

Response letter to bg-2019-303

We thank the editor and reviewer #2 for their renewed efforts improving our manuscript “Effect of legume intercropping on N₂O emission and CH₄ uptake during maize production in the Ethiopian Rift valley” and respond as follows:

Editor:

reviewer #2 has read the revised manuscript and made some comments and suggestions for some final changes. I agree with the suggestions especially think that you should make clear what is meant with CSA? If it is more than just a buzz-word that you can definitely be more specific in your manuscript on what 'practices' are meant. If it really is only a buzz-word, I think you should consider to remove it from your manuscript

Reviewer #2:

Introduction

Line 40: It still isn't clear what is meant by CSA. What does climate-smart agriculture actually mean? If it is a proposed way forward, what way is being proposed?

[We now have added text to the introduction detailing what CSA is \(in terms its components\) and how it is connected to our study \(L.40 in R2\).](#)

In Line 44 you mention ‘proof-of concept for ...specific CSA practices’. Which specific practices? If what is meant here is instead that we need practices that are ‘climate-smart’ but we haven’t yet figured out what those practices might be, then this paragraph should be rephrased to make that clear. Otherwise, can you list ‘climate-smart’ practices that have been proposed but still need to be tested? I.e. are you referring to the use of legumes? If so, mention that specifically.

[We agree with the reviewer that the formulation “specific CSA practices” is rather unspecific. We now list CSA practices and show how legume intercropping relates to CSA \(L. 40 ff.\) and replace “specific CSA practices” with “legume intercropping” \(L. 53\)](#)

Materials and Methods

Line 134-135: change the order of this sentence so that it ends with “six treatments: [list of treatments...]” rather than “four replicates: [list of treatments...]”

[-Rearranged](#)

Line 139: avoid using respectively when possible. Here, just state: “on May 30, 2015 and May 7, 2016”

[-Done](#)

Line 141: state specifically that all treatments except the unfertilized control received fertiliser application; also consider using “MF+...” for your intercropping treatments to make that clear.

[-Done](#)

Line 149: avoid using respectively when possible. Here, just state: “July 27 and Sept 4, 2015 and Aug 2 and Sept 8, 2016”

Done

Line 157-160: Can you include a picture as supplementary information, so it is clear what the method looked like? Were the locations truly random (randomly generated) or just different each week? Also, consider rephrasing the last sentence to include more information about deployment. I.e. “...were pushed gently ~3 cm into the soil and included 2-5 live legume plants in the head-space. The septum was left open during deployment; once the chamber was inserted into the soil, the septum was closed and the base of the chamber was sealed around the circumference using moist clay.”

A photograph of the chamber deployed between the rows has been added to the Supplementary Information.

Locations within each plot used for flux measurements were not generated randomly but chosen to cover small-scale variability within the middle rows and to avoid damaging legume roots.

The sentence describing chamber deployment has been revised according to the reviewer’s suggestions.

Line 183: Specify here that zero fluxes were included and, if correct, that coefficients were generally (as opposed to always) greater than 0.85.

We indeed did not discard any fluxes because of low R² values, which would heavily bias the data towards higher fluxes. This is now specified in L. 203.

General comment: as mentioned above, minimize the use of ‘respectively’. It will make the text easier to read. Suggested changes are to Lines: 25, 256, 269-270, 297, 427, 442 and Table 2.

-Done

Results

Line 254: “generally larger” is only true for the 3-week fluxes, so perhaps specify that, or list the 3-week ones followed by the six-week ones.

-3-week fluxes listed first as suggested

Line 264: be consistent with treatment names; here the ‘M-F’ treatment is called ON-control, elsewhere it is called the ‘ONOP treatment’ or the ‘unfertilized control’ or the ‘unfertilized maize monocrop’

-Fixed

Line 268: give units

-Done

Effect of legume intercropping on N₂O emission and CH₄ uptake during maize production in the Ethiopian Rift Valley

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Abstract

Intercropping with legumes is an important component of climate smart agriculture (CSA) in sub-Saharan Africa, but little is known about its effect on soil greenhouse gas (GHG) exchange. A field experiment was established at Hawassa in the Ethiopian rift valley, comparing nitrous oxide (N₂O) and methane (CH₄) fluxes in minerally fertilized maize (64 kg N ha⁻¹) with and without crotalaria (*C. juncea*) or lablab (*L. purpureus*) as intercrops over two growing seasons. To study the effect of intercropping time, intercrops were sown either three or six weeks after maize. The legumes were harvested at flowering and half of the above-ground biomass was mulched. In the first season, cumulative N₂O emissions were largest in 3-week lablab, with all other treatments being equal or lower than the fertilized maize monocrop. After reducing mineral N input to intercropped systems by 50% in the second season, N₂O emissions were comparable with the fully fertilized control. Maize yield-scaled N₂O emissions in the first season increased linearly with above-ground legume N-yield ($P=0.01$), but not in the second season when early rains resulted in less legume biomass because of shading by maize. Growing season N₂O-N emission factors varied from 0.02 to 0.25 in 2015 and 0.11 to 0.20% in 2016 of the estimated total N input ~~in 2015 and 2016, respectively~~. Growing season CH₄ uptake ranged from 1.0 to 1.5 kg CH₄-C ha⁻¹ with no significant differences between treatments or years, but setting off the N₂O-associated emissions by up to 69%. Our results suggest that leguminous intercrops may increase N₂O emissions when developing large

biomass in dry years, but when mulched, can replace part of the fertilizer N in normal years, thus supporting CSA goals while intensifying crop production in the region.

Key words: yield-scaled N₂O emissions, CH₄ uptake, legume-intercropping, maize, Africa

1. Introduction

With a rapidly increasing population and declining agricultural land in Sub-Saharan Africa (SSA), increasing productivity per area (intensification) is the only viable alternative for producing sufficient food and feed (Hickman et al., 2014a). Intensification entails increased use of inorganic fertilizers, which may cause emissions of nitrous oxide (N₂O). Abundant ammonium (NH₄⁺) may also reduce the soil CH₄ sink by competing with CH₄ for the active binding site of methane monooxygenase, the key enzyme of CH₄ oxidation (Bédard and Knowles, 1989). Climate smart agriculture (CSA) ~~is an approach is an approach of reorientation of agricultural practices to transform agricultural practices in a changing climate and has been proposed as a way forward~~ aims with the triple objective of increasing agricultural productivity, ~~while increasing~~ building climate resilience, ~~and~~ and reducing ~~greenhouse gas (GHG)~~ emissions (Neufeldt et al., 2013). ~~Potential CSA practices include: improved water management, use of improved livestock and crop species, conservation farming, agroforestry and crop diversification and as well as improved soil fertility management practices among others~~ (Makate et al., 2019). ~~Legume intercropping is one way to diversify and intensify Ccropping systems diversification in terms of legume intercropping offers the potential for sustainable intensification, while contributing to food and nutritional security of smallholder farmers (de Jager et al., 2019). -Legume intercropping can also be used to add biologically fixed nitrogen to soils and to build soil carbon and improve soil quality (Bedoussac et al., 2015). As such, it is a powerful approach could to reduce greenhouse gas emissions by replacing associated with inorganic fertilizers and use by replacing inorganic fertilizer use GHG emissions associated with their production. However, greenhouse gas emission~~ GHG measurements in SSA crop production systems ~~in general, and in legume intercropping systems in particular~~, are scarce and proof-of-concept for the mitigation potential of ~~specific CSA practices legume intercropping~~ is missing (Kim et al., 2016, Hickman et al., 2014b). Moreover, modelling studies predict significant negative impacts of climate change on crop productivity in

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59 Africa (Blanc and Strobl, 2013) and it is largely unknown how these and the countermeasures
60 taken to maintain agricultural productivity will affect GHG emissions.

61 Crop production is a major source of N₂O, the third-most important anthropogenic GHG after CH₄
62 and CO₂ (IPCC, 2014). Emission rates of N₂O reported for SSA crop production so far are low
63 (Kim et al., 2016) owing to low fertilization rates, but may increase with increasing intensification.
64 Inorganic and organic N added to soil provide ammonium (NH₄⁺) and nitrate (NO₃⁻) for
65 nitrification and denitrification, respectively, which are the two main processes of microbial N₂O
66 production in soil (Khalil et al., 2004). The rate of N₂O formation depends greatly on the extent
67 and distribution of anoxic microsites in soils, which is controlled by moisture, texture and the
68 distribution of decomposable organic matter and NH₄⁺ fueling heterotrophic and autotrophic
69 respiration, respectively (Schlüter et al., 2019, Wrage-Mönnig et al., 2018). The magnitude of soil
70 N₂O emissions depends on O₂ availability as controlled by soil moisture and respiration,
71 availability of mineral N and readily decomposable C (Harrison-Kirk et al., 2013) and soil pH
72 (Russenes et al., 2016), all of which are affected by management practices. Other important factors
73 are soil type (Davidson et al., 2000) and temperature (Schaufler et al., 2010). The N₂O yield of
74 nitrification and the production and reduction of N₂O during denitrification are further controlled
75 by soil pH (Bakken et al., 2012, Nadeem et al., 2019) and by the balance between oxidizable
76 carbon and available NO₃⁻ (Wu et al., 2018). Mulching and incorporation of crop residues leads to
77 increased N mineralization and respiratory O₂ consumption, thus potentially enhancing N₂O
78 emissions both from nitrification and denitrification (Drury et al., 1991), if soil moisture is
79 sufficient to support microbial activity and restrict O₂ diffusion into the soil. Accordingly, N₂O
80 emissions are variable in time, often following rainfall events (Schwenke et al., 2016).

81 Crop diversification by combining legumes with cereals, both in rotation and intercropping,
82 enhances overall productivity and resource use efficiency, if managed properly (Ehrmann and Ritz,
83 2014). Intercropping of maize with grain legumes is common in the rift valley of Ethiopia and
84 central component in CSA (Arslan et al., 2015). In low input systems common to the Rift Valley,
85 integration of legumes with cereals diversifies the produce and improves farm income and
86 nutritional diversity for smallholder farmers (Sime and Aune, 2018). Moreover, by partially
87 replacing energy-intensive synthetic N, intercropping with legumes may increase the sustainability
88 of the agroecosystem as a whole (Carranca et al., 2015). However, to make best use of the resource
89 use complementarity of inter and main crop, the planting time of the intercrop has to be optimized

90 so that the maximum nutrient demand of the two components occurs at different times (Carruthers
91 et al., 2000). The timing of intercrops could also affect N₂O emissions if N mineralization from
92 legume residues is poorly synchronized with the N requirement of the cereal crop. This can be
93 counteracted by reducing mineral N additions to intercropping systems, but the timing of the
94 intercrop (sowing date relative to the cereal crop) remains an issue that has, to the best of our
95 knowledge, not been studied with regard to N₂O emissions.

96 Intercropping and mulching may also affect the soil's capacity to oxidize atmospheric CH₄ as
97 abundant NH₄⁺ might inhibit methanotrophs (Laanbroek and Bodelier, 2004). However, field
98 studies with incorporation of leguminous or non-leguminous catch crops have been inconclusive
99 (e.g. Sanz-Cobena et al., 2014). In a meta-study on CH₄ fluxes in non-wetland soils, Aronson and
100 Helliker (2010) concluded that N inhibition of CH₄ uptake is unlikely at fertilization rates below
101 100 kg N ha⁻¹ y⁻¹ and that much to the contrary, N addition may stimulate CH₄ uptake in N-limited
102 soils. Ho et al. (2015) found that incorporation of organic residues stimulated CH₄ uptake even in
103 fairly N-rich Dutch soils. Apart from providing reactive nitrogen to the soil, leguminous intercrops
104 may also affect CH₄ uptake by lowering soil moisture and thus increasing the diffusive flux of
105 atmospheric CH₄ into the soil. For instance, Wanyama et al. (2019) found that CH₄ uptake in soil
106 was negatively correlated with mean annual water-filled pore space in a study on different land
107 use intensities in Kenya.

108 In a review on N₂O fluxes in agricultural legume crops, Rochette and Janzen (2005) concluded
109 that the effect of legumes on N₂O emission is to be attributed to the release of extra N by
110 rhizodeposition of soluble N compounds and decomposition of nodules rather than to the process
111 of nitrogen fixation itself. Intercropped legumes may thus affect N₂O emissions in two ways: by
112 directly providing organic N or by modulating the competition between plants and microbes for
113 soil N, for example by acting as an additional N sink prior to nodulation. Compared to mineral
114 fertilizers, N supply from biological fixation is considered environmentally friendly as it can
115 potentially replace industrially fixed N (Jensen and Hauggaard-Nielsen, 2003), provided that crop
116 yields remain the same. However, combining easily degradable crop residues with synthetic N can
117 lead to elevated N₂O emissions (Baggs et al., 2000), potentially compromising the environmental
118 friendliness of intercropping in CSA. It is well known that the effect of crop residues on N₂O
119 emission depends on a variety of factors such as residue amount and quality (C:N ratio, lignin and
120 cellulose content), soil properties (e.g. texture), placement mode (mulching, incorporation) and

soil moisture and temperature regimes (Sanz-Cobena et al., 2014, Li et al., 2016). So far, there is only a limited number of studies addressing the effect of legume intercropping on N₂O emissions and CH₄ uptake in SSA crop production (Baggs et al., 2006; Millar et al., 2004; Dick et al., 2008).

The main objective of the present study was to evaluate the effects of forage legume intercropping with maize on N₂O and CH₄ emissions during maize production in the Ethiopian Rift Valley. We hypothesized that forage legumes increase N₂O emissions and decrease CH₄ uptake depending on above-ground biomass, legume species and sowing date; legumes intercropped three weeks after sowing of maize would result in higher yields than those intercropped six weeks after maize and lead to increased N₂O emissions if used with full-dose mineral fertilization. With late intercropping, legume yields would be suppressed having no or little effect on N₂O emissions. Hence, choosing legume species, sowing date and accounting for potential N inputs from legume intercrops could allow for better management of legume intercropping in SSA with reduced GHG emissions.

2. Materials and methods

2.1 Study area

The field experiment was conducted during two years (2015-2016) at the Hawassa University Research Farm, 07°33'3.4"N and 38°30'20.4"E at an altitude of 1660 m a.s.l.. The mean annual rainfall is 961 mm, with a bimodal pattern. The rainy season between June and October accounts for close to 80% of the annual rainfall. Average maximum and minimum monthly temperatures are 27.4 and 12.9°C, respectively. The soil is clay-loam (46% sand, 26% silt, 28% clay) derived from weathered volcanic rock (Andosols), with a bulk density of $1.25 \pm 0.05 \text{ g cm}^{-3}$, a total N content of 0.12%, an organic C content of 1.64%, an available Olsen P content of 175 mg kg⁻¹ and a pH_{H2O} of 6.14.

2.2 Experimental design and treatments

Experimental plots (20 m²) ~~with six treatments~~ were laid out in a complete randomized block design (RCBD) with four replicates ~~and six treatments~~: unfertilized maize monocrop (M-F), fertilized maize monocrop (M+F), crotalaria intercropping three (M+Cr3w) and six (M+Cr6w) weeks after sowing maize and lablab intercropping three (M+Lb3w) and six (M+Lb6w) weeks

after sowing maize (Table 2). Seed bed was prepared in both years by mold board plow to a depth of 0.25 m followed by harrowing by a tractor. A hybrid maize variety, BH-540 (released in 1995) was sown on May 30, 2015 and May 7, ~~in 2015 and 2016, respectively~~. Maize was planted at a density of 53,333 plants ha⁻¹. Following national fertilization recommendations, diammonium phosphate (18 kg N, 20 kg P) was applied manually at planting and urea (46 kg N) four weeks after sowing maize, to all treatments except for the unfertilized control. The N fertilization rate was halved for the intercropping treatments in the 2016 season to account for carry-over of N from forage legumes grown in the previous year. The forage legumes crotalaria (*C. juncea*) and lablab (*L. purpureus*) were planted between maize rows at a density of 500,000 and 250,000 plants ha⁻¹, respectively.

The above-ground forage legume biomass was harvested at flowering and half of it was removed. The remaining half was spread manually between the maize rows after cutting the fresh biomass into ~10 cm pieces. Three- and 6-week intercrops were mulched on 27 July and 4 September in 2015 and 2 August and 8 September in ~~2015 and 2016, respectively~~. As the mulching was done plot wise, plots within the same treatment received different amounts of mulch depending on the legume yield of each plot. In the 2016 growing season, all treatments were kept on the same plots as in 2015, capitalizing on plot-specific N and C input from previous mulch. Aboveground dry matter yield was determined by drying a subsample at 72°C for 48 hours and C and N contents were measured by an element analyser.

2.3 N₂O and CH₄ fluxes and ancillary data

GHG exchange was monitored weekly at ~~random-different~~ spots within the middle maize row by static, non-vented chambers (Rochette et al., 2008). We used custom-made aluminum chambers with an internal volume of 0.144 m³ and a cross-sectional area of 0.36 m² (Fig. S1). The chambers were pushed gently ~3 cm into the soil including 2 - 5 legume plants in the headspace. The septum was left open during deployment; once the chamber was inserted into the soil, the septum was before-closeding the septum and the base of the chamber was sealeding around the circumference using the chambers around their circumference with moist clay.

Sampling was carried out weekly during the period June to September in 2015 and May to September in 2016 on 15 and 17 sampling dates, respectively. Gas samples were collected between 9:00 am and 2:00 pm. For each flux estimate, four gas samples were drawn from the chamber

headspace at 15 min intervals, starting immediately after deployment. Samples were taken with a 20 ml polypropylene syringe equipped with a 3-way valve. Before transferring the sample to a pre-evacuated 10 cc serum vial crimp-sealed with butyl septa, the sample was pumped 5 times in and out of the chamber to obtain a representative sample. Overpressure in the septum vials was maintained to protect the sample from atmospheric contamination during storage and shipment to the Norwegian University of Life Sciences, where the samples were analyzed by gas chromatography. Helium-filled blank vials were included to evaluate contamination, which was found to be less than 3% of ambient.

All samples were analyzed on a GC (Model 7890A, Agilent Santa Clara, CA, USA) connected to an auto-sampler (GC-Pal, CTC, Switzerland). Upon piercing the septum with a hypodermic needle, ca. 1 ml sample is transported via a peristaltic pump (Gilson minipuls 3, Middleton, WI, USA) to the GC's injection system, before reverting the pump to backflush the injection system. The GC is configured with a Poraplot U wide-bore capillary column connected to a thermal conductivity, a flame ionization and an electron capture detector to analyze CO₂, CH₄ and N₂O, respectively. Helium 5.0 was used as carrier and Ar/CH₄ (90:10 vol/vol) as makeup gas for the ECD. For calibration, two certified gas mixtures of CO₂, N₂O and CH₄ in Helium 5.0 (Linde-AGA, Oslo, Norway), one at ambient concentrations and one ca. 3 times above ambient were used. A running standard (every tenth sample) was used to evaluate drift of the ECD signal. Emission (CO₂, N₂O) and uptake (CH₄) rates were estimated by fitting linear (with R^2 generally ≥ 0.85) or quadratic functions to the observed concentration change in the chamber headspace and converting them to area flux according to eq. 1

$$F_{GHG} (\mu g m^{-2} h^{-1}) = \frac{dc}{dt} * \frac{V_c}{A} * \frac{M_n}{V_n} * 60 \quad \text{Eq. (1)}$$

where, F_{GHG} is the flux ($\mu g N_2O-N m^{-2} h^{-1}$ in case of N₂O; $\mu g CH_4-C$ in the case of CH₄), $\frac{dc}{dt}$ the rate of change in concentration over time (ppm min⁻¹), V_c the volume of the chamber (m³), A the area covered by the chamber (m²), M_n the molar mass of the element in question (g mol⁻¹) and V_n the molecular volume of gas at chamber temperature (m³ mol⁻¹). A quadratic fit was only used in cases where N₂O accumulation in the chamber showed a convex downwards and CH₄ uptake a convex upwards trend (i.e. decreasing emission or uptake rates with time) to estimate time-zero rates. R^2 values for fluxes $> 3 \mu g N_2O-N$ or $CH_4-C m^{-2} h^{-1}$ were generally ≥ 0.85 ; fluxes $< 3 \mu g$

had lower R^2 values in some cases but were still included to capture periods with low flux activity.

Fluxes were cumulated plot-wise by linear interpolation for each growing season.

In 2016, soil moisture and temperature at 5 cm depth were monitored hourly using data loggers (Decagon EM50, Pullman, WA, USA) together with ECH₂O sensors (Decagon) for volumetric soil water content (VSWC) and temperature at five points across the experimental field. The sensors were placed in the experimental field at 5 random spots. No data are available for the 2015 season, due to equipment failure.

Soil bulk density was measured at 10 random spots in the experimental field using 100 cm³ steal cylinders and drying them at 105-°C for 24 hours. To calculate daily water filled pore space values for the 2016 growing season, a particle density of 2.65 g cm⁻³ was assumed:

$$WFPS = VSWC / (1 - \frac{BD}{PD}) * 100 \quad \text{Eq. (2)}$$

where *WFPS* is the water filled pore space, *VSWC* the volumetric soil water content, *BD* the bulk density and *PD* the particle density. Daily rainfall data were collected using an on-site rain gauge.

2.4 Estimating N inputs and N₂O emission factors

N input from forage legume crop residues was estimated from measured above-ground dry matter yield, its N content and the amount of mulch applied. To account for belowground inputs a shoot to root ratio of two was assumed for both crotalaria and lablab (Fageria et al., 2014). Dry matter yields of forage legumes differed greatly depending on sowing time, with generally larger yields in 3-week than 6-week intercropping. Also, forage legumes sown three weeks after maize grew faster and were harvested and mulched earlier than those sown six weeks after maize. We assumed that 50% of the legume N (mulched and belowground) was released during the growing season but reduced this amount to 30% for the aboveground component (mulch) of the 6-week treatments to account for the later mulching date. The proportions becoming available during the growing seasons are conservative estimates based on Odhiambo (2010), who reported that about 50% of N contained in crotalaria, lablab and mucuna was released during a 16-week incubation experiment at optimal temperature and moisture conditions. Placing litter bags into dry surface soil, Abera et al. (2014) found that legume residues decomposed rapidly under *in situ* conditions in the Ethiopian Rift Valley, releasing up to 89% of the added N within 6 months.

239 For the second year, 50% of the N left after the growing season (below and aboveground) was
 240 assumed to become available, on top of the N-input from the newly sown forage legumes. Dry
 241 matter yields of forage legumes and estimated N input for the two years are presented in Table 1.

242 Treatment-specific, growing-season N₂O emission factors were calculated as:

$$243 \quad N_2O \text{ EF} = \frac{(N_2O_{treatment} - N_2O_{control})}{N_{input}} * 100 \quad \text{Eq. (3)}$$

244 where $N_2O \text{ EF}$ is the N₂O emission factor (% of N input lost as N₂O-N), $N_2O_{treatment}$ the cumulative
 245 N₂O-N emission (from sowing to harvest) in the fertilized and intercropped treatments, $N_2O_{control}$
 246 the emission from the ~~0N0P-M-F~~ treatment (background emission) and N_{input} the estimated total
 247 input of N.

248 Non-CO₂ GHG emissions were calculated as CO₂ equivalents balancing cumulative seasonal N₂O-
 249 N emissions with CH₄ uptake on the plot level and averaging them for treatments (Table 2, Fig.
 250 5).

251 **2.5 Grain yields and yield-scaled N₂O emissions**

252 Maize grain yield was determined by manually harvesting the three middle rows (to avoid border
 253 effects) of each plot, and was standardized to 12.5% moisture content using a digital grain moisture
 254 meter. All values were extrapolated from the plot to the hectare. To estimate yield-scaled N₂O
 255 emissions (g N₂O-N ton⁻¹ grain yield), cumulative emissions were divided by grain yield.

256 **2.6 Statistical analysis**

257 Differences in cumulative CH₄ and N₂O emissions between treatments in each cropping season
 258 were tested by analysis of variance (ANOVA) with LSD used for mean separation after testing the
 259 data for normality and homoscedasticity. Cumulative seasonal N₂O emissions for 2015 were log-
 260 transformed. Statistical significance was declared at $P \leq 0.05$.

261

3. Results

3.1 Weather conditions

The year 2015 was one of the most severe drought years in decades and, as a result, sowing in 2015 was delayed by 3 weeks as compared to 2016. Rain fell late during the growing season and the cumulative rainfall for April to October was about 100 mm lower in 2015 than in 2016 (Fig. 1d, g).

3.2 N₂O fluxes

N₂O emission rates in 2015 (treatment means, n=4) ranged from 1.1 to 13.7 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ for the control treatment (Fig. 1a). Similarly, for fertilized maize, N₂O emissions ranged from 2 to 23.5 $\mu\text{g N m}^{-2} \text{ h}^{-1}$. Emission fluxes were generally larger for the 3-week intercropped treatments: the 3-week crotalaria treatments emitted N₂O at rates of 1.7 - 34.3 and the 3-week maize-lablab emitted 1.9 - 62.7 $\mu\text{g N m}^{-2} \text{ h}^{-1}$, whereas the 6-week maize-crotalaria emitted 2.1 - 24.2 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ and the corresponding rate for the 6-week maize-lablab intercrop was when intercropped 3 or 6 weeks after maize, respectively, while maize-lablab emitted 1.9 - 62.7 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ when sown 3 weeks and 1.5 - 10.7 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ when sown 6 weeks after maize. The generally low emission rates in the latter system (6-week lablab intercropping) systems corresponded to poor growth of lablab due to shading by the maize plants. Irrespective of legume species, the highest emission rates were found for intercrops planted three weeks after maize (Fig. 1b, c). A peak of N₂O emission occurred in the 3-week intercropping systems around mid-August, 2015, which was significantly larger than in the unfertilized control (P=0.013), the fertilized maize monocrop (P=0.001), and the 6 weeks crotalaria (P=0.021) and lablab (P=0.002) intercrops.

During the 2016 season, N₂O emission rates in the M-F treatment (unfertilized 0N-control) varied between 2.5 and 22.8 $\mu\text{g N m}^{-2} \text{ h}^{-1}$, peaking at the beginning of the season when WFPS was >50%. There were no significant differences in WFPS values between treatments (data not shown). Fertilized maize had similar rates (3.1 - 24.2 $\mu\text{g N m}^{-2} \text{ h}^{-1}$) peaking at around four weeks after planting. Maize-forage legume treatments had larger emission rates, ranging from 1.8 to 40.2 for 3-week crotalaria planted 3 weeks after maize and 3.2 to 58.6 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ for 6-week crotalaria for crotalaria planted 3 and 6 weeks after maize, respectively and 3.9 to 38.0 for 3-week lablab and 1.9 to 45.2 $\mu\text{g N m}^{-2} \text{ h}^{-1}$ for 6-week lablab planted 3 and 6 weeks after maize, respectively. In general, emission rates were higher in the beginning than in the end of the cropping season (Fig.

1d-f). Despite higher fluxes for intercropping treatments than in the unfertilized control in week 1 (P=0.162) and 4 (P=0.061), there were no statistically significant differences in flux rates between the treatments.

3.3 Cumulative N₂O emissions

During the 2015 growing season, all treatments had equal or higher cumulative N₂O emissions than the unfertilized control, with the 3-week lablab intercropping system emitting significantly more N₂O than the unfertilized control (p=0.006) and the 6-week lablab intercrop (Fig. 2a). Comparing intercropping treatments with the fertilized control, lablab sown 3 weeks after maize clearly increased N₂O emissions but not significantly (P=0.35), whereas all other intercropping treatments had cumulative N₂O emissions comparable with fertilized maize control. Regarding sowing date, 3-week lablab had significantly higher N₂O emissions (P<0.01) than its 6-week counterpart, whereas no such effect was seen for crotalaria.

During the 2016 growing season, lablab intercropping 3-weeks after maize showed significantly higher (P<0.01) cumulative N₂O emissions than the unfertilized control, but there was no difference between fully fertilized maize monocrop and intercropped maize treatments fertilized with 50% of the mineral N applied in 2015, nor was there any effect of intercropping date (3 vs. 6 weeks; Fig. 2b).

3.4 Legume and maize yields

Aboveground yields of lablab were generally higher than those of crotalaria (Table 1). Intercropping three weeks after maize resulted in higher biomass yields compared to six weeks for both legume species. Both legumes grew poorly during the second growing season, particularly crotalaria. Maize grain yields differed greatly between the years and were roughly 20% higher in the wetter year of 2016 (Table 2). Better growth conditions for maize in the second year resulted in smaller yields of intercrop legumes.

3.5 N₂O emission factor and intensity

Growing-season emission factors (EF) varied from 0.02 to 0.25 in 2015 and 0.11 to 0.20% in 2015 and 2016, respectively (Table 2). Of the intercropped treatments, lablab intercropped 3 weeks after maize resulted in a significantly larger emission factor than fertilized maize and other intercropping treatments, whereas there was no significant difference in 2016. Overall, growing-season N₂O emission factors were ~ 40% higher in 2016 than in 2015, which is mainly due to the

smaller N input in 2016 which was 25 to 45% lower than in 2015, except for the 3-week lablab system which had an estimated 18% higher N input in 2016 than 2015 (Table 1). The latter was due to the extraordinary high lablab yield in the previous year and its stipulated carryover (Table 1).

Mean yield-scaled N_2O emissions in 2015 varied between 25 to 55 $\text{g N}_2\text{O ton}^{-1}$ grain yields. In 2015, 3-week lablab had a higher N_2O intensity than 6-week lablab, whereas all other differences were insignificant. In 2016, with mineral N fertilization reduced to 50%, N_2O emission intensities varied from 26 to 37 $\text{g N}_2\text{O ton}^{-1}$ grain, with no significant effect of legume species, sowing date or N fertilization (Table 2).

To further explore the variability of N_2O emissions, we plotted cumulative N_2O emissions plot-wise against legume N yield, but found no relationship (not shown). However, when plotting yield-scaled N_2O emission over legume N yield, a significant positive relationship ($P=0.01$) emerged for 2015, but not 2016 (Fig. 3a, b), suggesting that leguminous N input increased N_2O emissions more than maize yields in the dry year of 2015.

3.6 CH_4 fluxes

All treatments acted as net sink for CH_4 , with uptake rates ranging from 31 to 93 $\mu\text{g C m}^{-2} \text{h}^{-1}$ in 2015 (Fig. 4a-c). Uptake rates in 2015 were rather constant in time with somewhat elevated uptake rates towards the end of the season. There were no obvious treatment effects. By contrast, in the wetter year of 2016, CH_4 uptake showed a pronounced maximum in the beginning of June with uptake rates of up to 140 $\mu\text{g C m}^{-2} \text{h}^{-1}$ irrespective of treatment (Fig. 4d-f), when WFPS values declined to values below 25% (Fig. 4g). Methane uptake during this period tended to be greatest in the unfertilized control, while intercropping treatments had smaller uptake rates, which, however, were not significantly different from maize monocrop treatments. Differences between treatments at single sampling dates were insignificant throughout the season. Highest CH_4 uptake in 2016 was recorded with lowest WFPS (~10%).

3.7 Cumulative CH_4 uptake

Cropping season cumulative CH_4 uptake exceeded 1 kg C ha^{-1} in both years with no significant effect of intercropping, legume species or time of intercropping (Fig. S2a, b). Maize intercropped with crotalaria tended to take up less CH_4 but this effect was not statistically significant in 2015 or 2016 ($P=0.056$). Plotting cumulative CH_4 uptake plot-wise over legume dry matter yield did not

result in a significant relationship, but highest seasonal uptake rates occurred in plots with lowest legume dry matter yield (data not shown).

3.8 Total non-CO₂ GHG emissions

The relative contribution of CH₄ to the non-CO₂ GHG emission of the different cropping systems varied between 22 and 69% and was highest in the non-fertilized maize monocrop. Three-week lablab intercropping resulted in significantly higher total emissions compared with 6-week lablab intercropping and maize mono-cropping (Table 2). By contrast, in 2016, legume species but not intercropping time affected the non-CO₂ GHG emission balance ($P < 0.05$). Lablab intercropped 3 weeks after maize resulted in significantly higher ($P < 0.05$) total GHG emission than the unfertilized control but was indistinctive from the fertilized maize monocrop, or other intercrop treatments (Table 2, Fig. 5a, b).

4. Discussion

4.1 Maize-legume intercropping and N₂O emissions

Background N₂O emissions (in unfertilized maize monocrop) fluctuated between 1.1 and 23.0 $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$, which is in the range of previously reported emission rates for soils in SSA with low N fertilizer input (0 – 20 $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$; Pelster et al., 2017). Baseline emissions were somewhat higher in the wetter season of 2016, owing to ~100 mm more rainfall in the beginning of the season (Fig. 1d, g). Elevated emission rates $> 30 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ occurred in 2015 on few occasions in intercrop treatments, notably in mid-August when rain fell right after mulching of the 3-week intercrops. Mulching of the 6-week intercrops did not affect N₂O emissions, probably because the mulched legume biomass was too small to affect the flux (Fig. 1b, c; Table 1). In 2016, mulching of the 3-week legumes was followed by rainfall, increasing the WFPS to 50% (Fig. 1g), however, without resulting in elevated N₂O emission rates (Fig. 1e, f). Together, this suggests that the direct effect of mulching on N₂O emission is highly dependent on soil moisture and the amount of mulch and cannot be generalized, contrary to our hypothesis that legume intercrops would invariably increase N₂O emissions.

Legume dry matter yields varied strongly (100 to 3000 kg ha^{-1}) throughout the two experimental years (Table 1, Fig. 3), depending on species, intercropping time and weather. Lablab grew more

vigorously and realized larger dry matter yields than crotalaria (Table 1). Moreover, lablab is known to be a better N₂ fixer than crotalaria (Ojiem et al., 2007), presumably leading to higher N input, which would explain larger N₂O emissions with this intercrop (Fig. 2). Three-week intercrops performed generally better than 6-week intercrops. This was particularly apparent for the low-growing lablab (Table 1). Weather in the beginning of the season played a major role for the growth performance of the intercrops by controlling maize growth, which in turn controlled legume growth by shading. Together, this resulted in a wide range of potential leguminous N-inputs in our experiment, which could be used to examine their overall effect on N₂O emissions on a seasonal basis under the semi-arid conditions of the central Ethiopian rift valley. Surprisingly, we did not find any significant relationship between estimated total N input or legume N yield and cumulative N₂O emission. This may be due to the notoriously high spatial and temporal variability of N₂O emissions rates (Flessa et al., 1995), or reflect the fact that intercropping had no or opposing effects on N₂O forming processes. Cumulative N₂O emissions and legume N yields integrate over the entire season and do not capture seasonal dynamics of soil N cycling and N uptake, which could obscure or cancel out transient legume effects on N₂O emissions. Possibly, N released in intercropping treatments was efficiently absorbed by the main crop, even though intercropping did not lead to significantly higher maize grain yields in our experiment. Alternatively, changes in physicochemical conditions brought about by intercrops, such as potentially lower soil moisture due to more evapotranspiration, may have counteracted the commonly observed stimulating effect of legume N on N₂O emissions (Almaraz et al., 2009, Sant'Anna et al., 2018).

We found a significant positive relationship between N₂O intensity and legume N yields in 2015, suggesting that intercropped legumes indeed increase N₂O emissions relative to maize yields (Fig. 3a). It is impossible to say, however, whether this relationship was driven by the extra N entering the system through biological N fixation, or whether an increasing legume biomass affected physicochemical conditions in the rhizosphere favoring N₂O formation. In 2016, legume dry matter yields were much lower than in 2015, owing to early rains favoring maize growth, and no significant relationship with N₂O intensity was found (Fig. 3b). This illustrates that the effect of legume intercropping on N₂O emissions is highly dependent on sowing date and weather, both of which control the growth of legume and main crops and ultimately the amount and fate of leguminous N in the intercropping system. Our data suggest that excessive accumulation of leguminous biomass in SSA maize cropping enhances the risk for elevated N₂O emissions.

412 We expected N₂O emissions to respond more strongly to intercropping in the second year (2016),
413 as legume mulches were applied according to their plot-wise aboveground yields in the previous
414 year. Indeed, N₂O emission rates were clearly higher in intercropping treatments on the first
415 sampling date in 2016 (Fig. 1e, f), indicating increased N cycling in mulched plots (Campiglia et
416 al., 2011). This difference vanished quickly, however, suggesting that the effect of intercrop
417 mulches, even at high amounts (Table 1), on N₂O emissions in the subsequent year was negligible.
418 It is noteworthy that our estimates of the fraction of N carried over between the years were based
419 on literature data (Table 1), and that a considerable part of the mulched N may have been lost
420 during abundant rainfalls (300 mm) early in the 2016 season before crops were sown.

421 Cumulative N₂O emissions from intercrops, with mineral fertilization rate halved, were
422 comparable to those in the fully fertilized maize monocrop in 2016. This may be partly due to the
423 50% reduction in mineral N application to intercrop treatments, as found by others (Tang et al.,
424 2017). Another reason may be that a considerable proportion of the cumulative emission in 2016
425 occurred before or shortly after 3-week intercrops were sown, and was thus unaffected by growing
426 legumes. Overall, cumulative N₂O emissions were equal or higher in 2016 than in 2015, despite
427 reduced mineral N addition to intercrops and lower legume biomass. Ultimately, the lack of a clear
428 emission response to legume intercropping in the second year calls for studies tracing cumulative
429 mulching effects over multiple years and exploring their driving factors in more detail. In our
430 study, amount and timing of rainfall appeared to be more important for N₂O emissions in the
431 second year than amount and carryover of legume N.

432 Given our finding that N₂O intensity responded positively to legume biomass and its N content in
433 a drought year with poor maize growth, intercrop species as well as sowing and harvest dates
434 (relative to the main crop) emerge as viable management factors for controlling the accumulation
435 of legume biomass between the maize rows and hence the risk for increased N₂O emission.
436 Legume species and cultivar in intercropping systems are known to be critical for N loss, both
437 during the intercropping and the subsequent seasons (Pappa et al., 2011, Weiler et al., 2018). The
438 stimulating effect of crop residues on N₂O emission has been reported to depend on residue quality
439 and soil moisture, with denitrification being the likely process (Li et al., 2016). Our study provides
440 evidence that vigorous growth of high yielding legume intercrops can enhance N₂O emissions in
441 years unfavorable for maize growth, whereas in years with sufficient water availability early in the
442 growing season, maize growth is favored preventing excessive growth of the intercrop. Our study

therefore points to optimizing the sowing date in response to expected emergence and growth of maize as a promising option to control growth of the intercrop and hence to deal with the risk of increased N₂O emissions.

4.2 Seasonal N₂O and CH₄ emission, EF_{N₂O} and total GHG emission

Growing season N₂O emissions in fertilized treatments varied from 0.17 to 0.33 (2015) and 0.23 to 0.3 (2016) kg N₂O-N ha⁻¹ in 2015 and 2016 covering a period of 107 (2015) and 123 (2016) days, respectively (Fig. 2), and a range of estimated total N inputs from 36.4 to 97.8 kg N ha⁻¹ (Table 1). There are no N₂O emissions studies for maize-legume intercropping in the Ethiopian Rift valley so far. Hickman et al. (2014a) reported N₂O emissions of 0.62 and 0.81 kg N ha⁻¹ over 99 days for 100 and 200 kg N input ha⁻¹, respectively, for a maize field without intercropping in humid western Kenya, which seems to be higher than seasonal emissions we found. Baggs et al. (2006), working in the same region with maize intercropped with legumes in an agroforestry system reported N₂O emissions ranging from 0.2 to 0.6 kg N ha⁻¹ with higher emissions in tilled intercropping treatments; our values are in the lower end of the range they reported. The largest seasonal N₂O emission for intercropping reported so far from SSA is 4.1 kg N ha⁻¹ (84 days) after incorporating 7.4 t ha⁻¹ of a *Sesbania macroptilium* mixture in humid western Kenya (Millar et al., 2004). Compared to the N₂O emissions reported for humid tropical maize production systems, our data suggest that maize-legume intercropping based on mulching in the sub-humid to semi-arid rift valley appears to be a minor N₂O source, mainly because of the relatively small amount of legume biomass mulched (Table 1). Growing season N₂O emission factors (EF) in our study ranged from 0.02 to 0.25 in 2015 and 0.11 to 0.20% in 2016 of the estimated total N input in 2015 and 2016, respectively, including assumed N inputs from legume mulch as well as belowground additions and carryover between the years (Table 1). Even if the estimated EF is doubled to account for off-season emissions, it is still lower than the annual IPCC default value of 1% N₂O-N per unit added N (IPCC, 2014). Our estimated EFs thus seem to be at the lower end of those reported by Kim et al. (2016) for SSA smallholder agriculture estimated from literature data (0.01 to 4.1%). The reasons for the low EFs in our study are probably the high background emissions in the fertile soil of the Hawassa University research farm which supports high maize yields even in the unfertilized control (Table 1) and the low levels of N input. The soil has been used over decades for agronomic trials with various fertilization rates with and without crop residue retention and legume intercropping (e.g. Raji et al., 2019). Thus, our field trial has to be considered

representative for intensive management as opposed to smallholder systems with minimal or no fertilization history.

Methane uptake by the soil in both seasons varied between 1.0 to 1.5 kg CH₄-C ha⁻¹ without showing any significant treatment effect, even though maize-legume intercrops tended to take up less CH₄ than maize monocrops (Fig. S1). The observed trend might relate to competitive inhibition of CH₄ oxidation by higher NH₄⁺ availability (Le Mer and Roger, 2001, Dunfield and Knowles, 1995) in the presence of legume intercrops, even though estimated total N inputs remained below 100 kg N ha⁻¹, which is considered a threshold for NH₄⁺ inhibition (Aronson and Helliker, 2010). Alternatively, densely growing legumes may have lowered CH₄ uptake through impeding CH₄ and/or O₂ diffusion into the soil (Ball et al., 1997). We did not observe stimulation of CH₄ uptake by legume intercropping, which we attribute to the absence of N and P deficiency in this fertile soil. Methane uptake rates varied from 20 to 140 µg CH₄-C m⁻² h⁻¹ which is in the range of rates reported previously for SSA upland soils (Pelster et al., 2017). Seasonal CH₄ uptake in our experiment offsets between 22 and 69% of the CO₂ equivalents associated with N₂O emissions without revealing any significant treatment effect (Fig. S2a, b), but the offset was relatively largest in the unfertilized maize monocrop and smallest in lablab intercropping. Hence, CH₄ uptake is an important component of the non-CO₂ climate footprint of SSA crop production.

4.3 Legume intercropping and climate smart agriculture

Legumes are an important N source in smallholder farming systems, where mineral fertilizers are unaffordable or unavailable. Legume intercrops maximize resource use efficiency as total productivity is often higher than in mono-cropping systems (Banik et al., 2006). Moreover, N fixed biologically by legume intercrops can partly replace synthetic N fertilizers, if the release is synchronized with the nutrient demand of the cereal crop. On the other hand, surplus N from legumes may result in N losses as NO₃⁻, NH₃ and NO, N₂O or N₂. Mulching and incorporation of legume biomass has been found to increase N₂O emissions under temperate conditions (Baggs et al., 2000, Baggs et al., 2003) and under humid tropical conditions (Millar et al., 2004). Also under semi-arid, Mediterranean conditions, vetch (*V. villosa*) used as a winter catch crop and mulched in spring significantly increased N₂O emissions during the fallow period while rape did not (Sanz-Cobena et al., 2014). This was later confirmed by a ¹⁵N study, highlighting the role of N mineralization from legumes as a source of N₂O (Guardia et al., 2016). None of the studies found

an overall N₂O saving effect of catch crops when scaling up to the entire crop cycle, even though the latter study used reduced mineral N fertilization rates in treatments with catch crops. By contrast, reduced NO₃⁻ leaching and N₂O emission has been reported from maize intercropped with legumes in the semi-arid North China plain, which the authors attributed to enhanced N uptake by both the inter and main crop and reduced soil moisture in treatments with intercrops during the rainy season (Huang et al., 2017). This shows that legume intercrops have a potential to both increase or reduce N₂O emissions with consequences for the non-CO₂ footprint of cereal production and hence for the viability of intercropping as a central component of CSA (Thierfelder et al., 2017).

The legume intercrops used in our study had low C:N ratios (Table S1) and can be expected to release a significant part of their N through decomposition of roots and nodules or root exudation as well as during decomposition of mulches (Fustec et al., 2010). The effect of mulching on N₂O emissions depends on the C:N ratio with increased emissions for low C:N ratio residues (Baggs et al., 2000, Shan and Yan, 2013). In line with this, N₂O emissions in intercrop treatments of our study exceeded those in fertilized maize monocrop on several sampling dates, both during active growth of legumes and after mulching. Another important aspect is the amount of legume N carried over between years which depends, among others, on amount and quality of the legume and the weather between the growing seasons. Abera et al. (2014) showed that surface-placed residues of haricot bean and pigeon pea decompose quickly despite relatively dry conditions during offseason. Vigorous rainfalls in the beginning of the growing season like in 2016 (Fig. 1) could lead to dissolved N losses, which could lead to indirect N₂O emissions elsewhere, which should be taken into account when evaluating intercropping as a CSA strategy.

5. Conclusion

While legume intercrops have the potential to improve cereal yields and diversify produces for smallholders in central Ethiopian rift valley, a risk of enhanced N₂O emissions remains, which became apparent as increased “N₂O intensity” of the main crop in a drought year (2015). At the same time, our study points at possibilities to counteract this trend by actively controlling legume biomass development and hence potential N input through “climate-smart” choices of legume species, sowing date and mulch amounts in response to prevailing environmental conditions. This

approach, however, is complicated by the annual variability in growth conditions and requires active planning of sowing and mulching time by the farmer. Our study was conducted on a relatively nutrient-rich soil (as compared to typical smallholder farms) which supports high yields of both maize and leguminous intercrops. Under these conditions, intercropped legumes can potentially replace a considerable part of synthetic fertilizer, thus supporting common CSA goals. However, more studies are needed to fully explore intercropping options in the framework of CSA in the rift valley, particularly in nutrient-poor smallholder fields. Future studies on CSA approaches in the rift valley should address, in addition to greenhouse gas emissions, N-runoff and soil organic matter build up, ideally in long-term field trials with and without legume intercropping. Future studies should also attempt to combine flux measurements with inorganic N dynamics and BNF measurements. Given that seasonal N₂O emission factors and intensities in our study were in the lower range of published values for SSA, intercropping appears as a promising approach to sustainable intensification in the Ethiopian Rift Valley.

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Table 1: N inputs from forage legumes and fertilization per treatment. Shown are mean values (n=4 ± standard error)

Legume	DMY	Aboveground N yield ^a	Belowground N yield ^b	N from mulch ^c	Mineral N	Carryover ^d	Total N input
kg N ha ⁻¹							
2015							
<i>Crotalaria</i>							
3w	1516±183	53.3±6.4	17.7±2.1	26.6±3.2	64		75.8
6w	345±65	12.1±2.3	4.0±0.8	6.1±1.1	64		66.4
<i>Lablab</i>							
3w	2221±340	96.8±14.8	32.3±4.9	48.4±7.4	64		82.9
6w	467±137	20.3±6.0	6.8±2.0	10.2±3.0	64		67.7
2016							
<i>Crotalaria</i>							
3w	468±85	16.4±3.0	5.47±1.0	8.21±1.5	32	11.1±1.3	56.8
6w	65±44	2.3±1.5	0.75±0.5	1.13±0.8	32	2.5±0.5	36.4
<i>Lablab</i>							
3w	1256±221	54.7±9.6	18.25±3.2	27.4±4.8	32	20.2±3.1	97.8
6w	186±60	8.1±2.6	2.70±0.9	4.06±1.3	32	4.2±1.2	43.0

^a N content of crotalaria and lablab was 3.51 and 4.36%, respectively, measured in 2 representative samples,

DMY=Dry matter yield

^b assuming a shoot-to-root ratio of 2 and an average belowground N input from the standing legumes of 50% during the growing season

^c returning half of the aboveground yield as mulch; assuming an average N release of 50% and 30% for 3-week and 6-week treatments, respectively, during the growing season

^d assuming that 50% of the remaining N becomes available in the following cropping season

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763 Table 2: Grain yields, growing-season N₂O emission factors and non-CO₂ GHG emission associated with
764 N₂O and CH₄ and N₂O emission intensities for fertilized treatments with and without legume intercropping
765 during 107 days in 2015 and 123 days in 2015 and in 2016, respectively. N input was estimated as outlined
766 in Table 1. Shown are mean values (n=4 ± standard error). Different letters indicate statistical difference at
767 p < 0.05.

Treatment	2015				2016			
	Maize Grain yield (kg ha ⁻¹)	N ₂ O emission factor (%)	Non-CO ₂ GHG emission (kg CO ₂ eq. ha ⁻¹)*	N ₂ O emission intensity (g N ₂ O-N ton ⁻¹ grain)	Maize Grain yield (kg ha ⁻¹)	N ₂ O Emission factor (%)	Non-CO ₂ GHG emission (kg CO ₂ eq. ha ⁻¹)*	N ₂ O emission intensity (g N ₂ O-N ton ⁻¹ grain)
M-F	4313±235 ^a		17.4±12 ^a	29.7±4.2 ^{ab}	6558±217 ^a		29.7±18 ^a	26.3±4.0 ^a
M+F	5022±133 ^{ab}	0.07±0.07 ^{ab}	38.4±25 ^a	34.4±8.8 ^{ab}	8403±342 ^b	0.20±0.03 ^a	91.4±16 ^{ab}	37.0±4.0 ^a
M+Cr3w	5882±249 ^{ab}	0.17±0.05 ^{ab}	78.0±12 ^{ab}	42.2±5.5 ^b	8276±236 ^b	0.16±0.08 ^a	78.3±19 ^{ab}	33.6±4.7 ^a
M+Cr6w	5316±316 ^{ab}	0.07±0.06 ^{ab}	47.0±15 ^{ab}	34.8±5.4 ^{ab}	8283±148 ^b	0.16±0.05 ^a	69.0±12 ^{ab}	27.8±2.0 ^a
M+Lb3w	5989±528 ^b	0.25±0.06 ^b	120.5±27 ^b	54.3±6.1 ^{ab}	8557±262 ^b	0.15±0.03 ^a	111.7±9 ^b	36.8±2.1 ^a
M+Lb6w	5541±492 ^{ab}	0.02±0.01 ^a	21.2±7 ^a	24.6±1.5 ^a	8306±501 ^b	0.11±0.07 ^a	62.3±25 ^{ab}	26.8±3.9 ^a

768 * N₂O: 300 CO₂ eq; CH₄: 25 CO₂ eq
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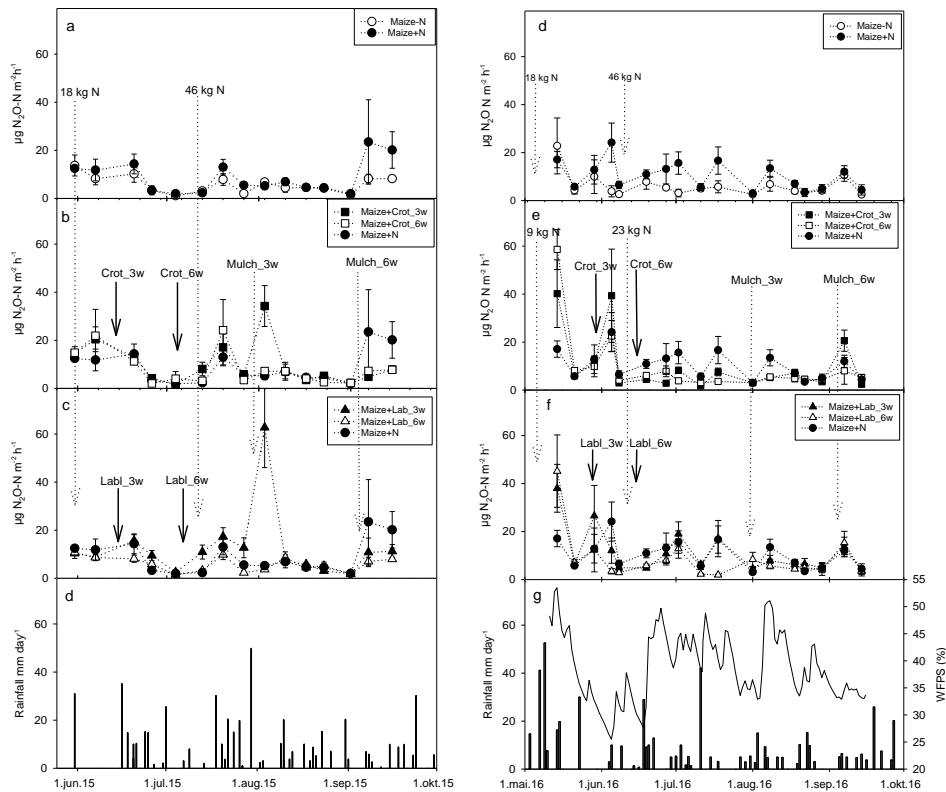


Figure 1: Mean N_2O emission rates ($n=4$; error bars = SEM) in 2015 (left panel) and 2016 (right panel) and daily rain fall and water-filled pore space (in 2016 only). Figures a and d show emission rates in the absence of intercrops, b and e with crotalaria and c and f with lablab intercrops.

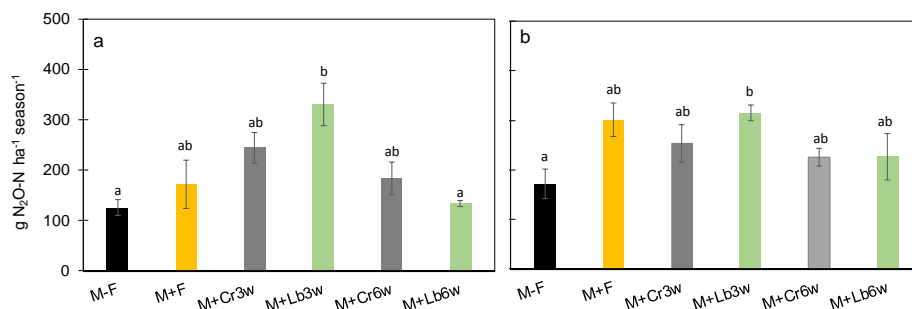


Figure 2: Cumulative seasonal N_2O-N (g N ha⁻¹ season⁻¹) in 2015 (a) and 2016 (b) throughout 107 and 123 days, respectively, in treatments with and without legume intercropping. Error bars denote SEM (n=4). Different letters indicate significant differences at p < 0.05. M+F: fertilized maize; M+Cr3w: fertilized maize with crotalaria sown 3 weeks after maize; M+Cr6w: fertilized maize with crotalaria sown 6 weeks after maize; M+Lb3w: fertilized maize with lablab sown 3 weeks after maize; M+Lb6w: fertilized maize with lablab sown 6 weeks after maize

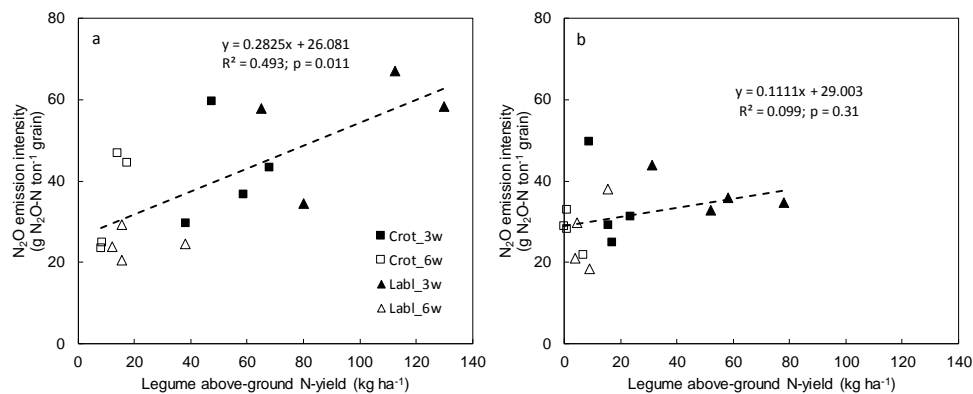


Figure 3: Relationship between N₂O emission intensity and aboveground intercrop legume N yield in intercrop treatments in 2015 (a) and 2016 (b). Shown are single-plot values for each treatment (n=4).

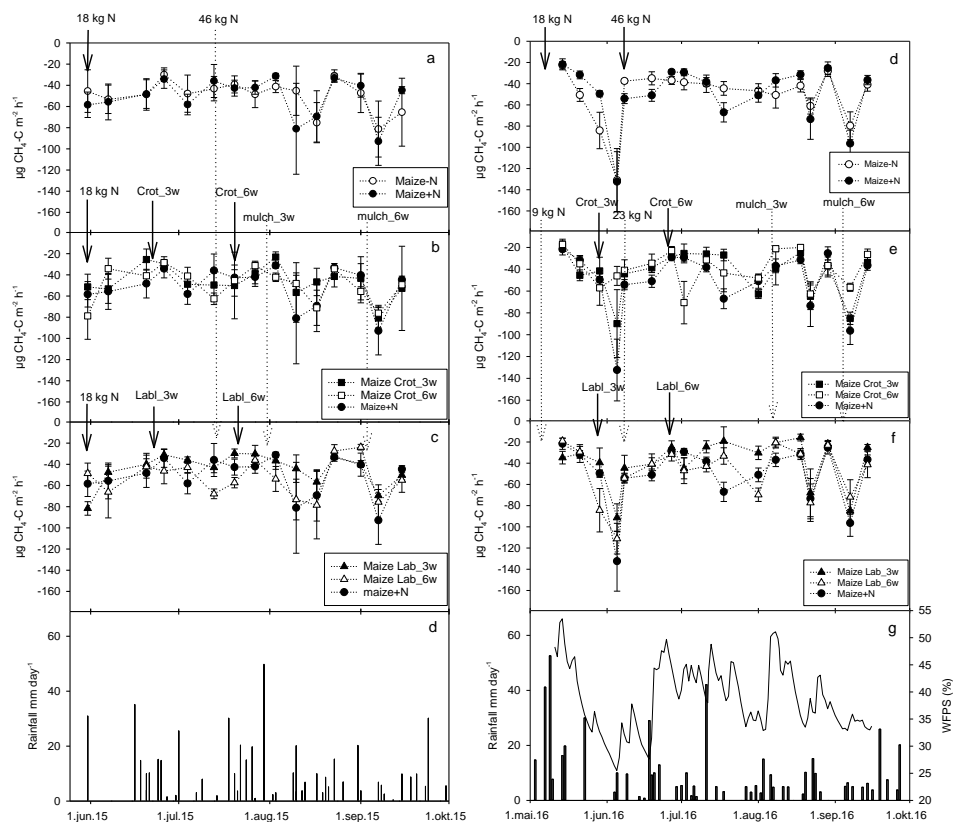
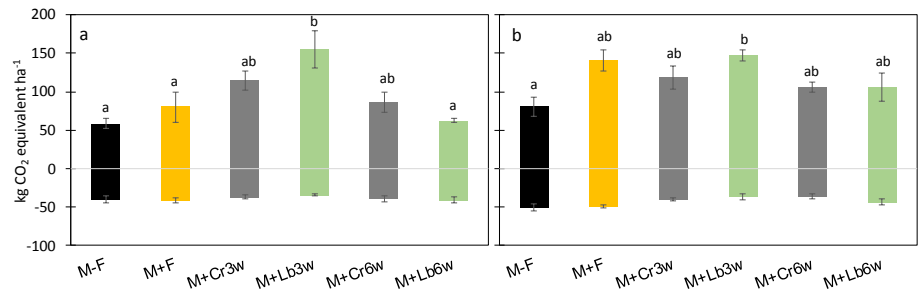


Figure 4: Mean CH₄ flux in 2015 (left panel) and 2016 (right panel) and daily rainfall and water-filled pore space (in 2016 only). Error bars show standard error of the mean (n=4). Figures a and d show emission rates in the absence of intercrops, b and e with crotalaria and c and f with lablab intercropping.

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819 Figure 5: Relative contribution of CH₄ uptake and N₂O emission to seasonal total non-CO₂ GHG
820 emissions in mono- and intercropping treatments in 2015 (a) and 2016 (b). Error bars indicate
821 standard deviation (n=4).