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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. 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 moisture, so the observed variation in crop yield and plant nutrition reflected differences in nutrient availability. The application of CaSa-compost increased the level of available P in the top-soil from 0.5 to 4.4 $mg\,kg^{-1}$ 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 effective in mitigating P deficiency and soil acidification. We conclude that all treatments are viable as substitute for synthetic fertilizers. However, 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.

1 Introduction

1.1 Specific characteristics of Andosols

Andosols occupy just 1–2 % of the land area world wide, although they are common in high altitude tropical environments, such as in the East African Rift Valley (Chestworth, 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 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 capacity (Chesworth, 2008; Driessen et al., 2000; Doerner, 2011; Zech, 2014). The dominant clay minerals in these soils are allophanes, imogolite, ferrihydrite and halloysite, 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 encouraging its accumulation (Driessen et al., 2000). The total carbon concentration of these soils is $> 6\%$ 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, 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

SOILD

2, 1221–1261, 2015

liming to increase P availability, and dressing with either manure and/or other organic matter, or with synthetic P fertilizer (Driessen et al., 2000; Tonfack, 2009). At the same time, erosion control is essential to minimize loss of top-soil (Abera and Wolde-Meskel, 2013).

1.3 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 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.*).

SOILD
2, 1221–1261, 2015

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 Figs. S2–S4) is located in the Ihanda Ward, 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 by sampling from the edges of the field (Table 1 and Fig. S1; some information is provided as Supplement, the respective figures and tables are indicated by an S). 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 (Chestworth, 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 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 × 3 m plots in the form of a Latin square (Richteret 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 treatments was applied to a single row and a single column (Fig. 1). The treatments were: (1) untreated (control), (2) additional nitrogen provided by applying a 1 : 4 urine : water solution, starting four weeks after planting with an application of 0.7 $dm^3 m^{-2}$, followed by 0.3 $dm^3 m^{-2}$ after six weeks and 0.2 $dm^3 m^{-2}$ after eight weeks, (3) a weekly application (from weeks 4–9) of 1.7 $dm^3 m^{-2}$ biogas slurry, (4) a pre-sowing application of 15.0 $dm^3 m^{-2}$ standard compost, and (5) a pre-sowing application of 8.3 $dm^3 m^{-2}$ CaSa-compost, passed through a 20 mm sieve.

We adjusted the amendments so that each treatment delivered a comparable quantity of mineral nitrogen (N_{min}). The N_{min} demand per cropping season ($D_{N_{min}}$) was estimated as 17.5 g m^{-2}, following KTBL (2009). According to Horn et al. (2010), 33 % of organic nitrogen contained in organic fertilizers ($N_{org,fertilizer}$) is mineralized during the course of a cropping season. 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 1), along with that provided by the amendments, the amount of materials to be amended to the soil, $m_{fertilizer}$,

SOILD
2, 1221–1261, 2015

measured in DM as kg m^{-2}, was calculated as follows:

$$m_{\text{fertilizer}} = \frac{D_{\text{N}_{\text{min}}} - \text{N}_{\text{min,soil}}}{\text{N}_{\text{min ,fertilizer}} + 0.33 \cdot \text{N}_{\text{org,fertilizer}}} \quad (1)$$

The status of the other plant nutrients following the amendments is given in Table 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, as 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 min.

We divided each plot into two 4.5 m^2 sections, one used to cultivate maize cv. Stuka, and the other planted to a mixture of common bean cv. Lyamungu 90, carrot cv. Nantes, cabbage cv. Glory of Enkhuizen and local landraces of onion, African egg plant (*Solanum aethiopicum*) and sweet pepper (Fig. 1). The maize was sown on 4 March with two grains per dibbing hole and thinned after germination. Carrot seed was directly sown into the plot on 6 March and the beans were sown on 14 March; 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 gouge 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, 30–60 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 available water capacity (AWC) was calculated as $\theta_{pF\,1.8} - \theta_{pF\,4.2}$. The porosity ($\varepsilon$) 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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

SOILD
2, 1221–1261, 2015

Field experiment using organic wastes from bioenergy and ecological sanitation

A. Krause et al.

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 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; in 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.

SOILD
2, 1221–1261, 2015

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 and Kimaro, 2011). The 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 and Kimaro (2011).

2.6 Nutrient balance

We calculated changes in the soil nutrient status (ΔNut) for each treatment and for the section of the plots which were cultivated with maize, according to the expression:

$$\Delta \mathrm{Nut} = \mathrm{Nut}_{app} - \mathrm{Nut}_{up} = \Delta \mathrm{Nut}_{av} + \Delta \mathrm{Nut}_{nav} + \mathrm{RO} \quad (2)$$

where Nut_{app} represented the quantity of nutrient supplied by the treatment (nutrient application), Nut_{up} the quantity of nutrient taken up by the maize plants, $\Delta \mathrm{Nut}_{av}$ the changes in the soil's available nutrient stock (where "available" referred to the nutrients

SOILD
2, 1221–1261, 2015

being extractable with CAL solution), ΔNut_{nav} the change in the soil's nutrient stock which was "non-available" and RO the loss through run-off (e.g leaching or erosion). The balance was calculated for P_{tot} and K_{tot}, first on a per plot basis, and then averaged across the three plots exposed to each given treatment.

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. 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) and the total rainfall was ~ 360 mm, of which 85 % fell before the end of April.

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 a result of 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. 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 $g\,cm^3$). 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 (with hand-hoe) and then compaction (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 at t_2, it was lower in the top-soils of urine, 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^3m^{-3}). These differences at the end of the growing season 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 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 likely related to differential nutrient availability.

The *chemical status* of the soil prior at t_0 is given in Tables S1 and 1. There was a significant treatment effect on P_{CAL} and pH in the top-soil (Table 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 in the biogas slurry treatment and in the standard compost treatment respectively, see Krause et al., 2015); (ii) that the provision of biochar promoted nutrient capturing in the soil by adsorption of P on

SOILD
2, 1221–1261, 2015

the biochar particles (Gronwald et al., 2015; Kamman et al., 2015); and (iii) that the availability of the recycled P was promoted by liming (Batjes and Sombroek, 1997).

The top-soil pH was higher at t_2 in the CaSa-compost treatment than in the control plots (5.9 vs 5.3). 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. 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: we found 100 kg of DM of biogas slurry, standard compost and CaSa-compost to be equivalent to, respectively, 6.8, 1.4 and 4.7 kg CaO. Here, 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}. 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.

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 $Al(OH)_3 + 3H^+ = Al_3^+ + 3H_2O$). 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 CEC_{eff} was not altered significantly by the addition of the relatively low level of nutrients provided by the amendments (Table 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), the quantity of dry biochar supplied would have been $\sim 2.2\,kg\,m^{-2}$, equivalent to a C_{tot} supplement of ~ 1.3–$1.6\,kg\,m^{-2}$, a level which is modest compared to common applications of biochar, which range from five to $20\,kg\,m^{-2}$ (Kamman 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 the amount of organic matter in the soil. Nevertheless, Kimetu et al. (2008) were able to show that treatment 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.

3.2 Biomass production

The harvested biomass of onion was significantly increased by the provision of compost; the size of the bulbs produced in plots provided with standard compost was $52.8\,g\,plant^{-1}$, and was $54.4\,g\,plant^{-1}$ in plots treated with CaSa-compost, compared with just $22.2\,g\,plant^{-1}$ from 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. Cabbage plants grown on the untreated soil remained small and did not develop any heads. Both with respect to the harvest and the market product, the CaSa-compost, the standard compost and the biogas slurry treatments were all greatly superior to the urine treatment: the four treatments delivered in average yields of heads of, respectively, 1016, 825, 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 plants grown on CaSa-compost to just 4.7 by those grown on the unamended soil.

The CaSa-compost also promoted the stem diameter and height of the *maize* plants (respectively 22.8 and 1950 mm), compared to the 16.1 and 1423 mm achieved by the plants grown on unamended soil. The treatment with biogas slurry, standard compost and CaSa-compost increased the above-ground biomass accumulated by maize by, respectively, 140, 154 and 211 % over that accumulated by plants in the control treatment (Table 4). 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 national average for 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 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 unfertilized plots and 380-430 $g\,m^{-2}$ from fertilized 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 fertilizer.

Two meta-analyses have suggested that the addition of $2 \pm 0.5\,kg\,m^{-2}$ 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 effect of biochar lies 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 was most probably associated with its acid neutralization, which served to improve the availability of various nutrients, in particular that of P. The positive effects of applying CaSa-compost may well continue to be felt over several cropping seasons, in the way that Major et al. (2010) showed in a four year study of a savanna Oxisol.

SOILD
2, 1221–1261, 2015
Field experiment using organic wastes from bioenergy and ecological sanitation
A. Krause et al.

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. The only nutrients that responded significantly were K ($p = 0.03$) and P ($p = 0.08$) in the maize grains (Table 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. 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 primary response of maize to P deficiency (Fig. 4). Here, an increase to each of the three parameters (biomass, nutrient concentration, nutrient uptake) was generated by an increased supply of the limiting nutrient, which was in our case P. 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. Nutrient uptake was proportional to biomass growth 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 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 Ca and Mg were not significant and the only significant effect observed was a decrease in K concentration in maize grains 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 $\Delta Nut < 0$ (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 $g\,m^{-2}$, compared to a recommended fertilizer rate for maize on P-deficient soils of 7.0–8.4 $g\,m^{-2}\,a^{-1}$) while Nut_{app} of K was very high (with, respectively, 53.8, 46.5 and 63.2 $g\,m^{-2}$, as opposed to a recommended fertilization for maize on soils with high K-content of 9.3–12.4 $g\,m^{-2}\,a^{-1}$) (KTBL, 2009; Finck, 2007). On the plots treated with biogas slurry, plants took up 19 % of the 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 fertilizer 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, 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}. For both P and K, ΔNut was positive for the biogas slurry, standard compost and CaSa-compost treatments. However, the only significant change recorded to the top-soil's P_{CAL} was in the CaSa-compost treatment. Here, about 1.1 $g\,P\,m^{-2}$ was assignable to ΔNut_{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 Andosols (Zech, 2014) (i.e. assignable to ΔNut_{nav} in both cases). Leaching (i.e. RO) of P is insignificant, since P rather gets immobilized (Finck, 2007). Some of the K that was provided by the amend-

SOILD
2, 1221–1261, 2015

ments may have leached during the rainy season (i.e. assignable to RO). According to Finck (2007), leaching is significant for K on light soils such as the present Andosol.

3.5 The potential to close the nutrient loop

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 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 $dm^3\,m^{-2}\,3\,a^{-1}$) on a total area of about 1800 m^2. Given the fact that ~6225 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.

SOILD
2, 1221–1261, 2015

3.6 Further aspects

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.

SOILD
2, 1221–1261, 2015

SOILD
2, 1221–1261, 2015

Field experiment using organic wastes from bioenergy and ecological sanitation

A. Krause et al.

4 Conclusions

Crop biomass production and economic yield were both significantly improved by the application of CaSa-compost, particularly with respect to beans and maize. For cabbage and onion, all three of the tested amendments were beneficial. The benefits derived from the amenders were due to improvements in the nutrient availability rather than to any increase in soil moisture content. Overall, all the treatments, but especially CaSa-compost, are viable as *substitutes for synthetic commercial fertilizer*.

Of particular significance was the observation that the *P deficiency* affecting the local Andosol could be *mitigated* using 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 productive. 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, a continuous program of composting over decades would probably be needed to fully ameliorate the top- and the sub-soil. 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.

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.

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 $\sim 8\,dm^3\,m^{-2}\,3\,a^{-1}$ 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 approach needs to be integrated into farm-scale nutrient management. 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, 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…

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Author contributions. A. Krause and M. Kaupenjohann designed the experiment and planned and evaluated soil chemical analysis. A. Krause carried out the experiment. A. Krause and T. Nehls planned 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 with contributions from all co-authors.

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SOILD

2, 1221–1261, 2015

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SOILD
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SOILD
2, 1221–1261, 2015

SOILD
2, 1221–1261, 2015

Field experiment using organic wastes from bioenergy and ecological sanitation

A. Krause et al.

Table 1. The characteristics of the soil profile. 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, u.a.: not analysed

	Depth	Color	Aggregate size distribution			structure	pH	ρ_B	FC_{field}	FC_{lab}	CEC_{eff}	BS	TOC	N_{tot}	C / N
	cm	Munsell	clay %	silt %	sand %		KCl	kg dm^{-3}	m^3 m^{-3}	m^3 m^{-3}	cmol kg^{-1}	%	%	%	
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	u.a.	1.08	0.36	u.a.	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	u.a.	u.a.	u.a.	u.a.	8.0	94.5	2.0	0.2	12.5
C	100+	u.a.	u.a.	u.a.	u.a.	No aggregates, subangular gravel	u.a.	u.a.	u.a.	u.a.	u.a.	u.a.	u.a.	u.a.	u.a.

Soil classification: *vitric* Andosol.

Table 2. Soil nutrient status before applying the amendments and the nutrient loads (plus Al) following amendment [$g\,m^{-2}$]. 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.

	FM	FM	DM	N_{min}	P	K	Mg	Ca	Al	Zn	Mn
	$L\,m^{-2}$	$kg\,m^{-2}$	$kg\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$	$g\,m^{-2}$
Soil nutrient stock (0–90 cm) before applying the soil amendments	900	1039	869	7.5	0.4	141	1107	2761	60	n.d.	u.a.
Urine[a]	1.2 L urine + 3.6 L H_2O			10.7	0.6	2.6	n.d.	n.d.	NA	NA	NA
Biogas slurry	10		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[b]			1.3	10.6	4.2	53.8	8.0	15.5	6.2	0.07	0.28
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

[a] Values based on Berger (2008) data for stored urine. [b] For the biogas slurry treatment, the nutrient load was derived from both grasses and slurry (∑ Biogas). u.a.: not analysed, n.d.: not detectable, NA: data not available.

SOILD
2, 1221–1261, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. Chemical analysis of the top-soil sampled after the termination of the experiment. Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$; $n = 3$).

Top soil 0–30 cm	pH KCl		P_{CAL} mg kg^{-1}	
Control without	5.3	a	0.5	a
Urine	5.4	ab	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

SOILD
2, 1221–1261, 2015

Field experiment using organic wastes from bioenergy and ecological sanitation

A. Krause et al.

Table 4. Harvest and market product of maize [$g\,m^{-2}$]. Control and urine treatments: $n = 4$, other treatments: $n = 5$. Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$).

	Harvest product Total above-ground biomass, FM			Market product Maize grains, air-dry		
	$g\,m^{-2}$			$g\,m^{-2}$		
Control without	1595	100 %	a	110	100 %	a
Urine	2019	127 %	a	172	156 %	ab
Biogas slurry	2229	140 %	a	263	238 %	ab
Compost	2464	154 %	ab	318	288 %	bc
CaSa-compost	3372	211 %	b	438	397 %	c

SOILD
2, 1221–1261, 2015

Table 5. Nutrient concentration in DM of maize grains [$g\,kg^{-1}$] compared to levels reported by Finck (2007) and Kimetu et al. (2008). Italic values reflect *p* values of significance (ANOVA, $n = 3$).

	N_{tot} $g\,kg^{-1}$	P_{tot} $g\,kg^{-1}$	K_{tot} $g\,kg^{-1}$	Ca_{tot} $g\,kg^{-1}$	Mg_{tot} $g\,kg^{-1}$
Control without	15.9	2.3	4.4	0.1	1.0
Urine	16.4	2.4	4.5	0.1	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

SOILD
2, 1221–1261, 2015

Table 6. Changes in the soil nutrient status (ΔNut) [$g\,m^{-2}$], along with nutrients provided by the treatment (Nut_{app}) and the nutrients taken up by the crop (Nut_{up}). Data based on three plots for each treatment.

	P [$g\,m^{-2}$]			K [$g\,m^{-2}$]		
	Nut_{app}	Nut_{up}	ΔNut	Nut_{app}	Nut_{up}	ΔNut
Control without	–	0.4	−0.4	–	3.3	−3.3
Urine	0.6	0.7	−0.1	2.6	6.1	−3.5
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

SOILD
2, 1221–1261, 2015

Field experiment using organic wastes from bioenergy and ecological sanitation

A. Krause et al.

Table A1. Chemical elements.

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

SOILD

2, 1221–1261, 2015

Table A2. Terms used in context of physico-chemical analyses.

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

SOILD
2, 1221–1261, 2015

Table A3. Terms used in context of calculations in Eqs. (1) and (2).

$m_{\text{fertilizer}}$	Amount of materials to be amended to the soil
$D_{N_{min}}$	Demand of N_{min} per cropping season
$N_{min,soil}$	N_{min} present in the top 90 cm of the soil
$N_{min,fertilizer}$	N_{min} provided by the amendments
$N_{org,fertilizer}$	Organic nitrogen contained in organic fertilizers
ΔNut	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
ΔNut_{av}	Changes in the soil's available nutrient stock
ΔNut_{nav}	Change in the soil's nutrient stock which was "non-available"
RO	Loss through run-off

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2, 1221–1261, 2015

Table A4. Other non-common abbreviations.

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

SOILD
2, 1221–1261, 2015

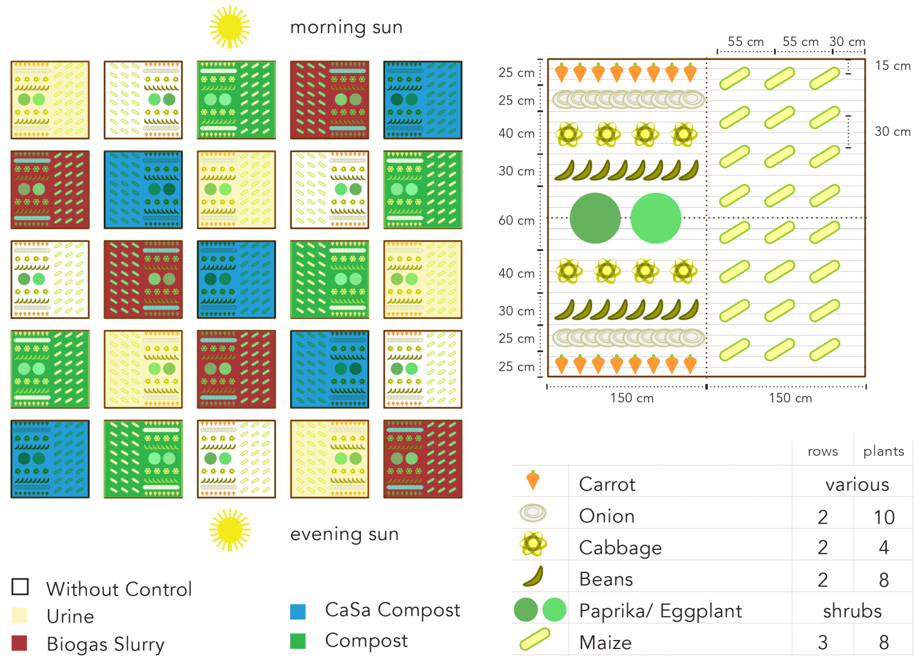

Figure 1. The experiment design: the plots were arranged as a Latin square.

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2, 1221–1261, 2015

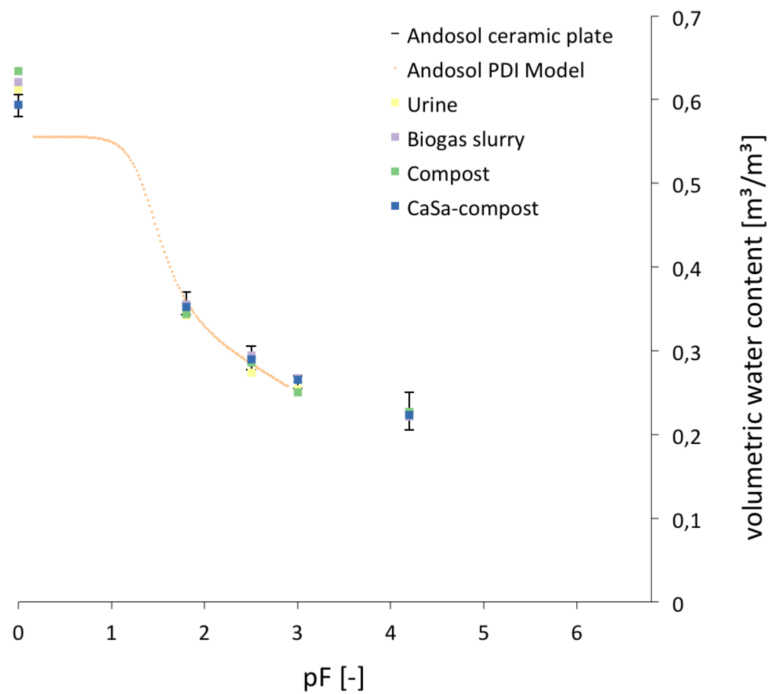

Figure 2. Water retention curve (WRC) of the untreated Andosol and for the soil treated with urine, biogas slurry, compost, CaSa-compost measured using the pressure plates and WRC of the untreated Andosol measured using the simplified evaporation method (Hyprop, UMS, Munich, Germany) with the Peters–Durner–Iden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

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2, 1221–1261, 2015

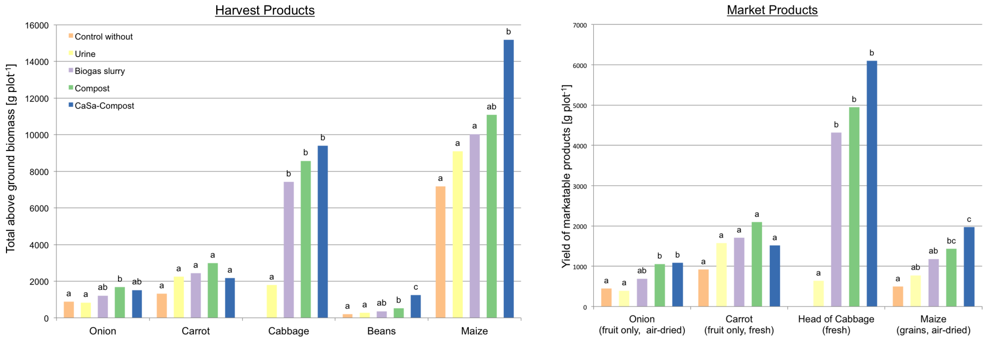

Figure 3. Total above-ground biomass production (“harvest product”) and marketable crop yields (“market product”) given as g per plot. Each plot comprised a 4.5 m^2 area sown to maize and a 4.5 m^2 area inter-cropped with onions, beans, cabbage, carrots, African egg plant and capsicum; different letters 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 see Table S3. Notes: The data represent the mean per plant biomass multiplied by the number of plants. Sample sizes for harvest products were 19 maize plants, 16 bean plants, 20 onion plants for all the treatments; there were four cabbage plants in the urine treatment and six in the biogas slurry, standard compost and CaSa compost treatments; for the carrots, the mean harvest per plot is shown. Sample sizes for market products were 14 maize plants in the control plot, 15 in the urine-treated plot, 16 in the biogas slurry-treated plot and 17 in the two compost-treated plots; there were 20 onion plants in all of the treatments, four cabbage plants in the urine-treated plots and six in the other three treatments; for the carrots, on average 70 % of the total harvest was marketable produce.

SOILD
2, 1221–1261, 2015

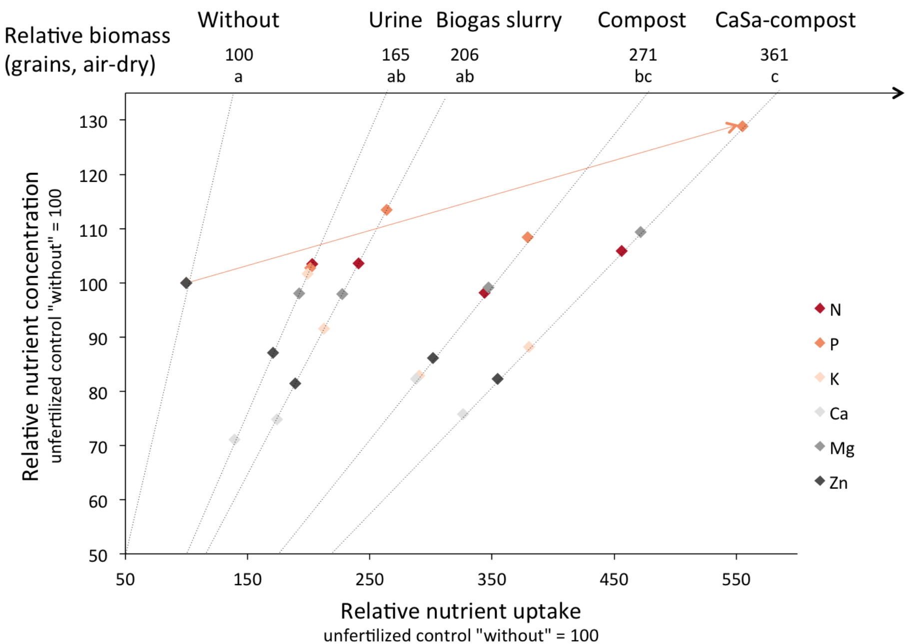

Figure 4. Vector nutrient analysis for maize yield, showing the responses of air-dry grain yield ($g\,plant^{-1}$), nutrient concentration in DM [$g\,kg^{-1}$] and nutrient uptake [$g\,plant^{-1}$]. Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$; $n = 3$). The response levels are given relative to the control treatment's performance. Nutrient vector analyis is based on shifts in (increase, decrease or no change) and the magnitude of biomass, nutrient concentration and the overall nutrient uptake. The arrow indicates the largest response and depicts a primary response of maize plants to mitigated P-deficiency. Plot data see Table S4.

SOILD
2, 1221–1261, 2015