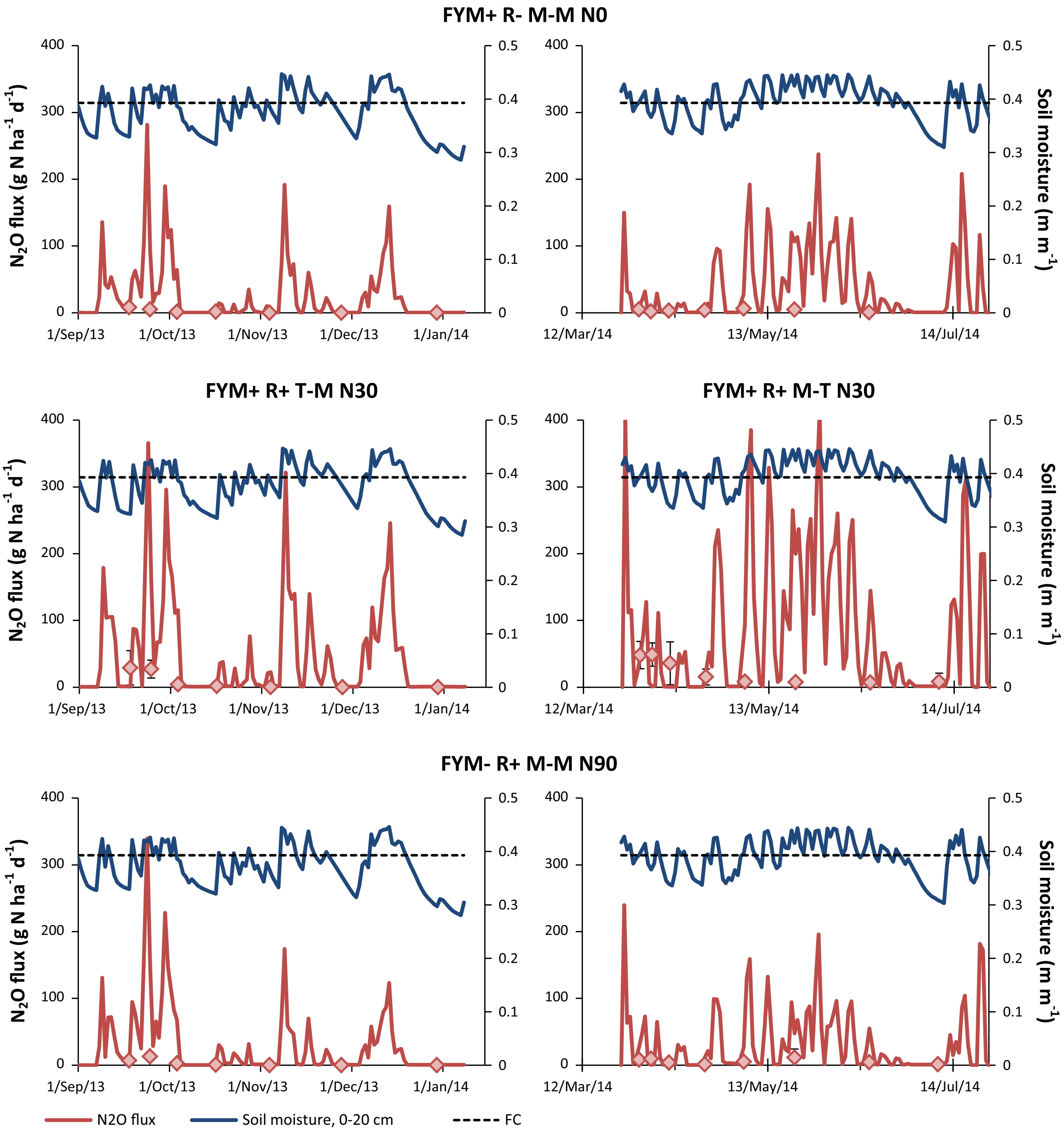

Fig. 5 Observed (*dots*) and simulated (*lines*) nitrous oxide emissions (g N ha^{-1} day^{-1}) and corresponding soil moisture in 0–20 cm (m m^{-1}; *upper blue curve*, *right axis*) in the three treatments studied in detail; *bars* denote the standard deviation of the mean; the *dotted straight line* shows the field capacity of the soil at 0–20 cm. (Color figure online)

mineral fertilizer-N was added, resulting on average in a zero-N-balance. Maize rotations with Tephrosia yielded a positive N-balance throughout. In the case of FYM+ R− M–T/T–M N30 a maximum average surplus of 116 kg N ha^{-1} year^{-1} was calculated.

N_2O emissions

Simulations revealed that annual N_2O emissions contributed between 30 and 70 % to total gaseous N-emissions. For the sake of easy comparability with

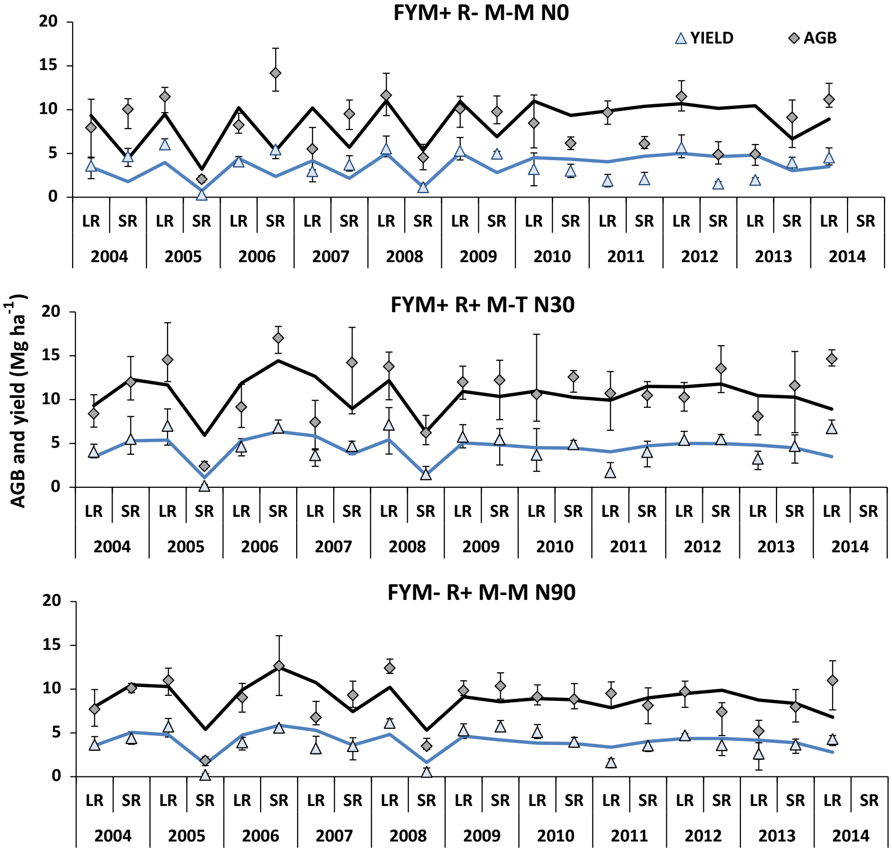

Fig. 6 Long-term observed (*dots*) and simulated (*lines*) aboveground biomass (AGB, Mg ha^{-1}) and yield (Mg ha^{-1}) of the three treatments studied in detail; *bars* denote the minimum to maximum observed range (n = 4); *LR* long-rain season, *SR* short-rain season

published data (and those presented in Fig. 5), the seasonal emissions only, omitting inter-season fallow periods (on average 7 weeks between the short- and long-rain season and 11 weeks between the long- and short-rain season), were also summed to two-season totals (~34 weeks or ~238 days).

FYM application, residue retention and crop rotation had a significant ($p < 0.001$) effect on simulated two-season N_2O emissions. Rotations that included Tephrosia emitted the largest amounts of N_2O (Fig. 7). Additionally applying FYM and/or retaining maize stover increased emissions significantly further. Highest average two-season emissions (12.0 kg N_2O–N ha^{-1}) were simulated for the FYM+ R+ M–T/T–M N30 treatment. Interestingly, the addition of 30 kg mineral N ha in this treatment significantly increased average emissions over the N0 treatment by 3.4 kgN_2O–N ha^{-1}. Otherwise mineral N application had no significant effect. The average two-season emission of the FYM− R− M–M N0 treatment, a treatment without any N-input, was 0.7 kg N_2O–N ha^{-1}. If this is considered some inevitable background emission of arable land use, then the difference between this amount and the emissions from the FYM− R− T–M/M–T N0 treatment, namely 4.2 kg N_2O–N ha^{-1}, would have to be attributed to the input of Tephrosia residues. This is equal to 26.8 g N_2O–N per kg Tephrosia N.

The standard deviation was high for all treatments, indicating a considerable year to year variation in N_2O emissions in response to changing rainfall regimes and soil moisture saturation degree—a major driver of N_2O emissions (compare Fig. 5). However, annual rainfall totals alone described only 11 % of the variance observed in N_2O emissions of all simulated treatments. Total N-inputs, on the other hand, accounted for almost 30 % of the observed variance (Fig. 8). The corresponding overall linear regression analysis yielded the equation N_2O_emissions = 0.023 * N_input, with the line intercept not significantly different from zero and thus not predicted.

Table 2 10.5-year average annual simulated N-dynamics

-------- Treatment ---------				Inorg. N	Org. N	N_2-fixation	NdfA	N-withdrawal maize harvest	Total gas. emissions	N-leaching	Input	Outputs	Balance
				------- kg N ha^{-1}		--------	%	----------------------------------		kg N ha^{-1}	---------------------------------		
FYM-	R-	M-T, T-M	N0	0	0	137	87	80	9.1	8.4	137	98	39
			N30	60	0	134	86	115	19.5	14.6	194	149	45
		M-M	N0	0	0			73	2.6	4.7	0	80	-80
			N30	60	0			118	3.4	4.5	60	126	-66
			N60	120	0			176	3.8	4.7	120	184	-64
			N90	180	0			216	3.8	18.0	180	238	-58
	R+	M-T, T-M	N0	0	16	135	87	83	15.3	16.4	151	114	37
			N30	60	16	135	87	114	23.6	16.6	211	155	56
		M-M	N0	0	32			71	9.5	4.6	32	85	-53
			N30	60	32			116	12.6	4.3	92	133	-41
			N60	120	32			172	13.4	4.6	152	190	-38
			N90	**180**	**32**			**209**	**11.7**	**22.0**	**212**	**243**	**-31**
FYM+	R-	M-T, T-M	N0	0	140	125	82	112	17.1	24.1	265	154	112
			N30	60	140	106	69	129	26.7	33.8	306	189	116
		M-M	**N0**	**0**	**140**			**127**	**9.0**	**3.9**	**140**	**140**	**0**
			N30	60	140			171	19.0	3.7	200	194	6
			N60	120	140			219	28.7	4.0	260	251	9
			N90	180	140			251	38.4	13.8	320	303	17
	R+	M-T, T-M	N0	0	86	135	87	95	20.0	25.2	221	140	81
			N30	**60**	**156**	**99**	**64**	**131**	**34.4**	**42.4**	**315**	**208**	**107**
		M-M	N0	0	172			147	20.9	3.9	172	172	0
			N30	60	172			193	31.7	3.7	232	228	4
			N60	120	172			235	41.6	9.2	292	286	7
			N90	180	172			254	51.3	29.0	352	334	18

Inputs are inorganic N fertilizer application, organic N applied in the form of farm yard manure and maize stover, and atmospheric N_2-fixation; outputs are N-withdrawal of maize, gaseous N-emissions and N-leaching; NdfA is the fraction of N-uptake that Tephrosia derived from the atmosphere; M–T, T–M rows display the averages of these two treatments; bold figures indicate treatments studied in detail in 2013–2014

Disentangled, individual N-inputs (inorganic N, organic N and N_2-fixation) together with annual rainfall explained even 72 % of the simulated N_2O emissions when applying a multiple linear regression model. Describing N_2O emissions by separating the two rotations (M–M vs. M–T/T–M) yielded significantly different slopes (=IPCC emission factors). They were 0.0344 for the M–T/T–M rotations and 0.0152 for the M–M rotation, both significantly larger than 0.01. Neither FYM nor residue retention changed these slopes significantly.

Given highest simulated N_2O emissions in combination with only one maize harvest per year, it was not surprising that the highest N-emission intensities were calculated for the treatments that involved a maize–Tephrosia rotation. These treatments emitted up to 1.4 kg N_2O–N per Mg of maize aboveground biomass harvested (and not partially retained) in 1 year (Fig. 7).

Discussion

CropSyst proved to simulate soil moisture, mineral N dynamics, N uptake and AGB and yield generally with sufficient accuracy, witnessed by the close fit between observed and simulated variables and the statistical measures of the model efficiency. The observation data set was sufficient to calibrate CropSyst, and in turn to estimate N-dynamics. More frequent observations of N_2O fluxes would have been desirable, but available resources did not allow increasing the measuring frequency. Further research should substantiate the efficacy of CropSyst to predict N_2O fluxes in tropical ecosystems.

Some minor discrepancies between simulated and observed AGB accumulation in 2013–2014 were observed. However, the model fit was quite remarkable in the light of the fact that the simulation period comprised 10.5 years (21 seasons) with observations

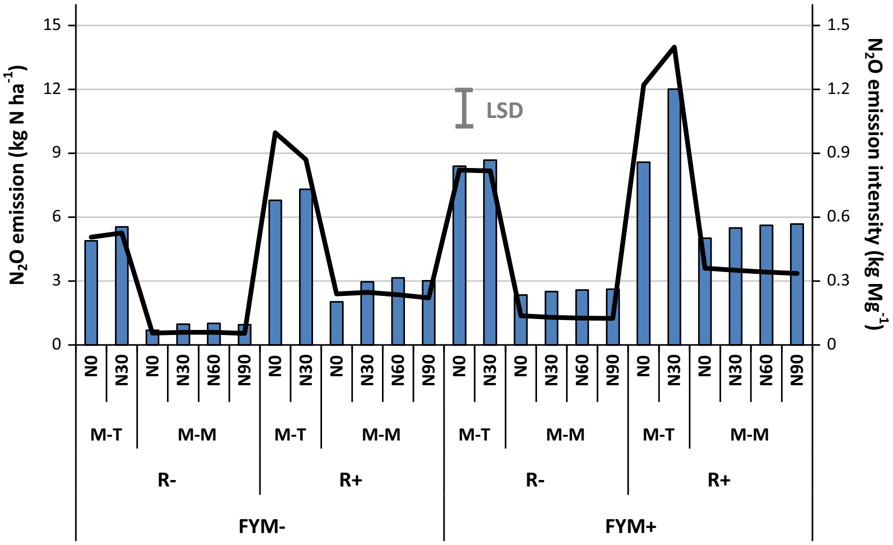

Fig. 7 10.5-year average sum of N_2O emissions (kg N ha^{-1}; *left axis*) of the two growing season per year, and N_2O emission intensity (kg Mg^{-1}; *line, right axis*); LSD_{FYM} and $LSD_{Residue} = 0.50$; $LSD_{Rotation} = 0.53$; $LSD_{FYM.Residue} = 0.71$; $LSD_{FYM.Rotation}$ and $LSD_{Residue.Rotation} = 0.87$ (min. rep.), 0.75 (max–min. rep.), 0.62 (max. rep.); $LSD_{Rotation.N} = 0.87$; $LSD_{FYM.Residues.Rotation} = 1.23$ (min. rep.), 1.07 (max–min. rep.), 0.87 (max. rep.); $LSD_{FYM.Rotation.N}$ and $LSD_{Residues.Rotation.N} = 1.23$; $LSD_{FYM.Residues.Rotation.N} = 1.74$ (=*bar in graph*)

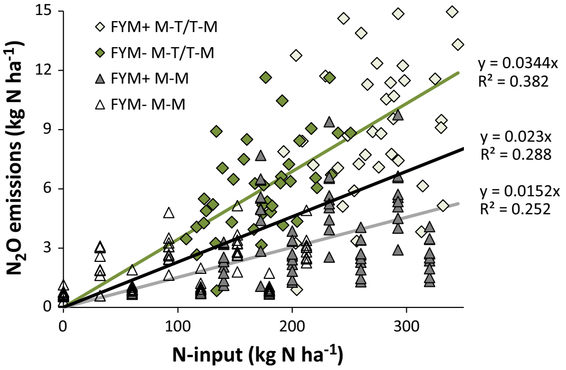

Fig. 8 Plotting the average sum of N_2O emissions (kg N ha^{-1}) of the two seasons per year against the total amount of N-supplied to the field in these two seasons

only available towards the end of this period. We are not aware of any published comparable long-term simulation study in tropical Africa, and as such the presented model application is the first of its kind.

Simulating long-term impacts of extreme treatments, such as 21 continuous seasons of monocropped maize without any N-input, still poses a challenge to process-based models such as CropSyst, especially on highly weathered, tropical soils with low inherent fertility prevailing in Western Kenya. Ten years of N application by FYM only in the FYM+ R– M–M N0 treatment had not depleted mineral N amounts as much as the model had predicted. It appears likely that the decomposition of SOM is more pronounced and longer-lasting than simulations would suggest. However, to pin down reasons for a poor model fit in these cases, observations of long-term soil organic matter dynamics in these trials are required, in combination with a more detailed lab analysis (fractionation) of soil organic matter fractions—work in progress.

Mono-cropped maize without manure application (but adequate mineral N applied) did grow less vigorous than maize that had received equal amounts of N in the form of manure—making us to rely on different values for the initial GAI, SLA and some N-uptake parameters to simulate both cases as accurately as possible. The most obvious cause could be a lack of macro-nutrients other than N, P or K (as 60 kg K_2O and 60 kg P per hectare were applied each season) or a lack of micro-nutrients, which were not applied unless through manure. Even though lack of sufficient amounts of micronutrients in the soil has been identified as a limitation to crop growth and the nutrient response the macronutrients N, P and K (White and Zasoski 1999), there are only a few publications that address the issue (Zingore et al. 2008; Kihara et al. 2012).

The overall efficiency of CropSyst to model the long-term trial expressed in terms of average RRMSE (30 % for AGB and 35 % for yield) is well within the range of other published studies (Sommer et al. 2007, 2013; Martre et al. 2014; Ngwira et al. 2014), even though the usefulness to compare such figures is limited given the different agro-ecosystems, crops and simulation times considered. It is often easier to calibrate crop models to observations made over short term-periods, as opposed to long-term observations. One the one hand, there is usually a lower number of total observations that have to be explained using the same site-calibrated model settings. On the other hand, long-term simulations require soil chemical and physical processes to be well understood and parameterized in the model, which may be less of a problem in studies where only one or two seasons are simulated, as poor simulations may result in biases between prediction and observations that may go unnoticed over a shorter simulation period. Cautious use of results and re-visiting simulations of model results that yielded a negative E is advisable. However, we were mainly discussing and taking forward overall averages, where even simulations with a negative E performed quite satisfactory, as such avoiding the pitfall of discussing individual seasonal results of poor simulation fit (apart from the last two seasons with intensified measurements).

CropSyst has been applied for a multitude of crops, cropping systems and agro-ecosystems for over 20 years, and has gone through a remarkable evolution (Stöckle et al. 2014). Publications in which CropSyst was applied explicitly for simulating N_2O emissions are yet limited. Stöckle et al. (2012) assessed the GHG footprint of conventional-versus no-tillage systems in Washington State in the inland northwest USA (see also Kruger et al. 2010). Confalonieri et al. (2006) used CropSyst to simulate the N balance of rice in Italy, but did not report simulated N_2O emissions.

In a strict sense, our study did not allow an ultimate assessment of the effectiveness of CropSyst to simulate N_2O emissions in the studied system, given the fact that none of the observed emissions ever were in the upper range of simulated daily fluxes, but that otherwise simulated low emissions in the majority of cases coincided with low observed emissions. Thus, neither coincidence (unfortunate timing of measurements) nor a systematic trend towards overestimating fluxes can be ruled out. It is therefore recommendable to repeat such simulation studies using more comprehensive sets of observed data, preferably including some model inter-comparison, as has been done e.g. by Chirinda et al. (2011). On the other hand, a previous multi model comparison study (Marchetti et al. 1997) revealed that denitrification rates simulated with routines implemented in CropSyst were among the lowest, which may be an indication for CropSyst rather giving conservative than excessive estimates of N_2O emissions. Also, simulations and observations went conform and identified the FYM+ R+ T–M or M–T N30 treatment as the one with the highest emissions amongst the three treatments monitored in more detail in 2013–2014.

Even though studies focusing on the N-balance, GHG emissions and, especially, the eco-efficiency of cropping systems in tropical Africa are not as abundant as for other regions of the world, we were not the first to study the impact of the inclusion of green manure cover crops (GMCC) on N_2O-emissions. In 2002 Baggs et al. (2006) measured the effects of tillage practice and residue quality on GHG in an improved-fallow agroforestry system in western Kenya only some ten kilometers away from our site but on a free draining silty clay loam (clay content 20 %). *T. candida* was among the tested GMCC species. When tilled into the soil, it increased N_2O emissions as compared to the control (natural fallow), as was the case in our study. In their case, short term (99 days) increases—calculated by merely interpolating eleven individual measurements—amounted to 2.1 g N_2O–N ha per kg N applied. This is significantly lower than the average increase of 26.8 g N_2O–N per kg Tephrosia N in our case. Reasons are, on the one hand, differences in methods applied (mere interpolation vs. daily time step mechanistic modeling), observation periods (99 vs. 238 days), and, most importantly, significant differences in soil texture (clay = 20 vs. >55 %). On the other hand, the effect of comparing short-term impacts—a freshly converted field in the case of Baggs et al. (2006) versus repeated application of significant amounts of Tephrosia biomass over a period of 10.5 years—could have added to the marked differences. In fact, our average simulated emissions of the very first season of the long-term trial in all cases were significantly lower than long-term averages. In the case of FYM− R− M–T/T–M N0 this was 1.1 kg N_2O–N ha^{-1} in first season as opposed to 4.7 kg N_2O–N ha^{-1} as a long-term average (compare Table 2).

Baggs et al. (2006) reported N_2O emissions for their tilled Tephrosia treatment of less than 0.6 kg N_2O–N ha^{-1} for the 99 days the study lasted, which is significantly lower than our long-term average, but close to the aforementioned first season emissions. This underlines the need to verify short-term reported responses in longer term experiments, as Baggs et al. (2006) had also asked for.

Our findings that inputs of organic matter into the soil increase N_2O emissions are in line with quite a few studies carried out in other tropical agro-ecosystems (Baggs et al. 2000; Millar et al. 2004; Kimetu et al. 2006) or by meta-analysis (Chen et al. 2013). Total emissions are also well within the range of globally observed amounts; vicariously for the hundreds of published studies the paper of Li et al. 2005 and the many studies cited therein may serve as good comparison.

In the context of emissions in smallholder type of land use systems in sub-Saharan African and the few studies available, some of our treatments actually range at the upper end of observed fluxes. Mapanda et al. (2011) studied the impact of moderate amounts of organic (manure) and inorganic fertilizer application on GHG emissions under maize in Zimbabwe on two different soils, a Chromic Luvisol (52 % clay) and a Haplic Lixisol (15 % clay). The average total N_2O emission (interpolation of 5 measurements per season lasting 122 days; two seasons in total) per single season from the Haplic Lixisol was 0.515 kg N_2O–N ha^{-1} under the treatment that had received 60 kg ha^{-1} ammonium nitrate fertilizer. This is very much in line with our two-season emissions under FYM− R− M–M N60 being approximately twice as high (1.0 kg N_2O–N ha^{-1}). The authors observed lower emissions in the treatments that had equivalent amount of manure-N (0.257 kg N_2O–N ha^{-1}), contrasting our results where FYM application increased emissions (FYM+ R− M–M N0: 2.3 kg N_2O–N ha^{-1}).

Comparable to our analogous treatments (zero-N), Chikowo et al. (2004, 2006) reported low N_2O emissions (0.4–0.6 kg N_2O–N ha^{-1}) from unfertilized maize fields in Zimbabwe that previously had 2-year fallows of *Acacia angustissima, Sesbania sesban* or unfertilized mono-cropped continuous maize. The authors also reported mineral N contents of the studied sandy, sandy-clay-loam or sand-loamy soils. Similar to our observations, as far as quantities and dynamic are concerned, they reported high mineral N-contents at the start of the season (up to 92 kg N ha^{-1} per 1.2 m depth) in response to the input of green manure biomass. Mineral N-contents dropped steadily in response to crop N-uptake but also fast leaching below the rooting zone. Chikowo et al. (2006) also estimated the percentage N derived from N_2-fixation which ranged between 55 and 94 % with some variation between the species studied, but very much in the range that CropSyst produced for Tephrosia in our study. They quantified the total atmospheric N-input from *Acacia angustissima* to be 129 kg N ha^{-1}, which, also, is similar to the annual fixed N that we quantified for Tephrosia.

Significantly lower N_2O emissions (largely less than 1 kg N_2O–N ha^{-1} $season^{-1}$) than ours were observed for sorghum, cotton and peanut fields in part receiving some N-fertilizer in semi-arid southwestern Burkina Faso on sandy-loamy or loamy soils with significant stone fractions (Brümmer et al. 2008). Also N_2O fluxes emitted from continuous cereals, legumes or both planted in rotation (with or without manure or mineral N application) in semi-arid Mali (Dick et al. 2008) were small (<2 kg N_2O–N ha^{-1} $year^{-1}$) in comparison to our data. Both studies underline that climate (semiarid vs. humid tropical) and related soil moisture regimes have a significant impact on GHG emission quantities.

The slope (=emission factors) describing the effect of N-inputs on N_2O emissions from the mono-cropped maize plots was only little (but significantly) higher than the IPCC (2006) Tier 1 emissions factor, EF1 (equal 0.01). However, our emission factor doubled when considering the T–M/M–T rotations, meaning that emissions predicted by IPCC with Tier 1 factors for such treatments could be too low. On the other hand, the amounts of Tephrosia biomass applied repeatedly over the 10.5 years in our long-term trial are quite massive. As has been highlighted elsewhere (Hoben et al. 2011), there is a risk of non-linear responses to excessive N-input.

The N-balance for the M–T/T–M systems was very positive leaving room for better fine-tuning GMCC based system and reducing emissions accordingly. For instances, it seems a waste to apply 30 kg ha^{-1} mineral fertilizer to Tephrosia if included in the crop rotation, which apparently had no other effect but reducing the N_2-fixation rate of Tephrosia. Likewise, it seems planting Tephrosia every second season corresponding to using 50 % of the land available per year, is not required, and that rate could be reduced without jeopardizing system sustainability while at the same time increasing the attractiveness of this GMCC to farmers. Here, a biophysical model application plays out one of its major strengths: using the "groundwork" presented in this paper, we can now design new treatments virtually, *ex-ante* and test the impact on system productivity, sustainability and eco-efficiency.

In regard to our observed N_2O emission intensities and the underlying rates of mineral N applications, we could not reproduce a trend towards lowest emissions per unit of product at intermediate fertilization rates, as has been claimed elsewhere (Van Groenigen et al. 2010). Organic N application (FYM, Tephrosia or maize stover) was the key driver of total emissions as well as emission intensities. Therefore, our results do not substantiate the idea that emission intensities could be reduced in response to intensification of agriculture in sub-Saharan Africa (Bellarby et al. 2013; Reay et al. 2012), or that manure application could be a potential mitigation strategy (Desjardins et al. 2005; Mapanda et al. 2011).

The difference between N_2O emissions in our study and that of other, in part very similar, studies highlights a fundamental problem of this type of research, namely a significant heterogeneity in time, space and across agro-ecosystems of emissions that are difficult to capture, especially short-term. Notable differences of methods applied (simple linear interpolation vs. sophisticated continues measurements vs. model-based assessment) hamper to some extent the reliability and comparability of studies and derivation of consistent emission factors (Rochette and Eriksen-Hamel 2008).

A notable surplus of N in the system (positive N balance), if incurred through massive amounts of organic matter input, should convert into a significant increase in SOM. Thus, increased N_2O emissions, at least partly, should be offset by carbon sequestration in the soil; an issue that has been highlighted e.g. by Li et al. (2005) and Stöckle et al. (2012). On the other hand, it is obvious that the treatments in our study that were pinpointed to have a negative N-balance, can only sustain crop growth by depleting SOM. Therefore, even if N_2O emissions in these treatments are rather low, additional CO_2 emissions could render them less climate-friendly than they appear at first glance. We are currently analyzing soil samples collected over the past 10 years in INM3 to find out whether the high-N_2O-emitting Tephrosia rotations are really net GHG emitters or whether soil organic carbon sequestration offsets N_2O emissions.

Negative N-balances in African smallholder cropping systems, similar to what we observed for treatments with N added only as mineral fertilizer, have been repeatedly reported (Vitousek et al. 2009; Liua et al. 2010). However, our study clearly highlights that even an addition of two times 90 kg N ha^{-1} in 1 year in the form of mineral fertilizer is not sufficient to turn around the negative balance, as the N-uptake and withdrawal did grow equally. Thus, arguing that (N) fertilizer subsidies are the only entry point for combating inadequate inputs, low productivity, land degradation and rural poverty (Vitousek et al. 2009) seems to be a too simplified message. On the other hand, it is hard to convince a smallholder to sacrifice half of his/her field for growing a GMCC merely based on the argument that this sustains soil fertility, when crop yields are not at least twice as high in the these "sustainable systems" to compensate for the set-aside area that would have been required to grow food, generate income and sustain livelihoods. Thus, after half a century of research on nutrient dynamics and farmer's best practices in sub-Saharan Africa, it seems there still remains quite a bit of (participatory) research to be done to find cropping systems that satisfy both, sustainability (with the strong ecological footing that natural scientists would like to see), and farmer's acceptability and eagerness to adopt.

Conclusions

In view of considerable differences in N_2O emissions—our study as well as others in Africa and concerning quantities as well as methods applied—it seems important to set proper standards for such measurements, such as has been suggested recently within the Standard Assessment of Mitigation Potential and Livelihoods in Smallholder Systems (SAMPLES) framework developed by the Consultative Group on International Agricultural Research's (CGIAR) Climate Change, Agriculture, and Food Security Program (CCAFS; Rosenstock et al. 2013), but also to invest in long-term trials that allow insights of long-term sustainability rather than short-term effects that may be seriously misleading.

The simulated N-fluxes and balances in the various treatments under study underpin the importance of inorganic *and* organic fertilizer inputs for systems sustainability; a core principal of integrated soil fertility management passionately promoted for at least a decade by many soil scientists and agronomists active in sub-Saharan Africa, e.g. those organized under The African Network for Soil Biology and Fertility (AfNet). Further analysis of soil samples collected over the last 10 years in CIAT's INM3 long-term trial will shed light onto soil organic matter buildup or depletion in the various treatments.

Even though this study did not discuss the agronomic performance in general (crop yields, income) and the socio-economic constraints associated with it, it seems obvious that the *either*- *or* decision underlying the setup of the INM3 long-term trial, i.e. to grow *either* GMCC (Tephrosia in our case) *or* maize in one season, requires revision, as crop yields were not sufficiently increased—doubled at least—to compensate for the loss associated with sacrificing 50 % of the land for a GMCC. Also, the retention of 2 Mg ha^{-1} maize stover seems to provide too little benefits to be justifiable—not even to mention the additional workload associated with removing all residues after harvest and reapplying part of them before planting that farmers may not accept easily. It seems smarter to optimize for systems where less land is set aside for a GMCC, and where the considerable amount of GMCC biomass produced (some 7 Mg ha^{-1} year^{-1} Tephrosia on average) may be spread over more area than just the piece of land where it was produced substituting then also for maize stover retention. A cropping systems simulation model like CropSyst in combination with a whole farm (tradeoff) model, once sufficiently calibrated to the systems, constitute an ideal tool to design such systems *ex-ante*, and subsequently testing them with farmers longer-term.

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