Authors' responses to the comments provided by three anonymous Referees

Overall, the INNOVATIVE ASPECTS of our work include:

- Realizing a practice-oriented experimental set-up including intercropping of local, market-relevant crops instead of academic testing of well studied but rather irrelevant grasses.
- Advancing the practical application of known principles including biochar application, EcoSan practices, and utilizing biogas slurry, by focussing on first season, as its success is crucial for implementation into practice, especially in smallholder agriculture in Sub-Saharan Africa.
- Studying, if significant alteration of hydraulic soil properties were present or not present, an aspect often overlooked or neglected in research about soil amendments.

<table>
<tr><th>#</th><th>Comments of anonymous Referee #1
SOIL Discuss., 2, C670–C671, 2016</th><th>Our responses</th></tr>
<tr><td>1</td><td>The results are of interest and of certain scientific relevance, and fit the scope of the journal.</td><td rowspan="2">We appreciate the general positive evaluation of the work we provided. We agree with the Referee's statement that parts of our manuscript were too descriptive and revised the manuscript accordingly. Therefore, we reworked former section 1.3, section 1.2 (p. 2-3) to point out more precisely the rational of using the analysed soil amendments. In addition, we shifted details about the materials used as amendments from the introduction to the section 2.2 on soil amendments (p. 4, lines 10-22).</td></tr>
<tr><td>2</td><td>But this manuscript is too descriptive and sometimes it seems more a project report than a scientific publication. The topic has been correctly introduced, but before the aim of the work is described in the final part of the introduction, a rather personalized description of previous experiments run with the materials used as amendments in the present manuscript seems a bit unconventional for this type of publications.</td></tr>
<tr><td>3</td><td>The description of the experimental design in the Materials and Methods section is not clear enough, and relies too much in that published in previous articles. This manuscript has to stand alone and a brief description of the amendments and a much clearer description of the experimental procedure have to be added to the text.</td><td>We agree and rephrased the chapter 2 on "Material and Methods" accordingly so that after this revision, the paper itself delivers all needed information. As above-mentioned, we described the soil amendments in more detail in section 2.2 (p. 4, lines 11-23).</td></tr>
<tr><td>4</td><td>For example, the number of replicate plots per treatment is not mentioned until page 1228, some basic information about the different amendments (pH, moisture/organic matter content, etc.) cannot be found throughout the manuscript, and the description of the grass cover used with that treatment in not clear.</td><td>After revising the manuscript, the number of replicates is given in the Abstract, in section 2.2. (p. 4, lines 4) and in section 2.7 (p. 7, lines 15-16).
We added an additional table (Table 2) providing information about the amendment's chemical characteristics, nutrient contents, etc.
We further agree that the description on the grass-cover in the biogas slurry treatment was rather difficult to understand so we rephrased it accordingly (p. 4, lines 11-13).</td></tr>
<tr><td>5</td><td>It is also strange the fact that two of the crops (African egg and pepper) are not used or mentioned in the results and discussion of the manuscript.</td><td>We planted African eggplant and pepper as part of the chosen intercropping system. The local agricultural expert recommended this be in line with local agricultural practices. However, these two plant species are perennial and harvesting started only in June 2014 when our experiment was finished. So we decided to integrate them in the intercropping but exclude them from analysis. We made this point clearer in our revised manuscript (p. 5, lines 3-6).</td></tr>
<tr><td>6</td><td>The latter section is too descriptive, and the text is quite difficult to read in a comprehensive way, as too many parameters are commented in too much detail.</td><td>We agree. To significantly improve the chapter "Results & Discussion", we changed the manuscript for the revised submission as follows:</td></tr>
</table>

		1. We eliminated section 3.5 where we formerly provide an outlook on how the tested soil amendments can contribute to close nutrient cycles on small-scale farms in Karagwe. We assume, by withdrawing this section we will enhance the focus on the results of the field experiment. Nevertheless, we shortened this section and integrated it in the revised conclusions (p. 12, lines 5-8). 2. We further eliminated section 3.6 for reducing the amount of information provided in chapter three and for supporting the readers' focus on the most important results of the experiment. (Please, also see our response to comment #10.) 3. We completely rewrote the chapter and tried to improve readability markedly.
7	The manuscript would benefit from a summarized results and discussion section, where the main effects of the different amendments are commented as a whole for the different crops.	We agree and adjusted the manuscript accordingly. We summarized the main results at the beginning of chapter 4 (p. 12, lines 2-5).
8	This part of the manuscript needs to read better and to include a deeper discussion of the results, which are simply compared to previous ones in the current version of the article. The effects observed in the soil and, especially, in the different crops, have to be related to the properties of the amendments and to the changes in the soil physico-chemical properties and nutritional status.	We agree that the observed effects need to be discussed in relation to the soil amendments. However, in our opinion we did so by discussing effects on plant growth, plant nutrition and changes in soil properties. For example, we discussed different P contents in the tested soil amendments and related them to the observed differences in CAL-extractable concentrations of soil P (p. 8, lines 12-22). Furthermore, we applied the vector nutrient analysis to identify the primary response of maize plants to improved P availability (p.10, lines 27-34). In addition, we discussed the different CaO-equivalents of the soil amendments in the context of the observed changes in soil pH (p.8, lines 23-34). We also discussed, that under the given tropical conditions, an increase in soil pH will positively affect the availability of nutrients in the soil, hence stimulate biomass growth. As typical for the local Andosol, nutrient deficiencies and acidity in the soil were most present on the unamend control plots, which depressed plant growth. Nevertheless, we worked on improving general comprehensibility of chapter four.
9	Section 3.4 (nutrient balancing) is not clear at the moment and may have to be reconsidered and rewritten by the authors in a more comprehensive way.	We agree and adjusted the text accordingly. We hope that now, section 3.4 is more comprehensible and can be better understood.
10	Section 3.6 (further aspects) is somehow speculative and may have to rely on the results of the present experiment.	We agree and reacted on this important comment by withdrawing section 3.6. We erased the subjective impressions and kept only two relevant aspects: (i) the effect of biogas slurry on beans plant was moved to section 3.2 (p. 10, lines 6-13), and (ii) the discussion of the practical application and the addition of urine to CaSa-compost, which are based on recent scientific results. The latter issue was shortened and moved to section 3.4 (p. 11, lines 24-30) hence integrated into the revised and improved discussion of nutrient balancing.

11	Once the manuscript is corrected, the conclusions of the article may have to be accordingly revised	We agree and reworked the conclusion when revising our manuscript.
12	The quality of figures 2-4 may have to be also improved and make them easier to understand. Move most of the information in the figure legends to the text (M&Ms) and leave only the basic information to understand and interpret the graphs there	We agree and changed the captions accordingly. For example, we moved information on the applied method from Fig. 2 to section 2.3 and the description of soil physical examinations (p. 5, lines 28-29).
#	**Response to Anonymous Referee #2** SOIL Discuss., 2, C676–C677, 2016	**Our responses**
1	The paper (…) deals with an interesting aspect that completely fits the scope of the journal, such as the effects of different soil amendments, mainly organic amendments, on a type of soil with requirements of P.	We appreciate the Referee's acknowledgement that our results are interesting and that our work fits the scope of SOIL journal.
2	However, I consider that this study does not represent an innovative contribution to the knowledge concerning soil management and constitutes a work mainly descriptive.	We agree that parts of the first manuscript were too descriptive. Consequently, we worked thoroughly on the revision of our manuscript. However, we don't agree with the lack of innovation in our work. We argue, that the innovative elements in our work are: 1. We conducted a field experiment using practice oriented intercropping system and field size. 2. The design of our experiment was highly adapted to local practices so that results can be easier transferred to the real world, e.g. using local crop species and comparing locally available materials such as compost, biogas slurry, biochar, and sanitized human excreta. 3. We chose a complex approach (to study a complex problem), which combines soil chemistry, soil physics and plant nutrition in one study. 4. We conducted an experiment on a special and interesting soil, a tropical Andosol with high P requirements. However, we interpreted this comment in the way, that we haven't justified sufficiently why our work is an innovative contribution to soil science. Hence, we reacted on this by (i) improving the Abstract, and (ii) adding a section to the introduction where we deduce the chosen research design from scientific results in the field of organic materials and biochar application of the past years (p. 3, lines 1-15).
3	The work is correctly outlined, but in some aspects (*description of the soil amendments*, *discussion of the results*, etc.) is a little confusing. For this, the following comments are some suggestions to improve the work.	We are thankful for the provided comments, which were helpful for us when revising our manuscript. To improve comprehensiveness of the *description of the soil amendments*, we added an additional table to the manuscript providing general information about the amendment's chemical characteristics such as pH, moisture, C and nutrient contents etc. (Table 2). Furthermore, we assume that we provided too many details and combined too many aspects in the chapter four. To significantly improve the *discussion of the results*, we changed the manuscript for the revised submission as follows:

		1. We eliminated section 3.5 where we formerly provide an outlook on how the tested soil amendments can contribute to close nutrient cycles on small-scale farms in Karagwe. We assume, by withdrawing this section we will enhance the focus on the results of the field experiment. Nevertheless, we shortened this section and integrated it in the revised conclusions (p. 12, lines 5-8). 2. We further eliminated section 3.6 for reducing the amount of information provided in chapter three and for supporting the readers' focus on the most important results of the experiment. 3. We completely rewrote the chapter and tried to improve readability markedly.
4	In the Abstract is not clear the soil parameters determined and only after reading the Materials and Methods section I found that the authors have studied more parameters than physico-chemical parameters (pH and EC); please, specify the parameters studied in the abstract.	We rewrote the Abstract and included a selection of the examined parameters (p. 1, lines 7-9).
5	The introduction perfectly reflects the topic and the main objectives of the study; however, the authors should explain in more detail some aspects of the previous studies that are slightly mentioned, to justify the use of these specific soil amendments.	We highly appreciate the general evaluation of the introduction we provided. We worked on the suggested improvements and we changed section 1.3 accordingly (p. 2, lines 22-38).
6	In the Materials and Methods section, the experimental design is adequately explained, except for the characteristics and origin of the soil amendments used (only described for urine). The characteristics of the soil amendments used constitute an essential aspect to evaluate the effects of their use in the soil-plant system.	We agree and rephrased chapter 2 on "Material and Methods" accordingly. We hope that it is now more comprehensible and can be better understood, especially for the origin of the soil amendments (p. 4, lines 11-23). Furthermore, we added an additional table (Table 2) providing information about the amendments' nutrient contents, pH, etc.
7	In addition, the methods for the determination of several parameters are described in the table and figure legends; the authors should include this in the part of Materials and Methods, because it is a little confusing.	We agree and changed the captions accordingly. For example, we moved information on the applied method from Fig. 2 to section 2.3 and the description of soil physical examinations (p. 5, lines 28-29).
8	In the Statistical analysis section, the authors comment the number of replications of each treatment. I consider that this aspect should be moved to the section of the plot preparation.	In our opinion, it is appropriate to have an extra section on statistical analysis at the end of chapter 2 on "Material and Methods", which includes also the number of replications. We argue that, in section 2.2 on plot preparation and soil amendments, the number of replications is shortly mentioned in connection with the experimental design arranged as Latin rectangle. In section 2.7 ("statistical analysis") we further explain number of replications by elucidating according to different parameters, which were assessed.
9	Why is different the number of replications in the treatments?	We apologizes that this fact was not explained sufficiently and we tried to make this point clearer in the revised manuscript (p. 7, lines 15-21).
10	In general, the Results and Discussion section should be revised and clarified, because apart from being mainly descriptive, some aspects in the discussion of the parameters are difficult to	We agree with the Referee's comment and we improved comprehensibility of chapter "Results and Discussion" in the thorough revision of our manuscript. We further agree, that the observed effects need to be discussed in relation to the

	understand. As an example, it is not clear the effect of the properties of the soil amendments on the soil characteristics (see previous comment related to the characteristics of the soil amendments).	soil amendments. However, in our opinion we did so by discussing effects on plant growth, plant nutrition and changes in soil properties. For example we discussed different P contents in the tested soil amendments and related them to the observed differences in CAL-extractable concentrations of soil P (p. 8, lines 12-22). Furthermore, we applied the vector nutrient analysis to identify a primary response of maize plants to improved P availability (p.10, lines 27-34). In addition, we discussed the different CaO-equivalents of the soil amendments in the context of the observed changes in soil pH (p.8, lines 23-34). We also discussed, that under the given tropical conditions, an increase in soil pH will positively affect the availability of nutrients in the soil, hence stimulate biomass growth. As typical for the local Andosol, nutrient deficiencies and acidity in the soil were most present on the unamend control plots, which depressed plant growth.
11	Why were the crops African egg and pepper not harvested?	We planted African eggplant and pepper as part of the chosen intercropping system. The local agricultural expert recommended this to be in line with local agricultural practices. However, these two plant species are perennial and harvesting started only in June 2014 when our experiment was finished. So we decided to integrate them in the intercropping but exclude them from analysis. We made this point clearer in our revised manuscript (p. 5, lines 3-6).
12	Section 3.6 should be included in the discussion of the results, since it is not clear if it is part of the conclusions or of the discussion of the results.	We agree and reacted on this important comment by withdrawing section 3.6. We erased the subjective impressions and kept only two relevant aspects: (i) the effect of biogas slurry on beans plant was moved to section 3.2 (p. 10, lines 6-13), and (ii) the discussion of the practical application and the addition of urine to CaSa-compost, which are based on recent scientific results. The latter issue was shortened and moved to section 3.4 (p. 11, lines 24-30) hence integrated into the revised and improved discussion of nutrient balancing.
13	In addition, it would be interesting to include a figure with the climatic data at the experimental site during the period of study, which can help in the discussion of the effects of the treatments on the soil, instead of mentioning only average values.	In the supplements, we included figures providing data on humidity, temperature, and daily precipitation measured during the experiment (Fig. S7-S9).
14	The Conclusions section should be summarized, only including the main aspects found in the study, avoiding speculations and general ideas	We agree and improved our conclusions especially by focussing on the main aspects found in our study.
#	**Response to Anonymous Referee #3** SOIL Discuss., 2, C678–C678, 2016	**Our responses**
1	This manuscript is a very valuable contribution to validate improved management of biogenic wastes into African real cropping systems.	We are thankful for the recognition of our work as valuable contribution to the journal as well as to advance the practical application of known approaches for waste and nutrient management in the context of African agriculture.
2	The approach is very complex, considering several issues incl. nutrient balance, the use of liquid and solid waste fluxes compared to composted ones, etc.	We definitely agree with this comment and the fact that this is a complex study of a complex problem.

3	Some issues should be better explained, especially the application rates of compared treatments, the volatilization of ammonia especially in the urine treatment, etc.	In our opinion, the application rates were sufficiently explained by mentioning them in section 2.2 as well as in Table 3. However, we agree that the readability of section 2.2 generally needed to be improved. We reacted on this by rephrasing this section and also worked on better explanation of the application rates (p. 4, lines 5-10). Concerning the ammonia volatilization when applying urine we agree, that this is an important parameter to consider. However, we erased all results of urine application from this manuscript, as these were not possible to evaluate because we had problems with the urine's quality. Nevertheless, in another part of our cumulative work we consider N-losses from ammonia volatilization, when applying material flow analysis and soil nutrient balancing to integrate the tested soil amendments into farm-scale nutrient management.
4	The Carbon stock related to the treatments could be also a good point to go abroad especially to include the non-chemical fertility related to organic resources.	We apologize but we didn't understand this comment very well. We evaluated changes in C stocks due to the used soil amendments. However, we did not observe any significant effect on soil carbon content. Hence, we did not further discuss results related to carbon provided by the treatments. We discussed the amount of biochar contained in CaSa-compost and the C content in comparison to other work to argue that is not likely to observe significant changes in the soil C stock in a short-term experiment and after only one application. However, we tried to make that point cleared in the revised manuscript (p. 8, line 35 to p. 9, line 3).

Organic wastes from bioenergy and ecological sanitation as soil fertility improver: a field experiment in a tropical Andosol

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Abstract

Andosols require the regular application of phosphorus (P) to sustain crop productivity. On an Andosol in NW Tanzania, we studied the short-term effects of amending standard compost, biogas slurry and CaSa-compost (containing biochar and sanitized human excreta) on (i) the soil's physico-chemical properties, on (ii) biomass growth and crop productivity, and on (iii) the plants' nutrient status. The practice-oriented experiment design included intercropping of seven locally grown crop species planted on 9 m^2 plots with five repetitions arranged as a Latin rectangle. Differences in plant growth (biomass production and crop yield e.g. of *Zea mays*) and crop nutrition (total C, N, P, K, Ca, Mg, Zn, etc.) were related to pH, CEC, total C and the availability of nutrients (N, P, K, etc.) and water (water retention characteristics, bulk density, etc.) in the soil. ~~In a practice oriented field experiment at an Andosol site in NW Tanzania, the effects of various soil amendments (standard compost, urine, biogas slurry and CaSa compost [biochar and sanitized human excreta]) on (i) the productivity of locally grown crop species, on (ii) the plants' nutrient status and on (iii) the soil's physico-chemical properties were studied.~~ None of the amendments had any significant effect on soil water availability, so the observed variations in crop yield and plant nutrition are attributed to ~~moisture, so the observed variation in crop yield and plant nutrition reflected differences in~~ nutrient availability. Applying CaSa-compost increased the soil pH from 5.3 to 5.9 and the level of available P from 0.5 to 4.4 mg per kg. Compared to the control, adding biogas slurry, standard compost and CaSa-compost increased the aboveground biomass of Zea mays by, respectively, 140, 154 and 211 %. ~~The application of CaSa-compost increased the level of available P in the top soil from 0.5 to 4.4 mg per kg and the soil pH from 5.3 to 5.9. Treatment with biogas slurry, standard compost and CaSa-compost increased the above-ground biomass of *Zea mays* by, respectively, 140, 154 and 211 %.~~ The grain yields of maize on soil treated with biogas slurry, standard compost and CaSa-compost were, respectively, 2.63, 3.18 and 4.40 t ha^{-1}, compared to only 1.10 t ha^{-1} on unamended plots. All treatments enhanced crop productivity and increased the uptake of nutrients into the maize grains. The CaSa-compost was ~~especially~~ most effective in mitigating P deficiency and soil acidification. We conclude that all treatments are viable as substitute for synthetic ~~fertilize~~fertilisers. ~~However~~Nevertheless, further steps are required to integrate the tested soil amendments into farm-scale nutrient management and to balance the additions and removals of nutrients, so that the loop can be closed.

Keywords: composted biochar, biogas slurry, EcoSan, Terra Preta practices, soil improvement, waste as resource, liming effect, hydraulic properties, crop nutrition, intercropping system, smallholder agriculture, Karagwe, Tanzania

Annotation: Some information is provided as supplementary materials; the respective figures and tables are indicated by an S (e.g. Table S1).

1 Introduction

1.1 Challenges cultivating Andosols

~~1.1 Specific characteristics of Andosols~~

Andosols occupy just 1-2 % of the land area ~~world wide~~worldwide. ~~, although ~~T~~t~~hey are common in high altitude tropical environments, such as in the East African Rift Valley (Ches~~t~~worth, 2008; Perret and Dorel, 1999). Their high inherent fertility suits them especially well for the cultivation of high value crops such as coffee, tobacco and banana. These soils feature a low bulk density, variable charge characteristic (strongly dependent on the soil's pH), a low base saturation (BS), thixotropy, a strong capacity to retain ~~both~~ phosphorus (P)~~ and water~~, a high pore volume, a high level of available water, ~~a high water content at permanent wilting point, a high pore volume,~~ a tendency to form micro aggregates~~,~~ and a pronounced ~~shrinkage~~ shrinking ~~capacity~~ (Chesworth, 2008; ~~Driessen et al., 2000; Doerner~~Dörner, 2011; Driessen et al., 2000; Zech, 2014). The dominant ~~clay~~ minerals in these soils are allophanes, imogolites, ferrihydrites and halloysites, and the concentrations of aluminium (Al), iron (Fe) and silicon (Si) are all high (Chesworth, 2008). Metal-humus complexes are frequently formed when the pH exceeds 5, while under more acid conditions Al-humus complexes in combination with silica predominate (Chesworth, 2008; Driessen et al., 2000). These structures serve to protect soil organic matter from degradation, ~~thereby~~ thus ~~encouraging~~ fostering ~~its accumulation~~C-sequestration ~~(Driessen et al., 2000)~~(Driessen et al., 2000; Chesworth, 2008; Abera and Wolde-Meskel, 2013)~~.~~. The total carbon concentration of these soils is often > 6 % throughout their profile (Chesworth, 2008). ~~The capacity of these soils to accumulate organic matter means that they can act as a CO_2 sink (Chesworth, 2008; Abera and Wolde-Meskel, 2013).~~

~~1.2 Challenges with cultivating Andosols~~

Andosols are rather sensitive to land use management (~~Doerner~~Dörner, 2011). For example, shifting cultivation practices tend to deplete soil fertility unless organic matter is deliberately added, while intensive mechanized cultivation risks compacting the soil with the hydraulic properties of the soil being readily compromised (Perret and Dorel, 1999; Dorel et al., 2000).

Plants on Andosols typically suffer from P deficiency (Buresh et al., 1997), as the soils have a high P fixation potential (Batjes, 2011). Thus, crop productivity and sustainable land use ~~where these soils occur~~ require consistent P replenishment, which generates a strong demand in Sub-Saharan Africa for appropriate soil amenders. ~~Buresh et al. (1997) have suggested that P can be provided either via a large, one-off application or else more gradually.~~ Fertility amelioration measures have included both liming to increase P availability, and ~~dressing~~ applying ~~with~~ either manure and/or other organic matter, or ~~with~~ synthetic P ~~fertilize~~fertiliser (Driessen et al., 2000; Tonfack~~,~~ et al., 2009). ~~At the same time, erosion control is essential to minimize loss of top-soil (Abera and Wolde-Meskel, 2013).~~

~~1.3~~1.2 Organic waste materials as soil amenders on Andosols in Karagwe, Tanzania

Andosols with strong P retention potential are also present in Karagwe (Kagera region, NW Tanzania), which is geographically located nearby volcanic areas of the East African Rift Zone (Batjes, 2011). Soil constraints for farmers in this region are the low soil pH (3.8-4.2), the low availability of nutrients (especially P) and widespread soil erosion (Krause et al., 2015). Small-scale farmers often have financially or logistically restricted access to rock phosphates or synthetic fertilisers and lack of sufficient amounts of organic matter to replenish Andosols (Buresh et al. 1997).

However, practices like ecological sanitation (EcoSan) and bioenergy production can contribute to local matter and nutrient cycling with Andosols receiving organic waste products (Krause et al., 2015). Human excreta constitute a valuable source of plant nutrients, available in every human settlement. EcoSan technologies can be implemented for the collection and sanitisation of toilet wastes (Esrey et al., 2001), such as urine diverting dry toilets (UDDT), composting toilets, and pasteurization of faeces to secure human health (Schönning and Stenström, 2004). The latter was recently tested in Karagwe in an EcoSan-pilot project named "Carbonization and Sanitation" (CaSa) (Krause et al., 2015). In the CaSa-approach, so-called microgasifier stoves (Mukunda et al., 2010) provided the heat for thermal sanitation of human faeces. In addition, further projects have been locally initiated to implement bioenergy technologies for cooking such as small-scale biogas digesters (Becker and Krause, 2011) and microgasifier stoves (Ndibalema and Berten, 2015). Hence, increasing dissemination of these technologies will supply waste matter such as biogas slurry from anaerobic digestion, powdery charcoal residues from gasification, and ashes (Krause et al., 2015).

These locally available resources can be directly applied to the soil or they can be processed as compost. The benefit of charcoal as a soil amender ("biochar") has been deduced from the fertility of Terra Preta soils (Sombroek, 1966; Lehmann and Joseph, 2009). CaSa-compost is a product following this ancient example of co-composting (pasteurised) human faeces, kitchen waste, harvest residues, terracotta particles, ashes, and urine mixed with char residues from gasification (Krause et al., 2015).

However, there is also reasonable doubt, that application of biochar is recommendable in all situations and on all soils. Mukherjee and Lal (2014) pointed out that especially field-scale data on crop response and soil quality lack for various soil-biochar combinations. From past experiments using biochar as soil amendment (Herath et al., 2013; Kammann et al., 2011; Kimetu et al., 2008; Liu J. et al., 2012; Major et al., 2010; Nehls, 2002; Petter et al., 2012; Schulz et al. 2013) and from meta-analysis by Biederman and Harpole (2013), Jefferey et al. (2011), and Liu, X. et al. (2013) the following lessons can be learned for future experiments: (i) pot experiments lead to over-estimations of possible positive impacts on biomass growth compared to field experiments; (ii) soil chemical *and* soil hydraulic properties should be examined at the same time to be able to distinguish the observed effects; (iii) assessment of biomass growth should be combined with the assessment of crop yield and the evaluation of plant nutrition; (iv) locally typical and economically relevant plants should be selected and cultivated according to local practice to assess a practical relevance of biochar application in the local agroecosystem and (v) long-term as well as short-term experiments are needed. Although the latter are often criticized to not enhance knowledge on changes of soil hydraulic properties as well as on soil organic matter and C-sequestration, they are of high practical relevance to farmers who rely on their harvests immediately.

In this study, we assessed if and how locally available organic waste materials change the availability of nutrients and water in the soil and improve the crop productivity in a one-season, practice-oriented field experiment. In particular, our **objectives** were (i) to examine the effect of CaSa-Compost, standard compost, and biogas slurry on the physico-chemical properties of the soil, and (ii) to assess their impact on biomass growth, crop yield and (iii) plant nutrition.

Andosols with strong P retention potential are also present in Karagwe (Kagera region, NW Tanzania), which is geographically located nearby volcanic areas of the East African Rift Zone passing in bordering countries of Rwanda and Uganda (Batjes, 2011). The leading soil constraints for this region's small-scale farmers are a low soil pH (3.8-4.2), the poor availability of nutrients (especially P) and widespread soil erosion (Krause et al., 2015).

In a prior publication we introduced known principles like ecological sanitation (EcoSan), bioenergy and Terra Preta practice (TPP) (Krause et al., 2015). The benefit of charcoal as soil amender (biochar) has been well recognized from the fertility of Terra Preta soils (Sombroek, 1966; Lehmann and Joseph, 2009). We concluded that these practical approaches could locally contribute to closing open nutrient cycles, especially to recycling P contained in human excreta and in addition to sequestering carbon (C) (Krause et al., 2015).

Furthermore, we introduced three projects in Karagwe and their applied approach of integrated resource management to capture C and nutrients from various waste products. In addition, we assessed substrates derived from these case studies for their nutrient content and we compared locally made compost ("standard compost"), biogas slurry and so-called CaSa-compost (the latter being derived from the project „Carbonization and Sanitation" (CaSa) and produced by incorporating biochar and sawdust as the source of carbon and treated human excreta as the source of nutrients). Our results revealed adequate fertilizing potential for all substrates compared to literature (*ibid*.).

With the present study, we attempted a comparison between the uses of these organic waste materials as soil amenders in a practice-oriented field experiment for one cropping season. Hereby, the **over-arching aim** of our research was to establish whether such soil amendments could (i) influence the availability of nutrients and water in the soil and (ii) generate an improvement in crop productivity. In particular, our **objectives** were (i) to examine the effect of the various amendments on the physico-chemical properties of the soil, and (ii) to assess their effectiveness with respect to biomass growth, crop yield and plant nutrition.

2 Materials and Methods

2.1 Field site

The experimental site (see Fig. S2-S4) is located in the Ihanda wWard, Karagwe district, Kagera region, NW Tanzania (1°33.987' S, 31°07.160' E; 1577 m. a. s. l.), a hilly landscape characterized by a semi-arid, tropical climate (Blösch, 2008). The annual rainfall ranges from 1000-2100 mm and the mean annual potential evapotranspiration is ~ 1200 mm (FAO Kagera, online). The pattern of rainfall is bimodal, featuring a long rainy season from March to May and a short one from October to November (Tanzania, 2012). The predominant cropping system comprises banana, intercropped with beans and coffee. Prior to the experiment, the soil was profiled surveyed by sampling from the edges of the field (Table 1 and Fig. S1). Stone and gravel concentrations increased with soil depth. The bulk density (ρ_B) of the top-soil lay within the range expected for an Andosol. The soil's total carbon (C_{tot}) and total nitrogen (N_{tot}) concentrations were classified, respectively, as medium and adequate, and its C/N ratio is suitable for cropping (Landon, 1991). The soil pH was in the range 3.6-3.8. The effective cation exchange capacity (CEC_{eff}) of dry matter (DM) in the soil was only 8-17 cmol kg^{-1} compared to a typical range of 10-40 cmol kg^{-1} of DM (Chesttworth, 2008). The soil's BS was quite high (Ca saturation of up to 70 %). Comparable levels of both CEC_{eff} and BS have been recorded in both in Kenyan Ultisols cultivated for about 35 years (Kimetu et al., 2008) and in an Ethiopian Andosol (Albera and Wolde-Meskel, 2013). Like the latter soil, the present one was deficient for Fe, copper (Cu) and zinc (Zn) (Table 2). The quantity of P available P in DM of the top-soil was 0.7 mg kg^{-1} (classified as "very low" according to KTBL, 2009), whereas that of potassium (K) was "very high" (244.7 mg kg^{-1}). The concentration of exchangeable Al was low and those of exchangeable Zn and Fe were below the detection limit.

2.2 Plot preparation and soil amendments

We arranged a series of 3 m x 3 m plots in the form of a Latin square rectangle (Richter *et al.*, 2009), with the five columns and five rows each separated from one another by a 0.5 m deep trench. Each of the five four treatments was applied to a single row and a single column and thus studied with five replications (Fig. 1). The treatments were: (1) untreated (control), (2) biogas slurry in a weekly application (from weeks 4-9 after sowing) of 1.7 dm^3 m^{-2} biogas slurryon a cover of cut grass, (3) standard compost with a pre-sowing application of 15.0 dm^3 m^{-2} standard compost, and (4) CaSa-compost with a pre-sowing application of 8.3 dm^3 m^{-2} CaSa-compost, passed through a 20 mm sieve. Macro- and micronutrients of the amendments were analysed according to standard methods as described in Krause et al. (2015). Values are given in dry matter (g kg^{-1}) as well as in the practice-oriented fresh matter concentrations (g dm^{-3}) in Table 2.

The employed biogas slurry derived from anaerobic digestion of banana tree stumps and cow dung (mixture 1:1 by volume). According to local practice, biogas slurry amended plots were covered with cut grasses prior to sowing. Therefore, the nutrient content of grass was analysed as well.

Standard compost was processed by local farmers during three months from fresh and dried grasses (0.91 m^3 m^{-3}), kitchen waste (0.06 m^3 m^{-3}), and ash (0.03 m^3 m^{-3}). The compost heap was regularly watered and covered with soil and grasses to mitigate evaporation.

CaSa-compost contained pasteurized human faeces (0.15 m^3 m^{-3}), biochar from gasification (0.17 m^3 m^{-3}; eucalyptus-sawdust, pyrolysis at T> 500°C, residence time ≥ 120 min), kitchen waste and harvest residues (0.15 m^3 m^{-3}; beans straw, banana peels), mineral material (0.31 m^3 m^{-3}; ash from eucalyptus wood, brick particles, local soil to add minerals and soil microorganisms), and lignin and cellulose sources (0.22 m^3 m^{-3}; sawdust, grasses). Stored urine, mixed with sawdust or biochar, was added to the compost as well (0.12 m^3 m^{-3}). Every week, 60-80 dm^3 of the above-mentioned matters were added to the shaded and grass-covered compost heap.

We adjusted the amendments so that each treatment delivered a comparable quantity of mineral nitrogen (N_{min}). The N_{min} demand per cropping season (~~D~~$N_{min,demand}$) was estimated as 17.5 g m^{-2}, following KTBL (2009). According to Horn et al. (2010), 33 % of organic nitrogen contained in organic ~~fertilize~~fertilisers ($N_{org,fertili\text{s}zer}$) is mineralized during the course of a cropping season. The amount of materials to be amended to the soil, $m_{fertiliser}$ (kg m^{-2}), was calculated ~~Thus,~~ based on the quantity of N_{min} present in the top 90 cm of the soil ($N_{min,soil}$ with about 7.5 g m^{-2}, see Table 3~~1~~), ~~along with~~and that provided by the amendments as follows~~, the amount of materials to be amended to the soil, $m_{fertilizer}$, measured in DM as kg m^{-2}, was calculated as follows~~:

$$m_{fertiliser} = \frac{N_{min,demand} - N_{min,soil}}{N_{min,fertilizer} + 0.33 \cdot N_{org,fertilizer}}$$

$$m_{fertilizer} = \frac{D_{N_{min}} - N_{min,soil}}{N_{min,fertilizer} + 0.33 \times N_{org,fertilizer}}$$ ~~(~~Eq.

~~(~~(1)

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Then, the ~~status~~ addition of the other plant nutrients (Table 3) ~~follow~~were calculated according to ~~ing the amendments is given in~~ Table 2~~2; these were calculated on the basis of the composition of each amendment.,~~ ~~following Krause et al. (2015).~~

~~The urine was initially collected in an urine diverting dry toilet (UDDT). Unfortunately, urinal deodorizer blocks were used in the UDDT, which obviously had a marked effect on the urine's quality (indicated by colour, P-concentration; no further analysis done).~~

Before planting, we ~~hand~~ hoed the soil by hand, as it is ~~the~~ common local practice. We applied the composts by first spreading evenly, then incorporating with a fork hoe. ~~For the biogas slurry treatment, the plot was covered by grass, following local practice.~~ Planting was carried out at the beginning of the rainy season (March 2014), and the plots were mulched in mid April (terminating rainy season) to minimize evaporative loss. We harvested the crops during June and July. Precipitation was recorded on a daily basis, while the air temperature and relative humidity prevailing 2 m above-ground were measured every 15 minutes.

We divided each plot into two 4.5 m^2 sections (Fig. 1), one used to cultivate maize cv. Stuka, and the other planted ~~to~~ with a mixture of common bean cv. Lyamungu 90, carrot cv. Nantes, cabbage cv. Glory of Enkhuizen and local landraces of onion. In addition~~,~~ African egg plant (*Solanum aethiopicum*) and sweet pepper ~~(Fig. 1)~~ were planted as important parts of the chosen local adjusted intercropping practice. However, these two plant species are perennial, biomass harvest exceeded the experimental timeframe, and therefore we excluded them from analysis.~~.~~

~~-~~The maize was sown on March 4 with two grains per dibbing hole and thinned after germination. Carrot seed was directly sown into the plot on March 6 and the beans were sown on March 14; carrot was thinned after 40 days. The other species were transplanted as seedlings in mid March. The maize and beans were entirely rain-fed, while the other crops were irrigated as required. The plots were hand-weeded once a week, and insects were controlled by spraying with a mixture of ash and “moluku” (prepared from the leaves of the Neem tree and the Fish Poison tree suspended in soapy water).

We sampled the soil (two samples per plot) using a 1 m Pürckhauer universal ga~~o~~uge auger on three occasions during the experiment: the first prior to sowing (t_0, beginning of February), the second at the end of the rainy season (t_1, end of April), and the final one after harvest (t_2, beginning of July). The soil sample was divided into three sub-samples: 0-30 cm, 30-60 cm and 60-90 cm. The two samples from each plot were combined. For the t_0 sample, 16 sampling sites were selected, from which four bulks were prepared for each soil layer to represent each quarter of the field. At t_1, all 25 plots were sampled, but at t_2 the sampling involved three of the five plots per each treatment.

2.3 Soil analyses

Water retention curve (WRC) and ρ_B were determined from undisturbed soil samples taken using a 0.1 dm^3 stainless steel cylinder. In the field, we monitored the top-soils' volumetric water content (θ) [m^3 m^{-3}] twice a week over the first six weeks after sowing at five points per plot, using a TDR probe (Field Scout 100, 8" rods, Spectrum Technologies, Aurora, USA). Furthermore, θ for each of the three soil layers was determined gravimetrically at t_0, t_1 and t_2. We performed double ring infiltration experiments to determine the infiltration rate (IR) as well as the field capacity (FC) for the untreated soil at t_0 and for the treated soils at t_2 following Landon (1991). The WRC was measured using pressure plates as well as using the laboratory evaporation method (Hyprop, UMS, Munich, Germany). The latter data was used to derive the general form of the Andosol's WRC and to parameterise the Peters–Durner–Iden (PDI) model (Peters et al., 2015) (Fig. 2). The available water capacity (AWC) was calculated as $\theta_{pF\ 1.8} - \theta_{pF\ 4.2}$. The porosity (□) and pore volume (PV) were calculated from dry bulk density and particle density (ρ_p) measured using a Multipycnometer (Quantchrome, Boynton Beach, USA).

We measured N_{min} and pH of the soil in situ at both t_0 and t_1, while at t_2 only the pH was taken; the method involved the suspension of 50 g soil in 100 mL 0.1 M KCl, which was assayed using, respectively, an AgroQuant 114602 test strip (Merck, Darmstadt, Germany) and a pH 330i glass electrode (WTW, Weilheim, Germany). Further chemical analyses were carried out on air- or oven-dried t_0 and t_2 samples, which were first passed through a 2 mm sieve. The oven-dried samples were used to determine the concentration of C_{tot}, N_{tot} and total sulfur (S_{tot}), following ISO DIN 10694 (1995) and ISO DIN 13878 (1998) protocols, using an Elementar Vario ELIII CNS-Analyzer (Elementar, Hanau, Germany). Concentrations of calcium acetate lactate (CAL) soluble P (P_{CAL}) and K (K_{CAL}) were determined with an iCAP 6000 ICP-OES device (Thermo Scientific, Waltham, USA) from air-dried soil suspended in CAL solution (0.05 M calcium acetate/calcium lactate and 0.3 M acetic acid) following the protocol given in chapter A 6.2.1.1 of VDLUFA (2012). Cations such as Al_3^+, Ca_2^+, Mg_2^+, Fe_2^+, Mn_2^+ and Zn_2^+ were exchanged with ammonium chloride (NH_4Cl) and their concentration measured using ICP-OES, following the protocol given in chapter A3.2.1.8 of König (2006). We calculated CEC_{eff} from the sum of the ion equivalents of K, Al, calcium (Ca), magnesium (Mg), manganese (Mn) and hydrogen (H). The BS represented the ratio between the sum of the ion equivalents of K, Ca and Mg and CEC_{eff}.

2.4 Biomass production

We harvested maize plants 14 weeks after ~~reaching~~ the ~~two leaf~~two-leaf stage, and the other crops at maturity. For maize, bean, cabbage, carrot and onion, the above-ground biomass was considered as "harvest product" [weight of fresh mass (FM) in g $plant^{-1}$], while "market product" represented the weight of maize grain, bean seed and onion bulb after a week's drying in the sun [air-dried mass in g $plant^{-1}$]. For maize, we measured the stem diameter and plant height, and for bean, we determined the pod number per plant.~~;~~ I~~i~~n each case, a random sample of plants was used, avoiding plants at the edge of the plot. The overall numbers of samples were: onion (10/20 plants), cabbage (all plants producing a head), bean (8/16 plants), and maize (5/24 plants, excluding plants without cobs). For the carrot, the weight of the whole set of plants on a plot was determined.~~;~~ ~~the yield of the African egg plant and pepper was not measured.~~To estimate the total production per plot (Fig. 3), we multiplied means of weight per plant and the total number of harvested plants per plot. Total above-ground biomass production was estimated for 19 maize, 16 bean, 6 cabbages, and 20 onion plants per plot for all the treatments (except for no cabbages on the control). Values for market products were estimated for developed maize cops, onion bulbs, cabbage heads, and carrots.

2.5 Plant nutritional status

Measurements of plant nutritional status were only made on maize; the plants were divided into the shoot, the corncob and the grains. Five harvested plants per treatment were bulked to give a single sample for each plant fraction per plot. The water content of the biomass was determined gravimetrically. Following oven drying, the material was ground, passed through a 0.25 mm sieve and analysed for C_{tot} and N_{tot} as above. We assessed concentration of P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, B_{tot}, Cu_{tot}, Fe_{tot}, Mn_{tot}, and Mo_{tot} after microwave digestion with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) using an iCAP 6300 Duo MFC ICP-OES device (Thermo Scientific, Waltham, USA), following the protocol given in chapter 2.1.1. of VDLUFA (2011.)

In addition, we conducted a vector nutrient analysis on harvest product, nutrient concentration and nutrient uptake following Imo (2012). Uptake and concentrations of the various nutrient elements were plotted based on the following scheme: the lower horizontal x axis represented the nutrient uptake, the vertical y axis the nutrient concentration and the z axis the biomass (~~Issac~~Isaac and Kimaro, 2011). The control treatment's performance ~~control plot outcomes~~ were normalized to 100, so that the levels of biomass production and nutrient concentration reflected the effect of the various soil treatments (Kimaro et al., 2009). Nutrient diagnosis was based on both the direction (increase, decrease or no change) and the length of the vectors (strength of response) following ~~Issac~~Isaac and Kimaro (2011).

2.6 Nutrient balance

For the section of the plots, which were cultivated with maize, w~~W~~e ~~calculated~~ estimated changes in the soil nutrient status (Δ Nut) for each treatment ~~and for the section of the plots which were cultivated with maize~~, according to ~~the expression~~:

$$\Delta\, Nut = Nut_{app} - Nut_{up} = \Delta\, Nut_{av} + \Delta\, Nut_{nav} \qquad \text{(Eq. (2)}$$

where Nut_{app} represented ~~the quantity of~~ nutrients supplied by the treatment (*nut*rient *app*lication), Nut_{up} ~~the quantity of~~ nutrients taken up by the maize plants, $\Delta\, Nut_{av}$ the changes in the soil's available nutrient stock (where “available” referred to the nutrients being extractable with CAL solution), $\Delta\, Nut_{nav}$ the change in the soil's nutrient stock, which was “non-available” ~~and RO the loss through run-off (e.g.~~either through leaching, interflow, surface run-off, soil ~~or~~ erosion, P-fixation, not yet mineralized, etc~~)~~. The balance was calculated for P_{tot} and K_{tot}~~;~~ firstly ~~on a~~ per plot ~~basis,~~ and then ~~averaged across the three plots exposed to each given~~per treatment as an average of three plots.

2.7 Statistical analysis

Analyses of variance (ANOVA) were performed using STATISTICA software (StatSoft Inc., Tulsa, Oklahoma, USA). The main effect was considered to be the soil treatment. Means were compared using the Tukey "honest significant difference" (HSD) test, with the α=0.05.

According to the design of the experiment as Latin rectangle, the number of replication of the four treatments did not differ and was n=5 for all treatments. However, we had to eliminate one outlier in the control treatment so that for statistical analyses n was 4. Hence, n=5 (for biogas slurry, compost and CaSa-compost treatment) was combined with n=4 (for the control treatment) for all parameters we collected during harvesting, e.g. biomass growth and crop yields. Because of financial restrictions we had to use a block design with n=3 for all soil chemical and physical parameters as well as examinations of nutrient content in the maize plants.

~~The number of replicates varied: for the harvest product, the number of replicates was five for the biogas slurry, standard compost and CaSa-compost treatments, but only four for the control and the urine treatments. For the comparisons of the nutrient concentration of the maize plants and the soil chemical and physical characteristics at t_2, a block design with three replicates was used. Means were compared using the Tukey "honest significant difference" (HSD) test, with the α threshold set to 0.05.~~

3 Results and Discussion

Between March and May, the mean air temperature was 21.6 °C (maximum 48.9 °C, minimum 13.5 °C) (Fig. S8) and the total rainfall was ~ 360 mm, of which 85 % fell before the end of April (Fig. S7).

3.1 The physico-chemical status of the soil

None of the amendments significantly affected the studied soil **hydraulic properties** IR (18-36 $cm\ h^{-1}$) and FC (0.28 and 0.20 $m^3\ m^{-3}$ in the top-soil and in the sub-soil respectively) as ~~as a result of~~measured with the double ring infiltration experiments. Also the WRC ~~(Fig. 2)~~ were not significantly influenced by the amendments and still show the typical shape of an Andosol (Fig. 2). This might be due to the low application dose of the amendments that did not influence ρ_B of the Andosol (0.99 and 1.02 $g\ cm^{-3}$). Nevertheless, we had the subjective impression during fieldwork, that CaSa-compost aided workability of the soil by making it more friable.

The top-soil's PV was estimated as 0.59-0.63 $m^3\ m^{-3}$ and might have been homogenized throughout the treatments by tillage (i.e. with hand-hoe) and then compaction (e.g. by walking on the plots when working). The calculated FC and AWC derived from the studied WRC were, respectively, ~0.35 and 0.13 $m^3\ m^{-3}$ and exhibited a low site heterogeneity with the coefficient of variance for $\theta_{pF\ 1.8}$ between 1.3 % in the control and 2.8 % in plots treated with CaSa-compost. The θ did not vary significantly across the three soil layers at neither t_0 nor t_1~~,~~. ~~but a~~At t_2, θ ~~it~~ was lower in the top-soils of ~~urine,~~ plots treated with the CaSa-compost (0.13 $m^3\ m^{-3}$) and on biogas slurry and standard compost treated plots (0.16 $m^3\ m^{-3}$) ~~and the CaSa-compost treated ones (0.13 $m^3\ m^{-3}$)~~ compared to the control plots (0.17 $m^3\ m^{-3}$). These differences at the end of the growing season might be ~~are~~ rather caused by higher evapotranspiration and interception losses due to higher biomass growth (see below) than by different soil hydraulic properties.

Similar findings are reported for the application of uncomposted biochar (10-17.3 t ha^{-1}) to a New Zealand Andosol which failed to influence either ρ_B, PV or AWC (Herath et al., 2013). Biochar application had also little effect on AWC either in a high clay content soil (Asai et al., 2009), or in soils featuring a high carbon concentration or a low ρ_B (Abel et al., 2013). ~~The~~ Hence, our results imply that none of the amendments altered the availability of moisture significantly, meaning that the observed treatment effects on crop yield and plant nutrition were most likely related to different~~ial~~ nutrient availability.

The **chemical status** of the soil prior at t_0 is given in Tables ~~S~~1 and 2~~1~~. There was a significant treatment effect on P_{CAL} and pH in the top-soil (Table 4~~2~~). The CaSa-compost treatment improved P_{CAL} at t_2 (4.4 vs 0.5 mg kg^{-1} in soil DM), but the level of P remained "very low" as in the remaining plots (classified based on KTBL, 2009). According to Finck (2007), a level of 10-30 mg kg^{-1} in DM is needed to ensure an adequate supply of P, while Landon (1991) has suggested that 13-22 mg kg^{-1} in DM should be adequate for most African soils. Possible explanations for the observation that only the CaSa-compost treatment altered P_{CAL} are: (i) that the treatment provided more P (1.7 g P dm^{-3} in FM) than the others did (0.3 and 0.5 g P dm^{-3} in FM, respectively, in the biogas slurry ~~treatment~~ and in the standard compost treatment ~~respectively(, see Krause et al. (2015~~Table 2~~)~~); (ii) that the provision of biochar promoted nutrient capturing in the soil by adsorption of P on the biochar particles (Gronwald et al., 2015; Kammann et al., 2015); and (iii) that the availability of the recycled P was promoted by liming (Batjes and Sombroek, 1997).

The latter can be supported by our findings, that the top-soil pH was higher at t_2 in the CaSa-compost treatment than in the control plots (5.9 vs 5.3) (Table 4).~~.~~ The optimal top-soil pH range for cropping is, according to Horn et al. (2010), 5.5-6.5. Glaser and Birk (2012) have shown that the highly productive Central Amazonian Terra Preta soils have a pH ~~of~~ between 5.2 and 6.4. Through influencing soil pH,~~The~~ the addition of biochar is particularly effective in soils suffering from poor P availability~~, through its control over soil pH~~ (Biedermann and Harpole, 2013). In an earlier publication, ~~(~~Krause et al.~~,~~ (2015) ~~we~~ derived estimates for the liming potential of the present soil amendments and found ~~: we found~~ 100 kg of DM of biogas slurry, standard compost and CaSa-compost ~~to be~~being equivalent to, respectively, 6.8, 1.4 and 4.7 kg of CaO. The applied equivalents ~~of the various soil amenders used here~~in this study are 0.03, 0.07, and -0.2 kg m^{-2} of CaO for biogas slurry, ~~0.07 for the~~ standard compost, and ~~0.2 kg CaO m^{-2} for the~~ CaSa-compost. ~~Here~~We found~~, we showed~~, that the application of CaSa-compost had an *immediate* effect on soil pH. Finck (2007) ~~has~~ recommended the application of lime ~~($CaCO_3$) of 0.2-0.4 kg m^{-2} every three years to maintain the soil pH,~~ equivalent to 0.1-0.2 kg ~~CaO~~ m^{-2} of CaO every three years to maintain the soil pH. ~~. The equivalents of the various soil amenders used here are 0.03 for biogas slurry, 0.07 for the standard compost and 0.2 kg CaO m^{-2} for the CaSa-compost.~~Thus, amending CaSa-compost in the applied rate was in the range for soil melioration if application of the treatment is repeated every three years.

~~Somewhat unexpectedly for an acid soil, the concentration of exchangeable Al was quite low. A regression analysis involving the concentration of exchangeable Al against the pH did not generate the expected slope of three, predicted if the dominant form of Al in the soil is Al_3^+ (reflecting the reaction equilibrium $Al(OH)_3 + 3H^+ = Al_3^+ + 3 H_2O$). Rather, the slope was two (with $R^2 = 0.55$). Andosols are known to accumulate organic matter through the formation of metal-humus and allophane-organo complexes; at pHs above 5, the latter structures dominate (Chestworth, 2008). Thus the likelihood is that the observed low concentration of exchangeable Al reflected the presence of complexes involving Al and organic matter.~~

~~The~~Neither concentration of total organic carbon (TOC) in the soil nor CEC_{eff} was ~~not~~ altered significantly by the ~~addition of the relatively low level of nutrients provided by the~~ amendments (Table 3~~1~~). Similarly, Liu et al. (2012) ~~have~~ reported that the CEC_{eff} is hardly disturbed by a single dose of biochar. From the volume of CaSa-compost applied (8.3 dm^3 m^{-2}) and its composition (~~Krause et. al., 2015~~Sect. 2.2), we estimated the quantity of dry biochar supplied ~~would have been~~by ~ 2.2 kg m^{-2}, equivalent to a C_{tot} supplement of ~-1.3-1.6 kg m^{-2}, a level which was modest compared to common applications of biochar~~,~~ ~~which~~ ranging~~e~~ from five to 20 kg m^{-2} (Kammann et al., 2011, Herath et al., 2013). Liu et al. (2012) have suggested a rate of 5 kg m^{-2} as the minimum necessary to significantly and sustainably ~~improve~~ increase ~~the amount of organic matter~~TOC in the soil. Nevertheless, Kimetu et al. (2008) were able to show that treating~~ment~~ ~~of~~ a highly degraded soil in the highlands of Western Kenya with just 0.6 kg C m^{-2} for three consecutive seasons, was effective in increasing ~~by some 45 %~~ the quantity of organic matter in the soil by 45 %.

For an acid soil, the concentration of exchangeable Al was unexpectedly low. The slope of a linear regression of the concentration of exchangeable Al against the pH is two and not three (Fig. S6), as predicted if the dominant form of Al in the soil is Al_3^+ (reflecting the reaction equilibrium $Al(OH)_3 + 3H^+ = Al_3^+ + 3 H_2O$). Andosols are known to accumulate organic matter through the formation of metal-humus and allophane-organo complexes. At pHs above 5, the latter structures dominate (Chesworth, 2008). Thus, most likely the observed low concentration of exchangeable Al reflected the presence of complexes involving Al and organic matter.

3.2 Biomass production

The harvested biomass of onion was significantly increased by ~~the provision of~~amending compost. The mass~~;~~ ~~the size~~ of the bulbs produced in plots provided with standard compost or CaSa-compost was, respectively, 52.8 ~~g plant^{-1},~~ and ~~was~~ 54.4 g plant^{-1} ~~in plots treated with CaSa-compost~~, compared ~~with just~~to only 22.2 g plant^{-1} ~~from~~ for the untreated plots (Fig. 3; further see Fig. S5 for visual impressions). In contrast, the soil amendments had no effect on the yield of carrots. C~~C~~abbage plants grown on the untreated soil remained small and did not develop any heads. ~~Both with respect to the harvest and the market product, tThe~~ In contrast, amending CaSa-compost, ~~the~~ standard compost ~~and~~ or ~~the~~ biogas slurry ~~treatments were all greatly superior to the urine treatment: the four treatments~~ delivered ~~in~~ average yields of heads of, respectively, 1,020~~16~~, 825, and 720 ~~and 159~~ g plant^{-1}.

~~-~~The above-ground biomass of the bean plants was significantly highest from those plots amended with CaSa-compost with 78 g plant^{-1}, compared to 32, 22, ~~17~~ and 12 g plant^{-1} grown on plots containing, respectively, standard compost, biogas slurry, ~~urine~~ and no amendment. There were also significant differences between the treatments with respect to the average pod number per plant, ranging from 18.8 ~~set by~~for plants grown on CaSa-compost to ~~just~~ only 4.7 ~~by~~ for those grown ~~on~~ in the ~~unamended~~ control soil.

The CaSa-compost also promoted ~~the~~ a greater stem diameter and height of the maize plants (respectively 22.8 mm and 1950 mm), compared to the 16.1 mm and 1423 mm achieved by the plants grown on unamended soil. The treatment with biogas slurry, standard compost and CaSa-compost increased the per unit area above-ground biomass accumulated by maize ~~by~~to, respectively, 140, 154 and 211 % ~~over that accumulated by~~compared to plants in the control treatment (Table 5). The amendments led to grain yields of 263 (biogas slurry), 318 (standard compost) and 440 g m^{-2} (CaSa-compost) compared to 110 g m^{-2} from the control plots.

The ~~per unit area~~ grain yield from the control plots was below both the average national ~~average for~~Tanzanian yield (2012: ~~(~~124 g m^{-2}) and that for East Africa ~~as a whole~~ (180 g m^{-2}), while the yield from the CaSa-compost treated plots matched those obtained in Croatia (434 g m^{-2}) ~~and~~ or Cambodia (441 g m^{-2}) (FAOSTAT, 2012). A field experiment in the Dodoma region of Tanzania produced a grain yield of about 100 g m^{-2} from un~~fertilize~~fertilised plots and 380-430 g m^{-2} from mineral ~~fertilize~~fertilised plots (Kimaro et al., 2009), while ~~a trial carried out~~ in the Morogoro region ~~using~~ the same maize cultivar ~~as here~~ yielded 117, 257 and 445 g m^{-2} from plots supplemented with, respectively, 0, 15 and 80 g N m^{-2} (Mourice et al., 2014). Thus, the benefit of providing CaSa-compost matched that of a ~~much~~ higher (i.e. extremely high) input of ~~nitrogenous~~ synthetic N ~~fertilize~~fertiliser, however, provided by locally available nutrients.

The observed benefits of CaSa-compost were largely in line with the known effects of biochar amendments to soils.~~.~~

Two meta-analyses have suggested that for various crops, the addition of 2 ± 0.5 kg m^{-2} biochar induces a -3 % to +~~-~~23 % crop yield response compared to unamended control plots (Jeffery et al., 2011; Liu et al., 2013). Maize responds to the supplement by increasing its grain yield by 16 % and its biomass by 14 %. On acidic soils (pH of < 5.0), the ~~ameliorative~~ positive effect of biochar ~~lies~~ is between 25 and 35 %. ~~Only one of the amendments used here contained biochar (the CaSa-compost), so the direct effect of biochar was difficult to isolate from the present data. Rather, the focus was on comparing the benefit of using locally available materials. Nevertheless, the outcomes were largely in line with the known benefits of biochar.~~ The positive effect of the CaSa-compost on the soil and on biomass growth was most probably due to it's liming effect, which ~~associated with its acid neutralization, which served to~~ improved the availability of various nutrients, in particular that of P. The positive effects of applying CaSa-compost may ~~well continue to be felt~~last for ~~over~~ several cropping seasons, ~~in the way that~~as shown by Major et al. (2010) ~~showed~~ in a four year study ~~of a savanna Oxisol~~.

Furthermore, we experienced that biogas slurry may not be suitable as a soil amender for bean crops, since the plants did not appear to respond well compared to compost or CaSa-compost. Although most of recent work using biogas slurry as soil amender observed positive plant response in terms of productivity (Baba et al., 2013; Clements et al., 2012; Garfí et al., 2011; Komakech et al., 2015) others also revealed decreasing yields (e.g. Sieling et al., 2013). Salminen et al. (2001) attributed observed negative plant response to organic acids and ammonia contained in biogas slurry, which can be phytotoxic for plants if not applied in moderate quantities. Nevertheless, composting could reduce the before-mentioned substances as shown by Abdullahi et al. (2008). Therefore, this material should be combined with other organic matter.

3.3 Analysis of plant nutritional responses

The shoot, grain and corncob biomass produced by the maize crop was responsive to the soil amendments, whereas their water content was not significantly affected. According to Finck (2007), the concentrations of each of the nutrients were below recommended levels. However, compared to the outcomes of the experiment in Kenya reported by Kimetu et al. (2008), the grain concentrations of both N and K were slightly higher, while those of P, Ca and Mg were similar. In our experiment, the dry shoot material was deficient with respect to both P (0.7-0.9 g kg^{-1}, instead of recommended concentrations of 2.0-3.5 g kg^{-1}) and N (8-11 g kg^{-1}, compared to a recommended range of 15-32 g kg^{-1}) (Bergmann, 1999; Marschner, 2011). ~~The~~ O~~o~~nly the nutrient concentrations in the maize grains ~~nutrients that~~ responded significantly to the treatments ~~were~~ especially for K (p=0.03) and P (p=0.08) ~~in the maize grains~~ (Table 6~~5~~). Here, we observed a dilution effect for K while concentration of P was slightly increased in maize grains grown on plots amended with CaSa-compost. With respect to the N concentration, there was no significant treatment effect, since the N inputs had been adjusted *a priori* so that each treatment offered the same amount of N.

~~Here, we observed a dilution effect for K while concentration of P was slightly increased in maize grains grown on plots amended with CaSa-compost. According to Finck (2007), the concentrations of each of the nutrients lay below recommended levels. However, compared to the outcomes of the experiment in Kenya reported by Kimetu *et al.* (2008), the grain concentrations of both N and K were slightly higher, while those of P, Ca and Mg were similar. In our experiment, the dry shoot material was deficient with respect to both P (0.7-0.9 g kg^{-1}, against a recommended concentration of 2.0-3.5 g kg^{-1}) and N (8-11 g kg^{-1}, compared to a recommended range of 15-32 g kg^{-1}) (Bergmann, 1999; Marschner, 2011).~~

The vector nutrient analysis illustrated ~~the~~ primarily~~y~~ the response of maize to mitigated P deficiency, with the longest arrow indicating the largest response (Fig. 4). Here, an increase to each of the three parameters (biomass growth, nutrient concentration, nutrient uptake) was generated by an increased supply of the limiting nutrient~~, which was in our case~~ P. This is because, (i) more P was supplied with CaSa-compost (see Sect. 3.1) and (ii) ~~It is known that liming aids P uptake in acid soils (Batjes, 2011) and~~ its availability was increased due to the raised soil pH (Batjes, 2011). Furthermore, ~~With respect to the N concentration, there was, as expected, no significant treatment effect, since the N inputs had been adjusted *a priori* so that each treatment offered the same amount of N.~~ n~~N~~utrient uptake by maize was proportional to biomass growth. Hence, ~~and~~ plants grown on plots amended with CaSa-compost were able to take up significantly greater amounts of N, P, K, Ca, Mg and Zn in their grains than those grown on the other plots (Fig. 4).

~~It is known that liming aids P uptake in acid soils (Batjes, 2011) and it was established that the CaSa-compost treatment raised the soil pH.~~ As the native soil's K_{CAL} was already very high, and further K was provided by the amendments (Table 3~~2~~) an antagonistic effect on nutrient uptake between K and Ca as well Mg would have been possible (Finck, 2007). However, ~~the~~ observed changes in concentrations of Ca and Mg were not significant, but there was a ~~and the only~~ significant ~~effect observed was a~~ decrease in K concentration in maize grains. However, this might possibly be due to ~~reflecting~~ the dilution ~~effect~~ imposed by ~~a~~ growth stimulation.

3.4 Nutrient balancing

~~Soil P_{tot} and K_{tot} were both depleted on the control plots and those treated with urine with a balance being Δ Nut < 0 (Table 6).~~ On the plots treated with biogas slurry, standard compost and CaSa-compost, Nut_{app} of P varied ~~from low to high (~~with, respectively, 4.2, 6.8 and 13.8 g m^{-2}~~, –~~. This can be assessed a low to high application compared to a recommended ~~fertilize~~fertiliser rate of 7.0-8.4 g m^{-2} yr^{-1} for maize on P-deficient soils (KTBL, 2009; Finck, 2007) ~~of 7.0-8.4 g m^{-2} a^{-1}.)~~ ~~while~~ On the contrary, Nut_{app} of K was very high ~~(~~with, respectively, 53.8, 46.5 and 63.2 g m^{-2}, ~~as opposed~~compared to a recommended ~~fertilization dose~~dose of 9.3-12.4 g m^{-2} yr^{-1} for maize on soils with high K-content ~~of 9.3-12.4 g m^{-2} a^{-1})~~ (~~*KTBL, 2009; Finck, 2007*~~*ibid.*). On the plots treated with biogas slurry, plants took up ~19 % of the total applied P_{tot}; the equivalents for the standard compost and CaSa-compost treatments were ~16 % and ~12 %, respectively. These rates are consistent with the ~15 % reported by Finck (2007) as being available in the first year after ~~fertilize~~fertiliser application. With respect to K, Nut_{up} was about ~10 % of Nut_{app} in the biogas slurry treatment, ~18 % in the standard compost treatment and ~17 % in the CaSa-compost treatment. These~~,~~ rates ~~which~~ differ greatly from the ~60 % figure suggested by Finck (2007). The disparity relates most likely to the soil's ~~inherently~~ high level of K_{CAL}.

Following the results of nutrient balancing we estimate that soil P_{tot} and K_{tot} were both depleted (Δ Nut < 0) on the control plots (Table 7). In the biogas slurry, standard compost and CaSa-compost treated plots, ~~For both P and K,~~ Δ Nut was positive for both P and K ~~for the biogas slurry, standard compost and CaSa-compost treatments~~. However, ~~the~~ the only significant change to the top-soil's P_{CAL} was recorded ~~only significant change recorded to the top-soil's P_{CAL} was~~ in the CaSa-compost treatment (Sect. 3.1.). ~~Here~~Hence, about 1.1 g P m^{-2} was assignable to Δ Nut_{av} in the plots supplied with CaSa-compost, with the rest being "non-available". Some of the latter may include P that had not been released through mineralization of the organic matter, while some may have been immobilized in the form of metal-humus complexes, which are characteristic ~~of~~ for Andosols (Zech, 2014) (i.e. assignable to Δ Nut_{nav} in both cases). Leaching ~~(i.e. RO)~~ of P is insignificant, since P rather gets immobilized (Finck, 2007). ~~Some~~ We assume that some of the K ~~that was~~ provided by the amendments may have been leached during the rainy season~~n (i.e. assignable to RO)~~ as mentioned by~~. According to~~ Finck (2007)~~,~~ ~~leaching is significant for K on~~for light soils such as the present Andosol. There were no signs of significant losses through soil erosion visible on the experimental site.

From our findings we recommend the addition of urine and sanitized faeces to the compost, since the matters provide a ready source of nutrients accelerating for example compost's N_{min} and total P content (compare Table 2). Given that biochar can capture both nitrate and phosphate, as shown by Gronwald et al. (2015) and Kammann et al. (2015), we assume that combining urine and biochar as compost additives enriches compost with N and P and reduces nutrient loss during and after composting. Especially, the loss of N in the form of the green house gas N_2O can be reduced as shown by Larsen and Horneber (2015). In addition, urine can contribute to the moisture required for successful composting.

~~**4 The potential to close the nutrient loop**~~

~~**5 To obtain an estimate of the volume of CaSa-compost which could be practicably produced, the assumption was made that the daily per person production of excreta was 0.3 kg of FM (0.33 dm^3), to which some 0.15 kg (0.25 dm^3) dry material can be added in the situation where the faeces are collected in an UDDT (Chaggu, 2004; Berger, 2008). Drying the material inside the UDDT removes about 30 % of the water in the solid mix, reducing the volume by 15 %. These solid parts, collected and dried in the UDDT, are composted together with other materials including harvest and kitchen residues, biochar and urine just like CaSa-compost of this study was produced (see Krause et al., 2015). The composting process imposes further reduction of the volume by about 30 % and finally results in about 850 dm^3 per person and over the course of a year. If the compost is applied at the rate of 8.3 dm^3 m^{-2} (the rate used in the present experiment), an area of about 100 m^2 a^{-1} can be effectively fertilized. The compost's P_{tot} would be about 1.4 kg, of**~~

which about 20 % would have been derived from the sanitized and composted excreta. The predicted effect of fertilization would be to increase maize grain yield from 10.9 kg to 43.5 kg on this area of about 100 m^2 in the first cropping season. The application of this compost would also combat soil acidity by delivering about 20.5 kg CaO in total (with 0.2 kg CaO m^{-2}), which would be sufficient to satisfy the soil's lime requirement for three years. Hence, the use of CaSa-compost would allow an estimated area of about 300 m^2 to be ameliorated per person per three years. Overall, for one family in Karagwe with 6 people living in one household, our final estimates result in a potential to produce CaSa-compost of ~ 5 m^3 a^{-1} which could be used as soil fertility improver (with 8.3 dm^3 m^{-2} $3a^{-1}$) on a total area of about 1,800 m^2. Given the fact that ~ 6,225 m^2 are planted per household (Tanzania, 2012) the calculated amounts would suffices to be solely applied on about 30 % of the cultivated land of small-scale farmers in Karagwe.

6 Further aspects

7 A widespread adoption of good soil amendment practice will depend not only on demonstrating its effectiveness, but also on a range of subjective issues. Hence, we want to share some of our personal experiences from the present experiment. In general, diluting urine with water was acceptable and application with the use of a jug was not disgusting. Unfortunately, the urine's fertilizer qualities were altered by passing it through a deodorizer block in the urinal inside the UDDT. Hence, the true benefit of the urine treatment was not easy to gauge in our experiment. Nevertheless, when the same material was added to CaSa-compost, there was no evidence of any detrimental effect. However, we did not make any analysis to follow-up on this. Given that biochar captures both nitrate and phosphate, as shown by Gronwald et al. (2015) and Kamman et al. (2015), we prefer and recommend the addition of urine to the compost, since it provides a ready source of N and also contributes to the moisture required for successful composting. Based on literature we assume, the combination of urine and biochar as compost additives is favourable, thereby combining enriching compost with N and P and reducing nutrient loss both during and after composting. Hereby, the loss of nitrogen in the form of the greenhouse gas N_2O can be reduced as shown by Larsen (2015). Furthermore, we experienced that biogas slurry may not be suitable as a soil amender for bean crops, since the plants did not appear to respond well; rather this material should be combined with other organic matter. Even though the CaSa-compost contained human excreta, it was not unpleasant to handle, and it was important for us to know, when working on the field, that the thermal treatment effectively removed any health hazard. The CaSa-compost also aided workability of the soil by making it more friable.

8

94 Conclusions

To summarise: for beans and maize, cCrop biomass production and economic yield were both significantly improved by the application of CaSa-compostwith respect to. For cabbage and onion, all three of the tested amendments were beneficial. The amendments, and especially CaSa-compost, improved the nutrient availability, as revealed by vector nutrient analysis. This can be attributed to changes in soil pH and the addition of nutrients.

~~The benefits derived from the amenders were due to improvements in the nutrient availability rather than to any increase in soil moisture content.~~

Of particular significance was the observation that the P deficiency affecting the local Andosol could be mitigated using CaSa-compost. The increase in available P achieved by the CaSa-compost treatment was more than sufficient to supply the crops' requirement. Thus we conclude that a gradual increase in soil P could be achieved by a regular application of the CaSa-compost.

The chosen rates of biogas slurry and standard compost supplementation were sufficient to maintain the soil's pH, whereas the CaSa-compost raised the soil pH, ~~making it more~~improving its productivity immediately~~ive~~. ~~Based on the calculated liming effect of biogas slurry, an annual application would be needed to counteract soil acidity, whereas incorporation of either the standard or the CaSa-compost would only be required every three years. However~~Thus we conclude that~~,~~ a continuous program of composting and compost amendments over decades would probably ~~be needed to~~ fully ameliorate the ~~top- and the sub-~~soil.

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We further conclude, that the application of local available biogas slurry needs to be tested for several crops before recommending the widespread utilization of this matter as it may contain substances, which could be phytotoxic for plants if not applied in moderate quantities. In addition, composting of biogas slurry prior to soil amendment, possibly with and without biochar, is of certain practical relevance but needs preceding scientific investigation to study the specific metabolisms taking place and to identify the consequent N-recovery-efficiency.~~ The increase in available P achieved by the CaSa-compost treatment was more than sufficient to supply the crops' requirement. Thus, a **gradual increase in soil P** should be achieved by a regular application of the CaSa-compost.~~

Finally, we conclude ~~We conclude~~ that all the treatments, but especially CaSa-compost, are viable as substitutes for synthetic commercial ~~fertilize~~fertilisers~~.After all, we recognize that the present experiment was short-term, so a more sustained study will be needed to monitor the long-term effect of CaSa-compost application on soil fertility and crop productivity.~~ We further conclude that local smallholders with 6 people per household can produce CaSa-compost at an estimated rate of ~5.1 $m^3\ yr^{-1}$, which would be sufficient to fertilise an area of ~1,850 m^2 at the rate of 8.3 $dm^3\ m^{-2}$ over the course of three years. By this means, it would be possible to fertilise about 30 % of the average area cultivated by smallholders in Karagwe. Therefore~~Following the discussion of the nutrient loop~~, ~~we conclude that (a) the area which could be fertilized with the amount of CaSa-compost produced by one family in Karagwe and an application rate of ~8 $dm^3\ m^{-2}\ 3a^{-1}$ and (b) the total land that this family cultivates on their small-holder farm are **not yet balanced**. Furthermore, as the amendments were adjusted based on N_{min}, the applied amount of CaSa-compost resulted in a comparatively high addition of K and P. Thus, it appears that this~~CaSa-~~-~~approach needs to be integrated into farm-scale nutrient management by conducting a~~. For example, further N could be derived from intercropping with legumes, such as beans, and this N input should be considered in the nutrient balance. In addition, organic fertilizing with CaSa-compost could be combined with urine application as a mineral fertilizer. Hence, the application dosage of the CaSa-treatment could be reduced, whilst the size of the fertilized land could be increased. In doing so, application of P and K would be on an adequate level.~~

Therefore, a detailed analysis of nutrient flows in the farm-household-system in Karagwe is required,and studying all potential additions and removals of nutrients to and from the planted land. This will be the next step of our research work.

With every step, it slowly grows….

Disclosure of conflict of interest

The authors do not have to declare any conflict of interest. All partner organizations of the projects agreed to the ecological research on the projects and that the products will be assessed and that the results will be published.

Author's contribution

A. Krause and M. Kaupenjohann designed the experiment and planned, discussed and evaluated soil chemical analysis. A. Krause carried out the experiment with the assistance of local workers. A. Krause and T. Nehls planned, discussed and evaluated the soil physical experiments that A. Krause conducted. E. George gave valuable advice for the fertilizing strategy, analysis of plant nutritional status and data analysis in general. A. Krause prepared the manuscript including drafting the text and preparing figures and tables; all co-authors cooperated by correcting the text and promoting the professional discussions.

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References

Abdullahi, Y.A., Akunna, J.C., White, N.A., Hallett, P.D., and Wheatley, R.: Investigating the effects of anaerobic and aerobic post-treatment on quality and stability of organic fraction of municipal solid waste as soil amendment, Bioresource Technol., 99 (18), 8631-8636, doi:10.1016/j.biortech.2008.04.027, 2008.

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., and Wessolek, G.: Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil, Geoderma, 202, 183-191, doi:10.1016/j.geoderma.2013.03.003, 2013.

Abera, G., and Wolde-Meskel, E.: Soil Properties, and Soil Organic Carbon Stocks of Tropical Andosol under Different Land Uses, Open J. Soil Sci., 3, 153-162, doi:10.4236/ojss.2013.33018, 2013.

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., and Horie, T.: Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield, Field Crop. Res., 111(1-2), 81–84, doi:10.1016/j.fcr.2008.10.008, 2009.

Baba, Y., Tada, C., Watanabe, R., Fukuda, Y., Chida, N., and Nakai, Y.: Anaerobic digestion of crude glycerol from biodiesel manufacturing using a large-scale pilot plant: Methane production and application of digested sludge as fertiliser, Bioresource Technol., 140, 342- 348, doi:10.1016/j.biortech.2013.04.020, 2013.

Batjes, N. H.: Global distribution of soil phosphorus retention potential, ISRIC Report 2011/06, Wageningen University and Research Centre, The Netherlands, 41 pp., 2011.

Batjes, N. H. and Sombroek, W. G.: Possibilities for carbon sequestration in tropical and subtropical soils, Glob. Change Biol., 3(2), 161-173, doi:10.1046/j.1365-2486.1997.00062.x, 1997.

Becker, P. and Krause, A.: Development of adaptive technologies in the project Biogas Support for Tansania „BiogaST“, Proceedings of the International Conference “Micro Perspectives for Decentralized Energy Supply 2011”, pp. 236-237, Technische Universität Berlin, ISBN 978-3-7983-2319-3, 2011.

Bergmann, W. (Ed.): Ernährungsstörungen bei Kulturpflanzen: Entstehung, visuelle und analytische Diagnose (Nutrition disorders of cultivated crops: origin, visual and analytical diagnostics), 3rd edition, Springer Spektrum, Heidelberg, Germany, 835 pp., 1999.

Biederman, L. A. and Harpole, W. S.: Biochar and its effects on plant productivity and nutrient cycling - a meta-analysis, GCB Bioenergy, 5(2), 202-214, doi:10.1111/gcbb.12037, 2013.

Blösch, U.: Thicket Clumps: a characteristic feature of the Kagera savana landscape, East Afr. J. of Vegetat. Sci., 19, 31-44, doi: 10.3170/2007-8-18315doi:10.3170/2007-8-18315, 2008.

Buresh, R. J., Smithson, P. C., and Hellums, D. T.: Building soil phosphorus capital in Africa, in: Replenishing soil fertility in Africa, Special Publication 51, Soil Science Society of America and American Society of Agronomy (SSSA), Chicago, United States, 111-149, doi:10.2136/sssaspecpub51.c6, 1997.

Chesworth, W. (Ed.): Encyclopedia of soil science, Springer Science & Business Media, Dordrecht, The Netherlands, 902 pp., doi:10.1007/978-1-4020-3995-9, 2008.

Clements, L.J., Salter, A.M., Banks, C.J., and Poppy, G.M.: The usability of digestate in organic farming. Water Sci. Technol., 66, 1864-1870, 2012.

Dörner, J., Dec, D., Zúñiga, F., Sandoval, P., and Horn, R.: Effect of land use change on Andosol's pore functions and their functional resilience after mechanical and hydraulic stresses, Soil Till. Res., 115, 71-79, doi:10.1016/j.still.2011.07.002, 2011.

Dorel, M., Roger-Estrade, J., Manichon, H., and Delvaux, B.: Porosity and soil water properties of Caribbean volcanic ash soils, Soil Use Manage., 16(2), 133-140, doi:10.1111/j.1475-2743.2000.tb00188.x, 2000.

Driessen, P., Deckers, J., Spaargaren, O., and Nachtergaele, F.: Lecture notes on the major soils of the world, World Soil Resources Reports No. 94, Food and Agriculture Organization (FAO), Rome, Italy, 307 pp., 2000.

Esrey, S.A., Andersson, I., Hillers, A., and Sawyer, R.: Closing the Loop - Ecological sanitation for food security, Publications on Water Resources No. 18. Swedish International Development Cooperation Agency (SIDA), Sweden/Mexico, ISBN 91-586-8935-4, 2001.

FAOSTAT (2012): Final data for 2012, item “maize”, country “all”, element “yield”, Statistical Databases of the Food and Agriculture Organization of the United Nations (FAO), 2012, http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor, last access: 22 Dec 2014.

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Finck, A.: Pflanzenernährung und Düngung in Stichworten (Plant nutrition and fertilization in keywords), 6th edition, Gebr. Borntraeger, Schweitzerbart Science publishers, Stuttgart, Germany, 253 pp., 2007.

Garfí, M., Gelman, P., Comas, J., Carrasco, W., and Ferrer, I.: Agricultural reuse of the digestate from low-cost tubular digesters in rural Andean communities, Waste Manage., 31 (12), 2584-2589, doi:10.1016/j.wasman.2011.08.007, 2011.

Glaser, B. and Birk, J. J.: State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio), Geochim. Cosmochim. Ac., 82, 39–51, doi:10.1016/j.gca.2010.11.029, 2012.

Gronwald, M., Don, A., Tiemeyer, B., and Helfrich, M.: Effects of fresh and aged biochars from pyrolysis and hydrothermal carbonization on nutrient sorption in agricultural soils, SOIL Discuss., 2, 29-65, doi:10.5194/soild-2-29-2015, 2015.

Herath, H. M. S. K., Camps-Arbestain, M., and Hedley, M.: Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol, Geoderma, 209, 188–197, doi:10.1016/j.geoderma.2013.06.016, 2013.

Horn, R., Brümmer, G. W., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., and Wilke, -B. M.: Scheffer/Schachtschabel - Lehrbuch der Bodenkunde (Textbook of soil science), 16th edition, Springer Spektrum, Heidelberg, Germany, 570 pp., 2010.

Imo, M.: Analysis of Nutritional Interactions in Cropping Systems, chapter 13 in: Crop Production Technologies, Sharma, P. and Abrol, V. (Eds.), InTech Open Access Publisher, 221-242, doi:10.5772/1109, 2012.

Isaac, M. E. and Kimaro, A. A.: Diagnosis of Nutrient Imbalances with Vector Analysis in Agroforestry Systems; J. Environ. Qual., 40, 860–866; doi:10.2134/jeq2010.0144, 2011.

ISO DIN 10694: Soil quality - Determination of organic and total carbon after dry combustion (elementary analysis) (ISO 10694:1995), International Organization for Standardization (ISO), Geneva, Switzerland, 1995.

ISO DIN 13878: Soil quality - Determination of total nitrogen content by dry combustion ("elemental analysis") (ISO 13878:1998), Association Française de Normalisation (AFNOR), La Plaine Saint-Denis Cedex, France, 1998.

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Jeffery, S., Verheijen, F. G. A., Van Der Velde, M., and Bastos, A. C.: A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis, Agr. Ecosyst. Environ., 144, 175–187, doi:10.1016/j.agee.2011.08.015, 2011.

Kammann, C. I., Linsel, S., Gößling, J. W., and Koyro, H. W.: Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil–plant relations, Plant Soil, 345(1-2), 195-210, doi: 10.1007/s11104-011-0771-5, 2011.

Kammann, C. I., Schmidt, H. P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C. Koyro, H. W., Conte, P., and Stephen, J.: Plant growth improvement mediated by nitrate capture in co-composted biochar, Nature Sci. Rep., 5:11080, 12 pp., doi:10.1038/srep11080, 2015.

Kimaro, A. A., Timmer, V. R., Chamshama, S. A. O., Ngaga, Y. N., and Kimaro, D. A.: Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops, Agr. Ecosyst. Environ., 134, 115–125, doi:10.1016/j.agee.2009.06.002, 2009.

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., and Pell, A. N.: Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient, Ecosystems, 11(5), 726-739, doi:10.1007/s10021-008-9154-z, 2008.

König, N. (Ed.): B 3.2.1. Druckaufschluss mit HNO3, in: Handbuch Forstliche Analytik (HFA) – Grundwerk, Loseblatt-Sammlung der Analysemethoden im Forstbereich, 2nd edition, published by Gutachterausschuss Forstliche Analytik (GFA), German Federal Ministry of Food and Agriculture (BMEL), Göttingen, Germany, 425-429, 2006.

Komakech, A. J., Zurbrügg, C., Semakula, D., Kiggundu, N., and Vinnerås, B.: Evaluation of the Performance of Different Organic Fertilisers on Maize Yield: A Case Study of Kampala, Uganda, J. Agr. Sci., 7(11), 28, doi:10.5539/jas.v7n11pxx, 2015.

Krause, A., Kaupenjohann, M., George, E., and Köppel, J.Krause, A., Kaupenjohann, M., George, E., and Nehls, T.: Nutrient recycling from sanitation and energy systems to the agroecosystem - Ecological research on case studies in Karagwe, Tanzania, Afr. J. Agric. Res.,–, 10(43), 4039-4052, doi: 10.5897/AJAR2015.10102, in press, 2015.

KTBL: Faustzahlen für die Landwirtschaft (Rule-of-thumb figures for agriculture), published by Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL), 14th edition, Darmstadt, Germany, 1280 pp., 2009.

Landon, J. R.: Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics, 1st paperback edition, Longman Scientific & Technical Ltd., Essex, England, pp. 474, 1991.

Larsen, O. and Horneber, D.: Einfluss von Biokohle auf Treibhausgasemissionen während der Kompostierung, in: Book of Abstracts of the scientific Workshop „Biokohle im Gartenbau – Verwertung von organischen Reststoffen zur Schließung von Energie- und Stoffkreisläufen“, Berlin, Germany, 23-24 June, 33-34, 2015.

Lehmann, J. and Joseph, S.: Biochar for Environmental Management - Science and Technology, 1st edition, Earthscan, London, United Kingdom, 416 pp., 2009.

Liu, J., Schulz, H., Brandl, S., Miehtke, H., Huwe, B., and Glaser, B.: Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions, J. Plant Nutr. Soil Sc., 175, 698-707, doi:10.1002/jpln.201100172, 2012.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., and Paz-Ferreiro, J.: Biochar’s effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data, Plant Soil, 373(1-2), 583-594, doi:10.1007/s11104-013-1806-x, 2013

Major, J., Rondon, M., Molina, D., Riha, S. J., and Lehmann, J.: Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol, Plant Soil, 333(1-2), 117-128, doi:10.1007/s11104-010-0327-0, 2010.

Marschner, P. (Ed.): Marschner's mineral nutrition of higher plants, 3rd edition, Academic press, Waltham, United States, 651 pp., 2011.

Mourice, S. K., Rweyemamu, C. L., Tumbo, S. D. and Amuri, N.: Maize cultivar specific parameters for decision support system for agrotechnology transfer (DSSAT) application in Tanzania, Am. J. Plant Sci., 5, 821-833, doi:10.4236/ajps.2014.56096, 2014.

Mukunda, H.S., Dasappa, S., Paul, P.J., Rajan, N.K., Yagnaraman, M., and Ravi, K.D., Deogaonkar, M.: Gasifier stoves – science, technology and field outreach, Curr. Sci. India, 98(5), 627-638, 2010.

Ndibalema, A. and Berten, A.: Lowtech-micro-gasifiers as a solution for deforestration and health problems caused by indoor air pollution, Practitioner proceedings of the International Conference “Micro Perspectives for Decentralized Energy Supply 2013” at Technische Universität Berlin, pp. 31-33. Edition Lalla Moulati, Alger, Algerie, 2015.

Nehls, T.: Fertility improvement of a Terra Firme Oxisol in Central Amazonia by charcoal applications, Final thesis in Geoecology, University of Bayreuth, Institute of Soil Science and Soil Geography, 81 pp., 2002.

Perret, S. and Dorel, M.: Relationships between land use, fertility and andisol behaviour: examples from volcanic islands, Soil Use Manage., 15(3), 144-149, doi:10.1111/j.1475-2743.1999.tb00080.x, 1999.

Peters, A., Iden, S.C. and Durner, W.: Revisiting the simplified evaporation method: Identification of hydraulic functions considering vapor, film and corner flow. J Hydrol, 527, 531-542, doi:10.1016/j.jhydrol.2015.05.020, 2015.

Petter, F.A., Madari, B.E., Silva, M.A.S.D., Carneiro, M.A.C., Carvalho, M.T.D.M., Júnior, M., ... and Pacheco, L.P.: Soil fertility and upland rice yield after biochar application in the Cerrado, Pesqu. Agropecu. Bras., 47(5), 699-706, doi:10.1590/S0100-204X2012000500010, 2012.

Richter, C., Piepho, H. P., and Thöni, H.: The 'Latin Rectangle' - its layout, randomisation, and analysis combined with a revision of the commonly used German terminology, Pflanzenbauwissenschaften, 13(1), 1-14, ISSN 1431-8857, 2009.

Salminen, E., Rintala, J., Härkönen, J., Kuitunen, M., Högmander, H., and Oikari, A.: Anaerobically digested poultry slaughterhouse wastes as fertiliser in agriculture, Bioresource Technol., 78 (1), 81-88, doi:10.1016/S0960-8524(00)00160-7, 2001.

Schönning, C. and Stenström, A.T.: Guidelines for the safe use urine and faeces in ecological sanitation systems, Swedish Institute for infectious disease control, EcoSanRes Programme, SEI, ISBN 91-88714-93-4, 2004.

Schulz, H., Dunst, G. and Glaser, B.: Positive effects of composted biochar on plant growth and soil fertility. Agronomy for sustainable development, 33(4), 817-827, doi: 10.1007/s13593-013-0150-0, 2013.

Sieling, K., Herrmann, A., Wienforth, B., Taube, F., Ohl, S., Hartung, E., and Kage, H.: Biogas cropping systems: Short term response of yield performance and N use efficiency to biogas residue application., Eur. J. Agron., 47, 44-54, doi:10.1016/j.eja.2013.01.002, 2013.

Sombroek W.: Amazon Soils - A Reconnaissance of Soils of the Brazilian Amazon Region, Dissertation, Agricultural State University of Wageningen, Centre for Agricultural Publications and Documentation, The Netherlands, 1966.

~~Sponagel, H., Grottenthaler, W., Hartmann, K. J., Hartwich, R., Janetzko, P., Kühn, D., Sabel, K. J., and Traidl, R.: Bodenkundliche Kartieranleitung, (Manual of soil mapping), 5th edition, Eckelmann, W. (Ed.), Schweitzerbart Science publishers, Stuttgart, Germany, 438 pp., 2005.~~

Tanzania, United Republic: National Sample Census of Agriculture 2007/2008 - Regional Report - Kagera Region, vol. Vh, published by various ministries of Tanzania and Zanzibar, Prime Minister's office, regional administration and local governments, National Bureau of Statistics and the Chief Government Statistician, Zanzibar, July, 339 pp., 2012.~~ Available at: http://harvestchoice.org/sites/default/files/downloads/publications/Tanzania_2007-8_Vol_5r.pdf, last access: June, 2015.~~

Tonfack, L. B., Bernadac, A., Youmbi, E., Mbouapouognigni, V. P., Ngueguim, M., and Akoa, A.: Impact of organic and inorganic fertilizers on tomato vigor, yield and fruit composition under tropical andosol soil conditions, Fruits, 64(03), 167-177, doi:10.1051/fruits/2009012, 2009.

VDLUFA: Methodenbuch - Band VII, Umweltanalytik, chapter A 2.1.1., 4th edition, published by Verband deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten e. V. (VDLUFA; Association of German Agricultural Analytic and Research Institutes), Darmstadt, Germany, 690 pp., 2011.

VDLUFA: Methodenbuch - Band I, Bodenuntersuchung, chapter A 6.2.1.1., 4th edition, published by VDLUFA, Darmstadt, Germany, 1570 pp., 2012.

Zech, W., Schad, P., and Hintermaier-Erhard, G.: Böden der Welt: ein Bildatlas (Soils of the wordl: a visual atlas), 2nd edition, Springer Spektrum, Heidelberg, Germany, 164 pp., 2014.

Tables

Table 1. The characteristics of the investigated *vitric* Andosol in Karagwe, Tanzania.

			Aggregate size distribution												
	Depth	Color	clay	silt	sand	structure	pH	ρ_B	FC_{field}	FC_{lab}	CEC_{eff}	BS	TOC	N_{tot}	C/N
	cm	Munsell	%	%	%		KCl	kg dm^{-3}	m^3 m^{-3}	m^3 m^{-3}	cmol kg¹	%	%	%	
Ap	20	2.5 YR 3/2	3.2	16.1	80.7	Very crumbly	3.8	0.94	0.38	0.35	16.7	99.6	3.5	0.3	12.9
Ah	37	2.5 YR 3/2	3.6	13.0	83.4	Blocky subangular to crumbly	3.8	0.88							
B1	53	2.5 YR 2.5/3	2.2	16.3	81.5	Crumbly to blocky subangular	NA~~ua.~~	1.08	0.36	NA~~ua.~~	11.2	97.1	2.7	0.2	13.3
B2	74	2.5 YR 3/3	2.2	20.1	77.8	Macro: prismatic; micro: blocky subangular	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	8.0	94.5	2.0	0.2	12.5
C	100+	~~ua~~NA~~.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	No aggregates, subangular gravel	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~	NA~~ua.~~
~~Soil classification: *vitric* Andosol~~															

Water holding capacity (WHC) was determined in the field (FC_{field}) and in the laboratory (FC_{lab}). ρ_B: bulk density, CEC: cation exchange capacity, BS: base saturation, TOC: total organic carbon, NA: not analysed

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Table 2: The characteristics of the tested soil amendments according to Krause et al. (2015).

		C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
							in dry matter						
		g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}
Gras		426	1.9	ua.	1.7	1.0	13.8	2.8	8.6	4.9	4.0	24.1	172
Biogas slurry		348 ± 6	19.9 ± 0.1	16.0 ± 0.8	3.1 ± 0.02	7.6 ± 0.2	92.9 ± 8.4	12.2 ± 0.1	17.4 ± 0.9	4.0 ± 0.7	4.3 ± 0.1	115.3 ± 1.7	283 ± 9
Compost		91 ± 8	5.3 ± 0.2	0.12 ± 0.04	1.2 ± 0.1	1.2 ± 0.1	8.5 ± 1.2	3.2 ± 0.2	10.0 ± 1.2	77.5 ± 1.6	65 ± 10	59.5 ± 4.3	641 ± 106
CaSa-compost		116 ± 11	6.0 ± 0.5	0.36 ± 0.07	1.3 ± 0.1	3.2 ± 0.2	14.6 ± 1.4	5.1 ± 0.5	29.6 ± 2.8	54.5 ± 1.4	84 ± 18	67.0 ± 4.7	480 ± 48
	pH						in fresh matter						
	in KCl	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	mg dm^{-3}	mg dm^{-3}
Gras		25 ± 13	0.1 ± 0.1	ua.	0.1 ± 0.1	0.1 ± 0.03	0.8 ± 0.4	0.2 ± 0.1	0.5 ± 0.3	0.3 ± 0.2	0.2 ± 0.1	1.4 ± 0.7	10 ± 5
Biogas slurry	7.7	15 ± 1	0.9 ± 0.04	0.7 ± 0.05	0.1 ± 0.01	0.3 ± 0.02	4.1 ± 0.4	0.5 ± 0.03	0.8 ± 0.1	0.2 ± 0.03	0.2 ± 0.01	5.1 ± 0.3	12 ± 1
Compost	7.4	33 ± 6	1.9 ± 0.3	0.04 ± 0.02	0.4 ± 0.1	0.5 ± 0.1	3.1 ± 0.7	1.1 ± 0.2	3.6 ± 0.7	28.1 ± 4.5	24 ± 5	21.6 ± 3.7	233 ± 53
CaSa-compost	7.5	60 ± 7	3.1 ± 0.3	0.2 ± 0.04	0.7 ± 0.1	1.7 ± 0.1	7.6 ± 0.9	2.7 ± 0.3	15.4 ± 1.7	28.3 ± 1.8	44 ± 10	34.9 ± 3.2	250 ± 29

Analyses as described in Krause et al. (2015): total concentrations of nutrients, P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, Mn_{tot}, Al_{tot}, and Fe_{tot}, were determined using HNO_3-digestion under pressure (König, 2005) and iCAP 6000 ICP-OES-device (Thermo Scientific, Waltham, USA). Total concentrations of C, N, S were analyzed according to ISO DIN 10694 (1995) for C_{tot}, ISO DIN 13878 (1998) for N_{tot}, and DIN ISO15178 (HBU 3.4.1.54b) for S_{tot}, and using Vario ELIII CNS-Analyzer (Elementar, Hanau, Germany). Mineral nitrogen (N_{min}) was extracted with potassium chloride (KCl) and analyzed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany). The method involved the suspension of 50 g material of the amenders in 100 ml 0.1 M KCl. Within the same solution, pH was measured by using a glass electrode (pH 330i, WTW, Weilheim, Germany). Values are displayed with mean value and standard deviation with n=1, 2 and 5, respectively, for grasses, biogas slurry, and compost as well as CaSa-compost.
The dominant form of available N_{min} was NH_4 for biogas slurry and NO_3 for compost as well as CaSa-compost respectively.

Table 23. Soil nutrient status before applying the amendments [g m^{-2}] and the nutrient loads [g m^{-2}] following of the amendments. [dm^3 m^{-2} and kg m^{-2}].

	FM	FM	DM	N_{min}	P	K	Mg	Ca	Al	Zn	Mn
	dm^3 m^{-2}	kg m^{-2}	kg m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}
Soil (0-90 cm)	900	1039	869	7.5	0.4	141	1107	2761	60	n.d.	uaNA.
Biogas slurry	10.2	10.2	0.4	4.9	3.4	41.3	5.4	7.7	1.8	0.05	0.13
Gras	15.6	1.2	0.9	5.8	0.9	12.5	2.6	7.8	4.4	0.02	0.16
∑ Biogas*	25.8	11.4	1.3	10.7	4.3	53.8	8.0	15.5	6.2	0.07	0.29
Compost	15.0	8.2	5.4	10.4	6.8	46.5	17.2	54.4	421.5	0.32	3.49
CaSa-compost	8.3	6.4	4.3	9.5	13.8	63.2	22.2	128.1	236.2	0.29	2.08

Concentrations in the dry soil were analysed as described in section Sect. 2.3.; calculations of the content in fresh matter of the treatments derived from concentrations provided by Krause et al. (2015), see Table 2 for description of methods.

In the soil (0-90 cm), concentration of exchangeable ("available") nutrients was extracted with Ca-acetat, Ca-lactat and $C_2H_4O_2$ (CAL) for P and K and exchanged with NH_4Cl for Mg, Ca, Zn, Mn, and Al. In the tested soil amendments, total concentrations of nutrients were determined after HNO_3 digestion under pressure using ICP-OES. Concentration of N_{min} was extracted by KCl solution for soil and the amendments and determined using test strips. The dominant form of available N_{min} was NH_4 for biogas slurry and NO_3 for compost as well as CaSa-compost respectively.

* Values based on Berger (2008) data for stored urine.

** For the biogas slurry treatment, the nutrient load was derived from both grasses and slurry (∑ Biogas).

* For the biogas slurry treatment, the nutrient load was derived from both grasses and slurry (∑ Biogas).

Non common abbreviations: DM: dry matter; FM: fresh matter; NA: not analysed, n.d.: not detectable,

Table 4~~3~~. Chemical analysis of the untreated Andosol in Karagwe, Tanzania and ~~treated~~ the amended top-soil (0-30 cm) horizons sampled at the end ~~after the termination~~ of the experiment.

Treatment	pH in KCl		P_{CAL} mg kg^{-1}	
Control ~~without~~Andosol	5.3	a	0.5	a
Biogas slurry	5.4	ab	0.7	a
Compost	5.5	ab	1.1	a
CaSa-compost	5.9	b	4.4	b

Different letters reflect means differing significantly from one another (HSD, Tukey test, α=0.05; n=3).

Table 54. Harvest and market products of maize [g m-2]and in relation to the untreated control (100 %). Control and urine treatments: n=4, other treatments: n=5.

	Harvest product Total above-ground biomass, FM			Market product Maize grains, air-dry		
	g m^{-2}	%		g m^{-2}	%	
Control withoutAndosol	1595	100 %	a	110	100 %	a
9.1 Urine	9.2 2019	9.3 127 %	9.4 a	9.5 172	156 %	9.6 ab
Biogas slurry	2229	140 %	a	263	238 %	ab
Compost	2464	154 %	ab	318	288 %	bc
CaSa-compost	3372	211 %	b	438	397 %	c

Different letters reflect means differing significantly from one another (HSD, Tukey test, α=0.05) with n=4 for control, and n=5 for other treatments.

Table 65. Nutrient concentration in DM dry matter of maize grains [g kg^{-1}] compared to levels reported by Finck (2007) and Kimetu et al. (2008)in literature.

	N_{tot}	P_{tot}	K_{tot}	Ca_{tot}	Mg_{tot}
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Control withoutAndosol	15.9	2.3	4.4	0.1	1.0
9.7 Urine	9.8 16.4	9.9 2.4	9.10 4.5	9.11 0.1	9.12 1.0
Biogas slurry	16.5	2.6	4.0	0.1	1.0
Compost	15.6	2.5	3.6	0.1	1.0
CaSa-compost	16.8	3.0	3.9	0.1	1.1
p (n=3)	*0.58*	*0.08*	*0.03*	*0.71*	*0.34*
Finck, 2007	17.5	4.0	4.9	2.1	1.4
Kimetu et al., 2008 (Kenya):					
Control	11.8	2.3	2.7	0.03	0.9
Biochar	12.5	2.2	2.6	0.1	0.8

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Table 76. Changes in the soil nutrient status (Δ Nut) [g m^{-2}],) along with nutrients applied by the treatment (Nut_{app}) and the nutrients taken up by the crop (Nut_{up}).

	$Nut._{app}$	$Nut._{up}$	Δ Nut.	$Nut._{app}$	$Nut._{up}$	Δ Nut.
	P	P	P	K	K	K
	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}	g m^{-2}
Control withoutAndosol	-	0.4	- 0.4	-	3.3	- 3.3
Biogas slurry	4.2	0.8	3.5	53.8	5.2	48.5
Compost	6.8	1.1	5.7	46.5	8.5	38.0
CaSa-compost	13.8	1.7	12.3	63.5	10.7	52.5

Data based on three plots for each treatment.

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Figures

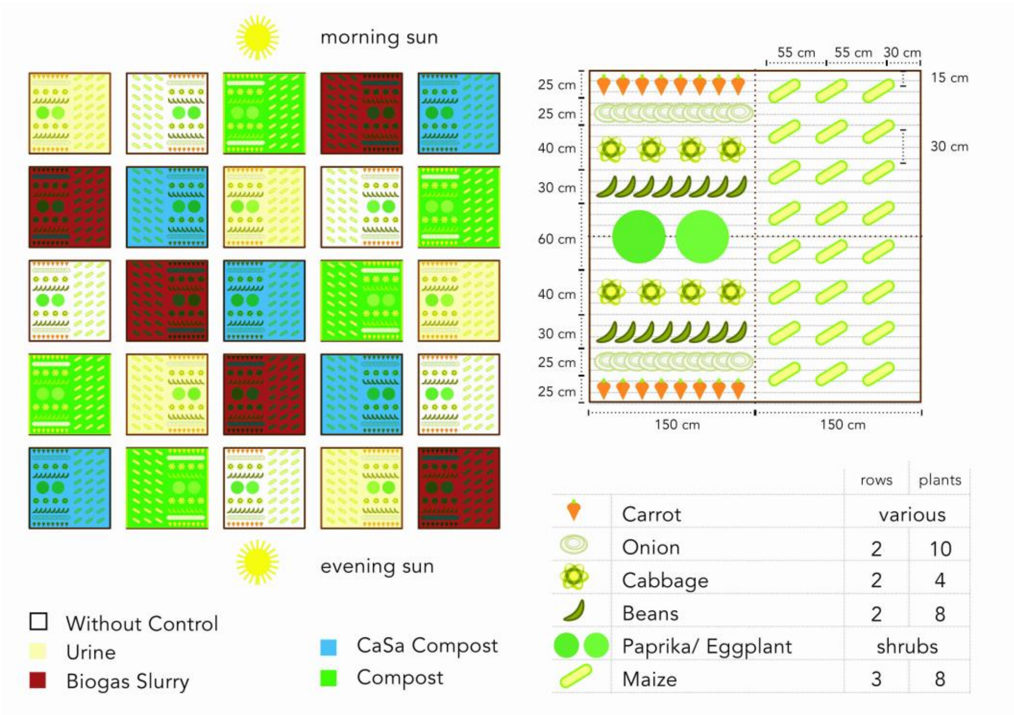
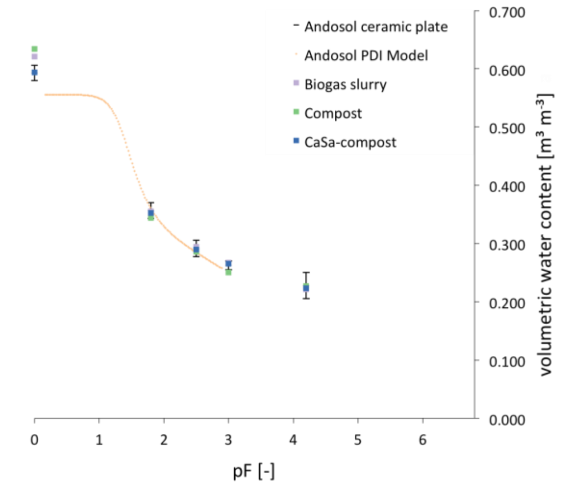


Fig. 1. The experiment design: the plots were arranged as a Latin ~~square~~rectangle with five columns and five rows (left side of the figure) and each plot was divided into two 4.5 m^2 sections for the cultivation of seven selected crops in an intercropping system (right side of the figure);

note that urine treatment was a *posteriori* excluded from the analysis due to technical problems.



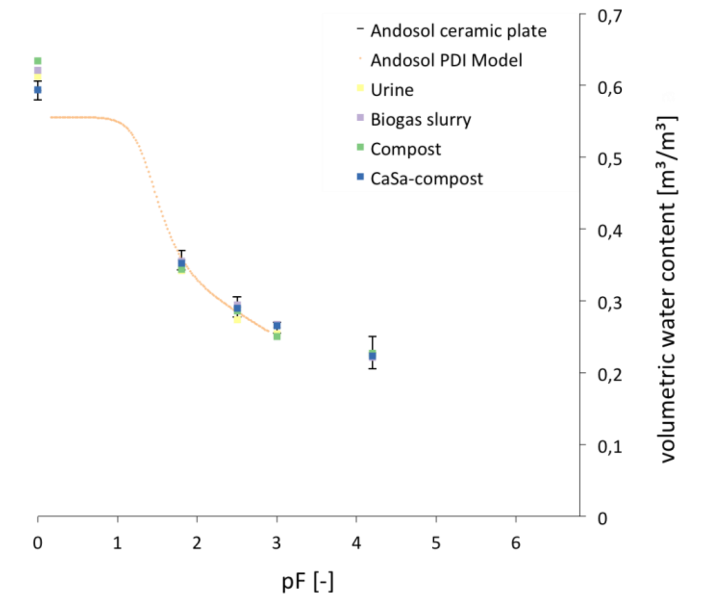


Fig. 2. Water retention curve (WRC) of the untreated Andosol and for the soil treated with ~~urine,~~ biogas slurry, standard compost, and CaSa-compost. The PDI-model for the control Andosol was fitted to data ~~measured using the pressure plates and WRC of the untreated Andosol~~ measured using the simplified evaporation method. ~~(Hyprop, UMS, Munich, Germany) with the Peters–Durner–Iden (PDI) model (Peters et al., 2015).~~Error indicators belong to “Andosol ceramic plate”. Plot data ~~see~~ is provided in Tables S1 and S2.

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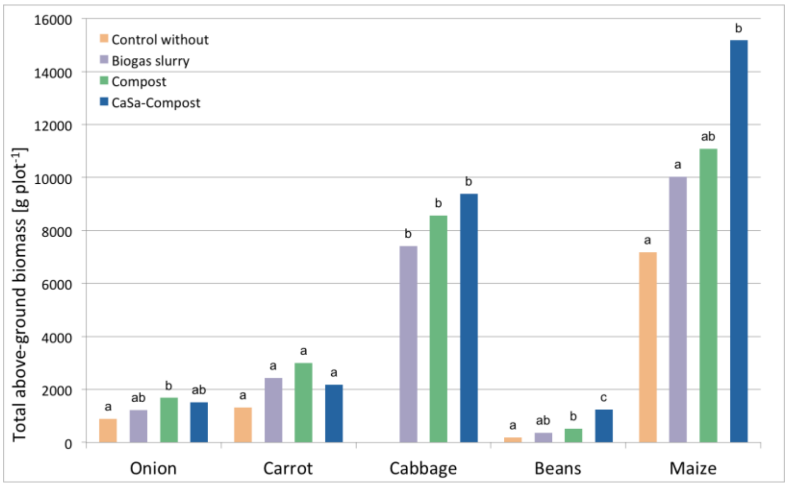


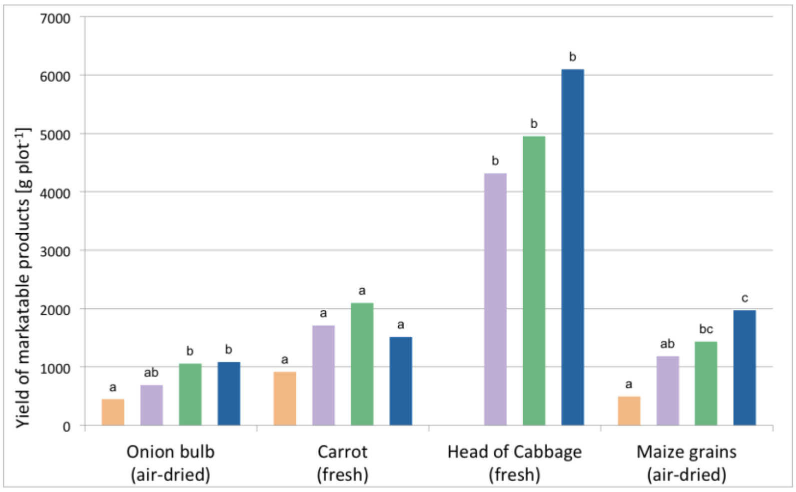
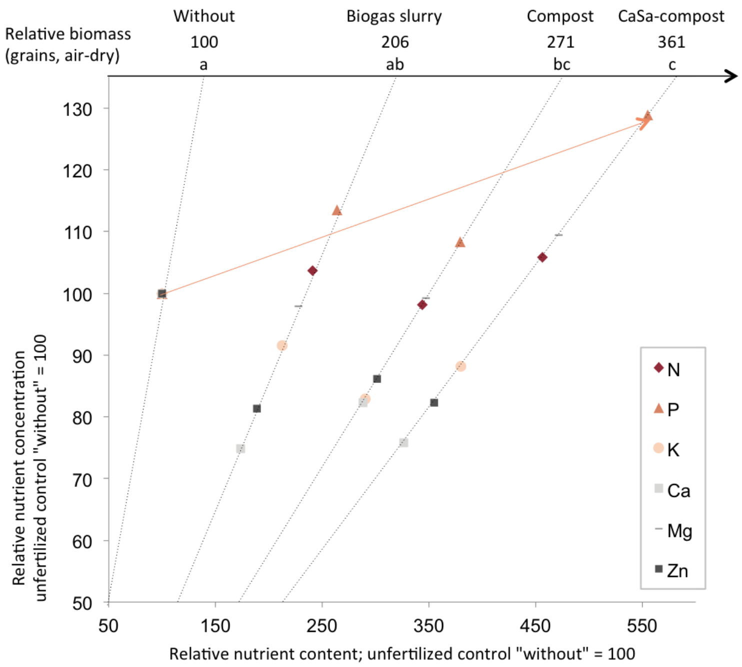


Fig. 3a+3b. Total above-ground biomass production and marketable ~~crop~~ yields of food crops given as g per plot. Each plot comprised a 4.5 m^2 area sown to maize and a 4.5 m^2 area inter-cropped with onions, beans, cabbage, carrots, African egg plant and ~~capsicum~~pepper. D~~; d~~ifferent letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha=0.05$; n=4 for the untreated control plots and n=5 for the amended plots). Plot data is provided in ~~see~~ Table S3.



~~Notes:~~

Fig. 4. Vector nutrient analysis for maize ~~yield~~, showing the responses of air-dry grain yield (g plant^{-1}), relative nutrient concentration in DM (~~[g kg^{-1}~~with the untreated Andosol = 100 %)~~]~~ and relative nutrient uptake (with the untreated Andosol = 100 %). ~~[g plant^{-1}].~~ Different letters reflect means differing significantly from one another (HSD, Tukey test, α=0.05; n=3). The arrow ~~indicats~~indicates the largest response and depicts a primary response of maize plants to mitigated P-deficiency. Plot data is provided in ~~see~~ Table S4.

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List of abbreviations

<u>Chemical elements:</u>

Al	Aluminium
C	Carbon
C_{tot}	Total carbon *(exemplarily also for total concentration of other elements)*
Ca	Calcium
Cu	Copper
H	Hydrogen
Fe	Iron
K	Potassium
K_{CAL}	CAL-soluble K *(likewise P_{CAL})*
Mg	Magnesium
Mn	Manganese
N	Nitrogen
N_{min}	Mineral nitrogen
N_{org}	Organic nitrogen
P	Phosphorus
S	Sulphur
Si	Silicon
Zn	Zinc

<u>Terms used in context of physico-chemical analyses:</u>

ANOVA	Analyses of variance
AWC	Available water capacity
BS	Base saturation
CAL	Calcium acetate lactate
CEC_{eff}	Effective cation exchange capacity
DM	Dry matter
FC	Field capacity
FM	Fresh mass
HSD	Honest significant difference

ICP-OES	Inductively coupled plasma optical emission spectrometry
IR	Infiltration rate
pF	Decadic logarithm of the negative pressure head
PV	Pore volume
t_0	Time of sampling beginning of February
t_1	Time of sampling end of April
t_2	Time of sampling beginning of July
WRC	Water retention capacity
ρ_B	Bulk density
ρ_p	Particle density
θ	Volumetric water curve

<u>Terms used in context of calculations in Eq. 1:</u>

D_{Nmin}	Demand of Nmin per cropping season
$m_{material}$	Amount of materials to be amended to the soil
Δ Nut	Changes in the soil nutrient status
Nut_{app}	Quantity of nutrient supplied by the treatment
Nut_{up}	Quantity of nutrient taken up by the plants
Δ Nut_{av}	Changes in the soil's available nutrient stock
Δ Nut_{nav}	Change in the soil's nutrient stock which was “non-available”
~~RO~~	~~Loss through run-off~~

<u>Other non-common abbreviations:</u>

Biochar	Charcoal used as soil amendment
CaSa	Project “Carbonization and Sanitation”
CaSa-compost	Product of CaSa-project containing composted biochar and sanitized excreta
cv.	Cultivar
m.a.s.l.	Meter above sea level
NW	Northwest
TU	Technische Universität
UDDT	Urine diverting dry toilet