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Organic wastes from bioenergy and ecological sanitation as a 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 the 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 (cation exchange capacity), total C and the availability of nutrients (N, P, K, etc.) and water (water retention characteristics, bulk density, etc.) in the soil. 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 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 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 most effective in mitigating P deficiency and soil acidification. We conclude that all treatments are viable as a substitute for synthetic fertilizers. 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 cycle can be closed.

1 Introduction

1.1 Challenges cultivating Andosols

Andosols occupy just 1–2 % of the land area worldwide. They are common in high-altitude tropical environments, such as in the East African Rift Valley (Chesworth, 2008; Perret and Dorel, 1999). Their high inherent fertility makes them especially well-suited for the cultivation of high-value crops such as coffee, tobacco and banana. Andosols 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 phosphorus (P), a high pore volume, a high level of available water, a tendency to form microaggregates and a pronounced shrinking (Chesworth, 2008; Dörner et al., 2011; Driessen et al., 2000; Zech et al., 2014). The dominant 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, thus fostering C sequestration (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).

Andosols are rather sensitive to land use management (Dörner et al., 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 require consistent P replenishment, which generates a strong demand in sub-Saharan Africa for appropriate soil amenders. Fertility amelioration measures have included both liming to increase P availability and applying either manure and/or other organic matter or synthetic P fertilizer (Driessen et al., 2000; Tonfack et al., 2009).

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 located nearby volcanic areas in 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 fertilizers and a 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 sanitization of toilet waste (Esrey et al., 2001), for example with urine-diverting dry toilets (UDDT), composting toilets, and pasteurization of faeces to ensure human health (Schönning and Stenström, 2004). The last point 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) provide 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 (pasteurized) 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 data gaps exist, in particular, concerning field-scale information on crop response and soil quality for various soil–biochar combinations. From past experiments using biochar as a soil amendment (Herath et al., 2013; Kammann et al., 2011; Kimetu et al., 2008; Liu 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 et al. (2013), the following lessons can be learned for future experiments: (i) pot experiments lead to overestimations 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 between the observed effects; (iii) the 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 the 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 for not enhancing knowledge on changes in 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 whether 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 plant nutrition.

2 Materials and methods

2.1 Field site

The experimental site (see Figs. S2–S4 in the Supplement) 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 to 2100 mm and the mean annual potential evapotranspiration is ∼ 1200 mm (FAO Kagera, online http://www.fao.org/fileadmin/templates/nr/kagera/Documents/Suggested_readings/nr_info_kagera.pdf). 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 surveyed by sampling 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 topsoil 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 of 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 (Chesworth, 2008). The soil's BS was quite high (Ca saturation of up to 70 %). Comparable levels of 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 (Abera and Wolde-Meskel, 2013). The quantity of available P in the topsoil 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}).

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

	Depth	Colour	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	NA	1.08	0.36	NA	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	NA	NA	NA	8.0	94.5	2.0	0.2	12.5
C	100+	NA	NA	NA	NA	No aggregates, subangular gravel	NA	NA	NA	NA	NA	NA	NA	NA	NA

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.

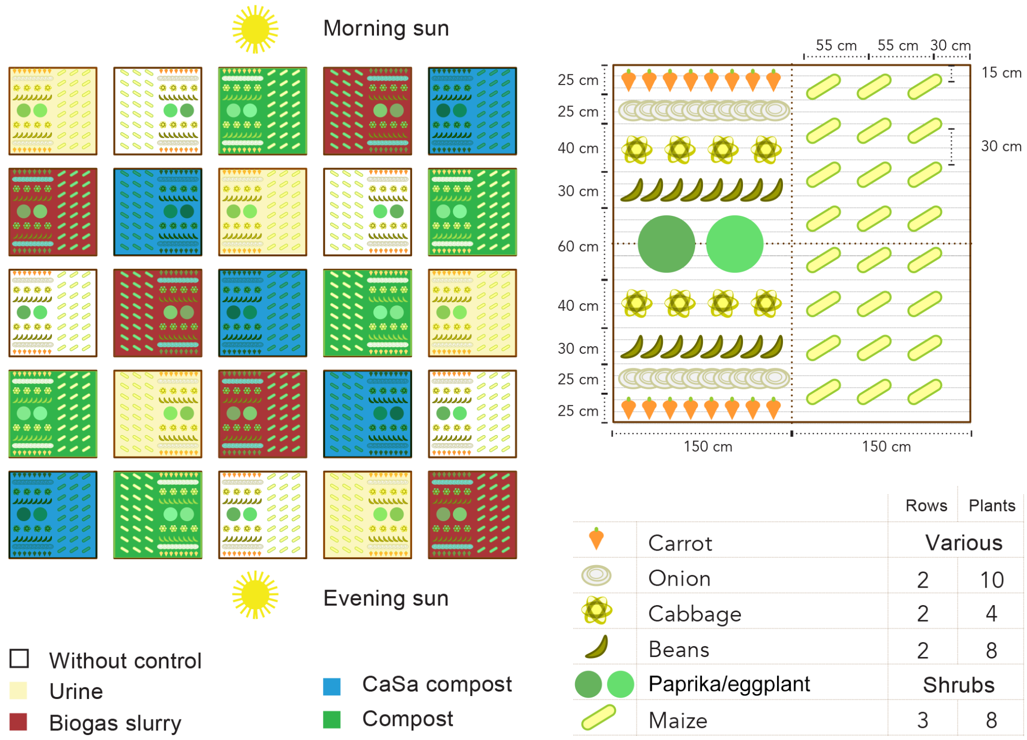

Figure 1. The experiment design: the plots were arranged as a Latin rectangle with five columns and five rows (left panel) and each plot was divided into two 4.5 m^2 sections for the cultivation of seven selected crops in an intercropping system (right panel); note that urine treatment was a posteriori excluded from the analysis due to technical problems.

2.2 Plot preparation and soil amendments

We arranged a series of 3 m × 3 m plots in the form of a Latin 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 four treatments was applied to a single row and a single column and thus studied with five replications (Fig. 1). The treatments were as follows: (1) untreated (control), (2) biogas slurry in a weekly application (from weeks 4 to 9 after sowing) of 1.7 $dm^3\,m^{-2}$ on a cover of cut grass, (3) standard compost with a pre-sowing application of 15.0 $dm^3\,m^{-2}$, and (4) CaSa compost with a pre-sowing application of 8.3 $dm^3\,m^{-2}$, 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 biogas slurry employed 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 3 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 $m^3\,m^{-3}$; bean 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 ($N_{min,demand}$) was estimated as 17.5 $g\,m^{-2}$, following KTBL (2009). According to Horn et al. (2010), 33 % of organic nitrogen contained in organic fertilizers ($N_{org,fertilizer}$) is mineralized during the course of a cropping season. The amount of materials to be amended to the soil, $m_{fertilizer}$ ($kg\,m^{-2}$), was calculated 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) and that provided by the amendments as follows:

$$m_{\text{fertilizer}} = \frac{N_{\text{min,demand}} - N_{\text{min,soil}}}{N_{\text{min,fertilizer}} + 0.33 \cdot N_{\text{org,fertilizer}}}. \quad (1)$$

Then, the addition of the other plant nutrients (Table 3) was calculated according to Table 2.

Before planting, we hoed the soil by hand, as it is common local practice. We applied the composts by first spreading them evenly and then incorporating them with a fork hoe. Planting was carried out at the beginning of the rainy season (March 2014), and the plots were mulched in mid April (end of 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 (Fig. 1), one used to cultivate maize cv. Stuka, and the other planted 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 eggplant (*Solanum aethiopicum*) and sweet pepper were planted as important parts of the chosen local adjusted intercropping practice. However, as these two plant species are perennial, biomass harvest exceeded the experimental time frame, and therefore we excluded them from analysis.

The maize was sown on 4 March with two grains per dibbing hole and thinned after germination. Carrot seed was directly sown on 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 gauge 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 subsamples: 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 mixed samples 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 for each treatment.

2.3 Soil analyses

The 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 topsoils' volumetric water content (θ) ($m^3\,m^{-3}$) twice a week over the first 6 weeks after sowing at five points per plot, using

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

	pH	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
		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, 2006) and an iCAP 6000 inductively coupled plasma optical emission spectrometry (ICP-OES) device (Thermo Scientific, Waltham, USA). Total concentrations of C, N and S were analysed 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 a Vario ELIII CNS analyser (Elementar, Hanau, Germany). Mineral nitrogen (N_{min}) was extracted with potassium chloride (KCl) and analysed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany). This 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.

Table 3. Soil nutrient status before applying the amendments and the nutrient loads of the amendments.

	FM $dm^3\,m^{-2}$	FM $kg\,m^{-2}$	DM $kg\,m^{-2}$	N_{min} $g\,m^{-2}$	P $g\,m^{-2}$	K $g\,m^{-2}$	Mg $g\,m^{-2}$	Ca $g\,m^{-2}$	Al $g\,m^{-2}$	Zn $g\,m^{-2}$	Mn $g\,m^{-2}$
Soil (0–90 cm)	900	1039	869	7.5	0.4	141	1107	2761	60	n.d.	NA
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
$\sum$ 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 Sect. 2.3. Calculations of the content in fresh matter of the treatments derived concentrations provided by Krause et al. (2015); see Table 2 for description of methods. * For the biogas slurry treatment, the nutrient load was derived from both grasses and slurry ($\sum$ Biogas). Uncommon abbreviations: DM: dry matter; FM: fresh matter; NA: not analysed; n.d.: not detectable.

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 were used to derive the general form of the Andosol's WRC and to parameterize 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 ($e$) 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 the 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 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 and using an Elementar Vario ELIII CNS analyser (Elementar, Hanau, Germany). Concentrations of calcium acetate lactate (CAL) soluble P (P_{CAL}) and K (K_{CAL}) were determined with an iCAP 6000 inductively coupled plasma optical emission spectrometry (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,

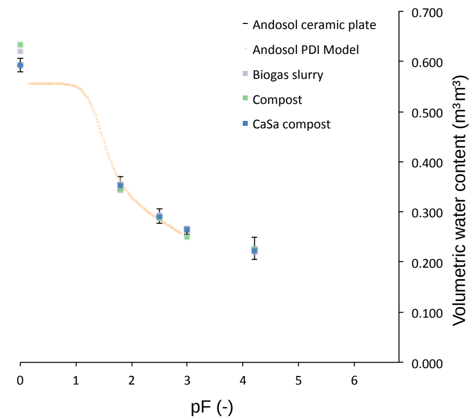

Figure 2. Water retention curve (WRC) of the untreated Andosol and of the soil treated with biogas slurry, standard compost and CaSa compost. The PDI model for the control Andosol was fitted to data measured using the simplified evaporation method. Error indicators belong to "Andosol ceramic plate". Plot data are provided in Tables S1 and S2.

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 the two-leaf stage, and the other crops at maturity. For maize, bean, cabbage, carrot and onion, the above-ground biomass was considered as the "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 beans, 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 as follows: onion (10/20 plants), cabbage (all plants producing a head), bean (8/16 plants) and maize (5/24 plants, excluding plants without cobs). For carrots, the weight of the whole set of plants on a plot was determined. 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 cabbage and 20 onion plants per plot for all the treatments (except for the control, which did not include cabbage). 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 (Isaac and Kimaro, 2011). The control treatment's performance was 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 Isaac and Kimaro (2011).

2.6 Nutrient balance

For the section of the plots which were cultivated with maize we estimated changes in the soil nutrient status (Δ Nut) for each treatment, according to

$$\Delta \mathrm{Nut} = \mathrm{Nut}_{app} - \mathrm{Nut}_{up} = \Delta \mathrm{Nut}_{av} + \Delta \mathrm{Nut}_{nav}, \tag{2}$$

where Nut_{app} represented nutrients supplied by the treatment (**nut**rient **app**lication), Nut_{up} nutrients 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 being extractable with CAL solution), $\Delta\,\mathrm{Nut}_{nav}$ the change in the soil's nutrient stock, which was "non-available" due to leaching, interflow, surface run-off, soil erosion, P fixation, not yet being mineralized, etc. The balance was calculated for P and K, firstly per plot and then per treatment as an average of three plots.

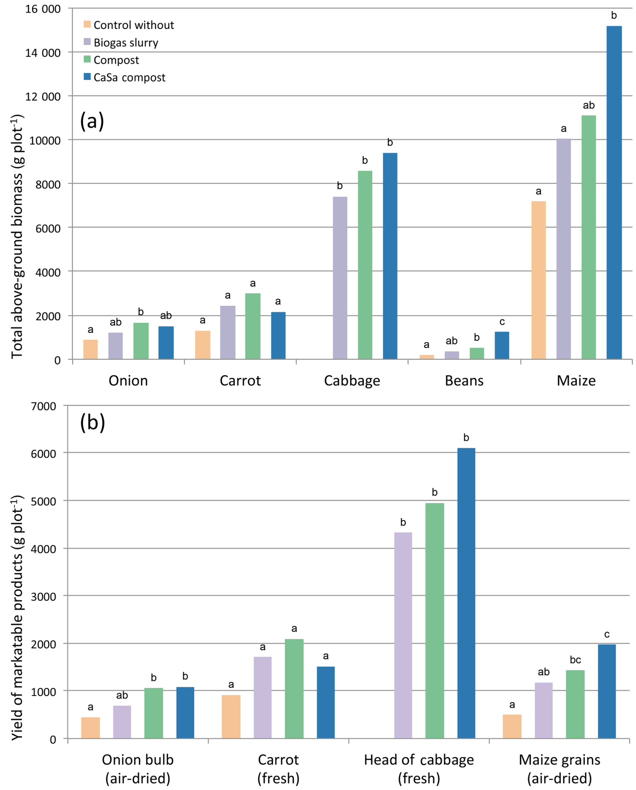

Figure 3. Total above-ground biomass production and marketable yields of food crops given as grammes per plot. Each plot comprised a 4.5 m^2 area sown with maize and a 4.5 m^2 area intercropped with onions, beans, cabbage, carrots, African eggplant and pepper. Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$; $n = 4$ for the untreated control plots; $n = 5$ for the amended plots). Plot data are provided in Table S3.

2.7 Statistical analysis

Analyses of variance (ANOVA) were performed using the 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 $\alpha = 0.05$.

According to the design of the experiment as a Latin rectangle, the number of replications 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.

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 topsoil and in the subsoil respectively) as measured with the double-ring infiltration experiments. Also, the WRCs were not significantly influenced by the amendments and still showed the typical shape of an Andosol (Fig. 2). This may 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 the workability of the soil by making it more friable.

The topsoil's PV was estimated as being 0.59–0.63 $m^3\,m^{-2}$ and may have been homogenized throughout the treatments by tillage (i.e. with a 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. At t_2, θ was lower in the topsoils of plots treated with the CaSa compost (0.13 $m^3\,m^{-3}$) and on biogas slurry and standard compost treated plots (0.16 $m^3\,m^{-3}$) compared to the control plots (0.17 $m^3\,m^{-3}$). These differences at the end of the growing season may be caused by higher evapotranspiration and interception losses due to higher biomass growth (see below) rather 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). 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 nutrient availability.

The chemical status of the soil prior at t_0 is given in Tables 1 and 2. There was a significant treatment effect on P_{CAL} and pH in the topsoil (Table 4). 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 and in the standard compost treatment (Table 2)); (ii) that the provision of biochar promoted nutrient capturing in the soil by the 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).

Table 4. Chemical analysis of the untreated Andosol in Karagwe, Tanzania, and the amended topsoil (0–30 cm) horizons sampled at the end of the experiment.

Treatment	pH in KCl		P_{CAL} in $mg\,kg^{-1}$	
Control 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, $\alpha = 0.05$; $n = 3$).

The last point can be supported by our findings, that the topsoil 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 topsoil pH range for cropping is 5.5–6.5 according to Horn et al. (2010). Glaser and Birk (2012) have shown that the highly productive Central Amazonian Terra Preta soils have a pH between 5.2 and 6.4. Through influencing soil pH, the addition of biochar is particularly effective in soils suffering from poor P availability (Biedermann and Harpole, 2013). In an earlier publication, Krause et al. (2015) derived estimates for the liming potential of the present soil amendments and 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 of CaO. The applied equivalents in this study were 0.03, 0.07 and 0.2 $kg\,m^{-2}$ of CaO for biogas slurry, standard compost and CaSa compost. We found, that the application of CaSa compost had an *immediate* effect on soil pH. Finck (2007) recommended the application of lime equivalent to 0.1–0.2 $kg\,m^{-2}$ of CaO every 3 years to maintain the soil pH. Thus, amending CaSa compost at the applied rate was in the range for soil melioration if the application of the treatment is repeated every 3 years.

Neither concentration of total organic carbon (TOC) in the soil nor CEC_{eff} was altered significantly by the amendments (Table 3). Similarly, Liu et al. (2012) 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 (Sect. 2.2), we estimated the quantity of dry biochar supplied by $\sim 2.2\,\mathrm{kg\,m^{-2}}$, equivalent to a C_{tot} supplement of ~ 1.3–$1.6\,\mathrm{kg\,m^{-2}}$, a level which was modest compared to common applications of biochar ranging from 5 to $20\,\mathrm{kg\,m^{-2}}$ (Kammann et al., 2011; Herath et al., 2013). Liu et al. (2012) have suggested a rate of $5\,\mathrm{kg\,m^{-2}}$ as the minimum necessary to significantly and sustainably increase TOC in the soil. Nevertheless, Kimetu et al. (2008) were able to show that treating a highly degraded soil in the highlands of western Kenya with just $0.6\,\mathrm{kg\,C\,m^{-2}}$ for three consecutive seasons, was effective in increasing 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 $Al(OH)_3 + 3H^+ = Al_3^+ + 3H_2O$). 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

Amending compost significantly increased the harvested biomass of onion. The mass of the bulbs produced in plots provided with standard compost or CaSa compost was, respectively, 52.8 and 54.4 g plant^{-1}, compared to only 22.2 g plant^{-1} 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. Cabbage plants grown on the untreated soil remained small and did not develop any heads. In contrast, amending CaSa compost, standard compost or biogas slurry delivered average yields of heads of, respectively, 1020, 825 and 720 g plant^{-1}.

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

The CaSa compost also promoted a greater 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 per unit area above-ground biomass accumulated by maize to, respectively, 140, 154 and 211 % 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.

Table 5. Harvest and market products of maize and in relation to the untreated control (100 %).

	Harvest product total above-ground biomass, FM			Market product maize grains, air-dry		
	g m^{-2}	%		g m^{-2}	%	
Control Andosol	1595	100	a	110	100	a
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, $\alpha = 0.05$) with $n = 4$ for control and $n = 5$ for other treatments.

The grain yield from the control plots was below both the average national Tanzanian yield (2012: 124 g m^{-2}) and that for eastern Africa (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 mineral-fertilized plots (Kimaro et al., 2009), while in the Morogoro region the same maize cultivar 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 higher (i.e. extremely high) input of synthetic N fertilizer, 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 $2 \pm 0.5\,\mathrm{kg\,m^{-2}}$ 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 positive effect of biochar is between 25 and 35 %. The positive effect of the CaSa compost on the soil and on biomass growth was most probably due to its liming effect, which improved the availability of various nutrients, in particular that of P. The positive effects of applying CaSa compost may last for several cropping seasons, as shown by Major et al. (2010) in a 4-year study.

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 recent work using biogas slurry as a soil amender observed a 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

Table 6. Nutrient concentration in dry matter of maize grains compared to levels reported in the literature. The italic writing indicates the statistical p values, which belong to the nutrient concentrations in the respective column.

	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 Andosol	15.9	2.3	4.4	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

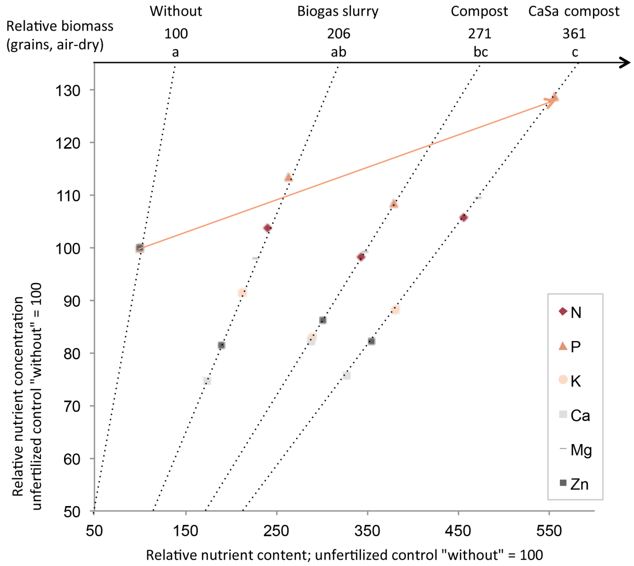

Figure 4. Vector nutrient analysis for maize, showing the responses of air-dry grain yield (g plant^{-1}), relative nutrient concentration in DM (with the untreated Andosol: 100 %) and relative nutrient uptake (with the untreated Andosol: 100 %). Different letters reflect means differing significantly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

et al. (2001) attributed observed a 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 aforementioned 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 its 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). Only the nutrient concentrations in the maize grains responded significantly to the treatments, especially for K ($p = 0.03$) and P ($p = 0.08$) (Table 6). Here, we observed a dilution effect for K, while the 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.

The vector nutrient analysis illustrated primarily the response of maize to mitigated P deficiency, with the longest arrow indicating the largest response (Fig. 4). Here, an increase in each of the three parameters (biomass growth, nutrient concentration, nutrient uptake) was generated by an increased supply of the limiting nutrient P. This is because (i) more P was supplied with CaSa compost (see Sect. 3.1) and (ii) its availability was increased due to the raised soil pH (Batjes, 2011). Furthermore, nutrient uptake by maize was proportional to biomass growth. Hence, 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).

As the native soil's K_{CAL} was already very high and further K was provided by the amendments (Table 3), an antagonistic effect on nutrient uptake between K and Ca as well Mg would have been possible (Finck, 2007). However, observed changes in concentrations of Ca and Mg were not significant, but there was a significant decrease in K concentration in maize grains. However, this may possibly be due to the dilution imposed by growth stimulation.

3.4 Nutrient balancing

On the plots treated with biogas slurry, standard compost and CaSa compost, Nut_{app} of P varied with, respectively, 4.2, 6.8 and 13.8 g m^{-2}. This can be considered a low to high application compared to a recommended fertilizer rate of 7.0–8.4 g m^{-2} yr^{-1} for maize on P-deficient soils (KTBL, 2009; Finck, 2007). By contrast, Nut_{app} of K was very high with 53.8, 46.5 and 63.2 g m^{-2}, compared to a recommended dose of 9.3–12.4 g m^{-2} yr^{-1} for maize on soils with high K content (KTBL, 2009; Finck, 2007). On the plots treated with biogas slurry, plants took up ∼ 19 % of the total applied P; 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. These rates differ greatly from the ∼ 60 % figure suggested by Finck (2007). The disparity relates most likely to the soil's high level of K_{CAL}.

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, Δ Nut was positive for both P and K. However, the only significant change to the topsoil's P_{CAL} was recorded in the CaSa-compost treatment (Sect. 3.1.). 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 for Andosols (Zech et al., 2014) (i.e. assignable to Δ Nut_{nav} in both cases). Leaching of P is insignificant, since P gets immobilized (Finck, 2007). We assume that some of the K provided by the amendments may have been leached during the rainy season as mentioned by Finck (2007) 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 greenhouse 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 Conclusions

To summarize: for beans and maize, crop biomass production and economic yield were significantly improved by the application of CaSa compost. 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.

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, improving its productivity immediately. Thus, we conclude that a continuous program of composting and compost amendments over decades would probably fully ameliorate the soil.

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.

Finally, we conclude that all the treatments, but especially CaSa compost, are viable as substitutes for synthetic commercial fertilizers. We further conclude that local smallholders with six people per household can produce CaSa compost at an estimated rate of ∼ 5.1 m^3 yr^{-1}, which would be sufficient to fertilize an area of ∼ 1850 m^2 at the rate of 8.3 dm^3 m^{-2} over the course of 3 years. By this means, it would be possible to fertilize about 30 % of the average area cultivated by smallholders in Karagwe. Therefore, the CaSa approach needs to be integrated into farm-scale nutrient management by conducting a detailed analysis of nutrient flows in the farm household system and studying all potential additions and removals of nutrients to and from the planted land.

Table 7. Changes in the soil nutrient status (Δ Nut) along with nutrients applied by the treatment (Nut_{app}) and the nutrients taken up by the crop (Nut_{up}).

	Nut_{app} P $g\,m^{-2}$	Nut_{up} P $g\,m^{-2}$	Δ Nut P $g\,m^{-2}$	Nut_{app} K $g\,m^{-2}$	Nut_{up} K $g\,m^{-2}$	Δ Nut K $g\,m^{-2}$
Control Andosol	–	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.

Copyright statement

Disclosure of conflict of interest: the authors do not have any conflict of interest to declare.

Appendix A

Table A1. List of abbreviations.

Chemical elements	
Al	Aluminium
C	Carbon
C_{tot}	Total carbon (the same form is also used 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	Sulfur
Si	Silicon
Zn	Zinc
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
PDI	Peters–Durner–Iden
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
TDR	Time domain reflectometry
TOC	Total organic carbon
WHC	water holding capacity
WRC	Water retention capacity
ρ_B	Bulk density
ρ_p	Particle density
θ	Volumetric water curve
Terms used in context of calculations in Eq. (1)	
$D_{N_{min}}$	Demand of N_{min} per cropping season
$m_{material}$	Amount of materials to be used in soil amendment
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"
Other uncommon 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
EcoSan	Ecological sanitation
m a.s.l.	Metres above sea level
NA	not analysed
NW	Northwest
TU	Technische Universität
UDDT	Urine-diverting dry toilet

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

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