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RESEARCH ARTICLE

EXPLORING THE RECYCLING OF MANURE FROM URBAN LIVESTOCK FARMS: A CASE STUDY IN ETHIOPIA

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SUPPLEMENTARY MATERIALS

Includes:

A. Explanation of modeling approaches, parameters and assumptions for scenario analysis,

B. Explanation of the scenarios,

C. Supplementary figures of the scenario analysis (including 2 figures),

D. Description and detailed results of the field experiment.

A. Explanation of modeling approach, conversion efficiencies, set of assumptions and parameters used in the model for scenario analysis

Model concept

Jimma is one of the circa 20 cities with 0.1 million to 0.4 million people in the south-west of Ethiopia, next to the capital Addis Ababa with 3.4 million people in 2018. Jimma was chosen as 'model' city to explore the effects of population growth, urbanization, intensification of urban and peri-urban agriculture (UPA) and technological measures on food production and nitrogen (N) flows and recycling in animal manure, kitchen waste and sewage waste for the period 2015–2050. Previous field work had provided some basic data of UPA farms in Jimma (and also in Addis Ababa and Adama) by the authors[1,2].

Cities are often an asymmetrical, uneven and multi-dimensional continuum of zones, with slow changes between the center and urban, peri-urban and rural settings around the center. The idea of a circular patterns of zones of early settlements and cities dates back to the ideas of Von Thünen[3], and was adopted in our model. Hence, Jimma was considered to consist of a circular city center with an urban zone, a peri-urban zone and a rural zone around the center. The city center, and the urban and peri-urban zones were considered as Jimma city, while Jimma city with the rural zone around it was considered here as 'Jimma'. The size of the zones was based on literature data, interviews with local officials and expert judgement. In the end, the total area of the four zones and the population was chosen such that the overall mean population density of Jimma was about 200 residents km^{-2}, which is more or less the average of the highlands in Ethiopia, i.e., the central/south-western area of the country where most people are living (i.e., not considering the sparsely populated and semi-arid south-eastern part of the country). Thus, Ethiopia was conceptualized in circular settlements (villages, cities), which vary in size according to the population (density), and Jimma was considered to be a model city for this concept.

Based on earlier surveys[1,2] and following the ideas of Von Thünen, the productivity of the land was considered to be highest near the center and least in the rural area. Average cereal grain yield in Africa is < 2 $t \cdot ha^{-1} \cdot yr^{-1}$ and in Ethiopia 2.5 $t \cdot ha^{-1} \cdot yr^{-1}$[4,5]. We assumed compound dry matter yields of 2 $t \cdot ha^{-1} \cdot yr^{-1}$ in the rural area and of 3 $t \cdot ha^{-1} \cdot yr^{-1}$ in the urban and peri-urban areas in the base year 2015. Compound crop protein-N yields in the base year were set at 40, 60 and 75 $kg \cdot ha^{-1} \cdot yr^{-1}$ for the rural, peri-urban and urban zones, respectively. Livestock production was derived from farm surveys[1,2].

We assumed in all four zones a mean gross protein consumption of 22 kg $capita^{-1}$ yr^{-1} in 2015, which is the African average[4,5], with 20% food losses and food waste. Animal-sourced protein consumption was set at 14% of the total protein consumption, based on statistical data[4,5]. The average supply of protein of animal origin has been decreasing in Ethiopia from about 13% in 2008 to about 10% in 2017, due to a precarious food supply situation. We assumed that the animal-sourced protein intake in Jimma was slightly higher than the Ethiopian average, because of the productivity of the land around Jimma.

Model calculations

A simple N mass flow model was developed in Windows Excel to explore the effects of scenarios of possible developments. Calculations were done for the four zones of Jimma (Table 1, main text) at annual basis (2015–2050). The model had four modules (1) protein consumption and household waste production, (2) milk, meat and egg production and manure production, (3) crop production and N balances, and (4) economic cost of manure and waste collection, composting and transport. The first three modules were largely based on the ideas of the NUFER model[6,7] and follows the principles of substance flow analysis, in this case N. The fourth module was developed for the purpose of this study; it considers the costs of manure and waste collection, storage, composting, transport and compost delivery/marketing.

The NUFER model has been used to analyze the effects of urban expansion of Beijing, China on N and P flows for the period 1978–2008[8]. NUFER has also been used for several case studies at regional level in China[7,9], and for case studies in Hungary[10] and Kenya[11]. NUFER (NUtrient flows in Food chains,

Environment and Resources use) is a ‘static’ model, developed to analyze N and P use efficiencies and losses in crop and animal production, food processing and consumption in rural and urban households at regional level. NUFER consists of a database with statistical data, and of various calculation modules, which calculate the transfer of N (and P) from one compartment to another (and from one N form to another N form), using transfer coefficients. In NUFER, food systems of a city/region/country are perceived as “pyramids” with four main compartments namely crop production including the rootable soil layer, animal production, food processing and households (consumption). The space outside the pyramid includes the environment (air, surface water, groundwater) and other food systems (pyramids). Nutrients enter the pyramid via fertilizers, biological N_2 fixation, atmospheric deposition, and imported products from other regions or countries. They leave the pyramid via exported products and losses to air and water. There are internal exchanges of N and P within the pyramid between compartments via crop and animal products from the sites of production, processing to consumption and waste production/recycling. Natural grasslands, rough grazing, forests, lakes, and seas are perceived as natural ecosystems and products harvested from these systems are considered as inputs to the pyramid[6,12,13].

Below, we briefly describe the simple N mass flow model in Windows Excel. For each of the four zones of Jimma (city center, urban area, peri-urban area, and rural area; see Table 1 in the main text) the model calculates for each year, from 2015 to 2050:

- Total human population
- Total plant and animal-source protein requirements of the population
- Total milk, meat and egg consumption and total plant-source protein consumption
- Total production of kitchen waste N, and total N losses from kitchen wastes
- Total production of sewage waste N, and N losses from sewage wastes
- Total feed-protein required by dairy cattle, beef cattle (+ goat/sheep) and poultry
- Total crop-protein (including feed-protein) production and the crop N requirements
- Total import of feed-protein and plant-protein needed to satisfy the remaining demand[1]
- Total N-excretion by dairy cattle, beef cattle (including goat/sheep) and poultry
- Total amount of collected animal manure N, and N losses from manure during storage
- The cost of manure and wastes collection
- The cost of manure and wastes composting
- The loss of C and N during composting
- The cost of compost delivering to farms
- Total amounts of compost N available and the ‘additional’ N (fertilizer + BNF) needed to satisfy crop demand
- Overall N use efficiency of the food system and the total N surplus

Table S1 provides an overview of the baseline data parameter values in the Business as usual (BAU) scenario. Baseline data refer to the population, surface areas, protein consumption, milk, meat and egg consumption in the four areas. There was no information available about any differentiation in diets of urban, peri-urban and rural areas in Jimma in 2015. Hence, consumption was set at uniform levels for all areas, and were derived from literature[14,15].

In the model, population and changes in population drives protein N demand. The relative proportions of plant-derived, milk-derived, meat-derived and egg-derived protein consumption in 2015 were derived from survey data.

[1] In case the local crop production does not meet the local demand.

The conversion efficiency of feed protein into milk, meat and egg was derived from literature (e.g, Snijders et al.[16–18], Oenema and Tamminga[17], McDonald et al.[18]). These values and the self-sufficiency coefficients of milk, meat and egg production, the percentage feed scavenging from non-agricultural land, mortality losses, N losses from wastes and manure during storage, the collection and composting of waste and manures in the four zones have the nature of 'guestimates', because there are no accurate data.

The costs for manure and waste collection, composting and transport were derived from interviews with locals; these costs are uncertain, also because there are no existing commercial services for manure and waste collection, storage, composting, transport and delivery/marketing. There is extensive data available on the cost of manure transport in some countries in Europe (e.g., the Netherlands; https://www.agrimatie.nl/SectorResultaat.aspx?subpubID=2232 & sector ID = 2255 & thema ID=2282&indicatorID=6622), but the socio-economic conditions in Jimma and Ethiopia are completely different and hence these data cannot be used. Evidently, there is a need for further research here.

The model accounts for new additional N inputs (via biological N_2 fixation and fertilizers), recycling of manure and waste N in cropland, and for N losses during manure and waste storage and composting and following application to cropland. The required additional N input via biological N_2 fixation and mineral N fertilizers (N-input$_N$; kg·ha^{-1}·yr^{-1}) was estimated from the following mass balance: N-input$_N$ = crop protein-N yield × NUE^{-1} – (N-input$_M$ × FRV$_M$), where N-input$_M$ is the N input via manure and composts (kg·ha^{-1}·yr^{-1}), FRV$_M$ is the fertilizer N replacement value of manures and composts (%, ranging from 40% to 60%; Table 2 in the main text), and NUE is the N use efficiency in crop production (%, ranging from 40% to 60%; Table 2 in the main text).

Farm-gate balances were derived from the difference between the inputs via imported animal feed (from the rural areas into UPA) and additional N (via biological N_2 fixation and mineral fertilizer), and the output of harvested crop and animal produce. Care was taken that the 'Law of mass conservation' (in this case the mass of N) holds in all calculations. We assumed that the soil was not a (temporary) net source of N, although soil N mining is a rather common phenomenon in the rural areas of Ethiopia[1,2].

The model is available for reviewers (uploaded to the website of *FASE* journal) and to readers at request. Please send an email to the first author (soltuta@gmail.com). The model will be made available also on the *FASE* Journal portal.

The assumptions of conversion efficiencies and parameters used in model calculations (Table S1) are summarized below.

Table S1 Overview of the baseline data and parameter values in the Business as usual (BAU) scenario for the base year 2015

Parameters	City center	Urban area	Peri-urban area	Rural area
Population (million)	0.02	0.1	0.15	0.12
Protein-N consumption (kg·capita^{-1}·yr^{-1})	22	22	22	22
Milk consumption (kg·capita^{-1}·yr^{-1})	33	33	33	33
Milk protein-N content (g·kg^{-1})	5.17	5.17	5.17	5.17
Meat consumption (kg·capita^{-1}·yr^{-1})	5	5	5	5
Meat protein-N content (g·kg^{-1})	25.1	25.1	25.1	25.1
Egg consumption (kg·capita^{-1}·yr^{-1})	4	4	4	4
Egg protein-N content (g·kg^{-1})	18.81	18.81	18.81	18.81
Food waste and losses (%)	20	20	20	20
Self-sufficiency milk production (%)	0	20	30	> 100
Self-sufficiency meat production (%)	0	20	30	> 100
Self-sufficiency egg production (%)	0	20	30	> 100
Surface areas (km^2)	78.5	235.5	392.5	1256
Agricultural land (% of total area)	0	5	20	60
Mean crop yield (dry matter) (kg·ha^{-1}·yr^{-1})	na	3000	3000	2000
Mean crop protein-N content (g·kg^{-1})	na	25	25	20
Conversion of feed-N into milk N (%)	na	10	10	10
Conversion of feed-N into meat N (%)	na	5	5	5

Conversion of feed-N into egg N (%)	na	20	20	20
Feed N scavenged by dairy cattle (%)	na	20	20	20
Feed N scavenged by beef cattle (%)	na	20	20	20
Feed N scavenged by poultry (%)	na	20	20	20
Mortality losses dairy production (%)	na	10	10	10
Mortality losses meat production (%)	na	10	10	10
Mortality losses poultry production (%)	na	10	10	10
N losses kitchen waste storage (%)	50	50	50	50
N losses human waste storage (%)	50	50	50	50
N losses cattle manure storage (%)	na	50	50	50
N losses poultry manure storage (%)	na	50	50	50
N content kitchen waste ($g \cdot kg^{-1}$)	5	5	5	5
N content sewage waste ($g \cdot kg^{-1}$)	na	10	10	10
N content cattle manure ($g \cdot kg^{-1}$)	na	5	5	5
N content poultry manure ($g \cdot kg^{-1}$)	na	20	20	20
Fertilizer-N effectiveness of compost (%)	na	40	40	40
N use efficiency applied fertilizer N (%)	na	40	40	40
N-use efficiency BNF (%)	na	100	100	100
Amount of kitchen waste collected (%)	50	50	50	50
Amount of human waste collected (%)	0.1	0.1	0.1	0.1
Amount of cattle manure collected (%)	50	50	50	50
Amount of poultry manure collected (%)	50	50	50	50
Collection cost kitchen waste ($ETB \cdot Mg^{-1}$)	100	100	100	100
Collection cost human waste ($ETB \cdot Mg^{-1}$)	300	300	300	300
Collection cost cattle manure ($ETB \cdot Mg^{-1}$)	100	100	100	100
Collection cost poultry manure ($ETB \cdot Mg^{-1}$)	100	100	100	100
Composting cost kitchen waste ($ETB \cdot Mg^{-1}$)	100	100	100	100
Composting cost human waste ($ETB \cdot Mg^{-1}$)	300	300	300	300
Composting cost cattle manure ($ETB \cdot Mg^{-1}$)	100	100	100	100
Composting cost poultry manure ($ETB \cdot Mg^{-1}$)	100	100	100	100
Composting N losses (%)	30	30	30	30
Mean compost transport distance (km)	20	20	15	10
Compost transport cost ($ETB \cdot Mg^{-1} \cdot km^{-1}$)	10	10	10	10
Transaction costs of compost ($ETB \cdot Mg^{-1}$)	50	50	50	50

Note: na = not applicable, ETB = Ethiopian Birr. These parameter values were either based on local statistical data[19,20], field survey and interview data[1,2], literature data and guestimates (see text).

Population growth rate in the baseline data was set at 3% yr^{-1}, but in reality, differs between rural and urban areas[4]. Population growth was 4.36% yr^{-1} in Addis Ababa in the period 2016–2020[19].

Estimates of protein intake by residents differ somewhat between the available literature sources[15,21,22]. We assumed a gross protein intake of 22 $kg \cdot person^{-1} \cdot yr^{-1}$ for the year 2015. This is slightly lower compared to the total protein intake of 23 $kg \cdot person^{-1} \cdot yr^{-1}$ recorded in 2005 and with an increase of 1% yr^{-1}[14], but slightly higher compared to the data of FAOSTAT[4]. Food waste losses were set at 20%, based on data that indicate that food waste in SSA is on average 150 kg of food $person^{-1}$, and that 15%–35% of the food harvested may be lost, depending on the crop[15,23,24]. The total protein food loss at global level is estimated at 22%[23,24], which is close to our assumption. The 2.5 $kg \cdot person^{-1} \cdot yr^{-1}$ of animal protein intake we assumed for the year 2015 is slightly lower than the animal protein intake of 2.9 $kg \cdot person^{-1} \cdot yr^{-1}$ reported for Ethiopia by the year 2003[15,25], but slightly higher compared to the data of FAOSTAT[4]. The animal-sourced products intake (20%) we assumed for the base year 2015 is comparable to the estimated animal protein intake in SSA[15,21,22].

The fertilizer N replacement value of composts (40%–60%) we assumed is an average compared to the relative efficiencies of manure N as compared to commercial fertilizer N that ranges from less than 30% to greater than 100%[26]. Similarly, our assumption of animal productivity that we defined in terms of feed N conversion is an

average compared to the N in feed protein converted to and deposited in animal protein that ranges between 5% and 45%[17,27].

B. Explanation of the scenarios

Four main contrasting scenarios for possible future developments were defined (Table 2, main text). This section provides some further background of the chosen scenarios (variants). The baseline or Business as usual (BAU) reflects stagnant developments in urbanization, crop and animal production and production efficiency, but a steady population growth of 3% yr^{-1}[28]. Stagnant crop yields were assumed to be the result of soil fertility decline, lack of sufficient fertilizer input and lack of development in agronomic advice and support. While initial calculations indicate that sufficient food was produced for the people and animals in Jimma in the base year (2015), this BAU scenario indicates that massive amounts of food will have to be imported from other areas and/or from abroad to secure the set food protein intake by the residents by 2050. This scenario served as a worse case.

Urbanization is still rather limited in Ethiopia (20% urban people in 2015), but is increasing rapidly by $\geqslant$ 3% yr^{-1}. The urbanization scenario (URBAN) was set up to explore the effects of increased growth of urban people (5% yr^{-1}) and a modest growth of the rural population (1% yr^{-1}). The increased urbanization was meant to reflect increased economic development in the urban areas and increasing prosperity of especially urban people. The changes in productivity and production efficiency partially reflect the changes that have occurred in China during the last 30–50 year[29]. We assumed a modest increase in protein consumption per capita of 1% yr^{-1} and also an increase in animal-sourced food consumption of 1% $capita^{-1}{\cdot}yr^{-1}$ (Table 2, main text). Cereal productivity in China has increased by on average 70–90 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ during the past 55 years[4]. For Jimma, we assumed an increase in compound crop yield of 3% yr^{-1}, which boils down for the rural areas to a mean increase of 100 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ for the period 2015–2050 and to a modest initial increase of 60 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ during the first 5 years. Evidently, this assumed increase in average compound crop yield is at the upper level of what is agronomically and technically feasible, and cannot be extrapolated further. It requires massive input or agronomic knowledge and support, as is being done in the Chinese case (e.g., Chen et al.[30,31] and Cui et al.[32]). Because of the increased population growth in the urban area, we assumed a steady decrease in the area of cropland in the urban and peri-urban areas (2% yr^{-1}), and also a decrease in the percentage of feed that can be scavenged by livestock in communal areas in the urban environment (Table 2, main text). As a result of the decreasing agricultural area in the urban and peri-urban zones, more food and feed protein is needed to be imported from the rural areas (and other areas) to be able to meet the demand in the urban areas.

The scenario of increased (intensification of) livestock production in UPA (UPALP) builds on the URBAN scenario. We assumed that livestock production in UPA was doubled relative to the production in URBAN, and that the increase in animal-sourced food consumption by the urban people was also doubled, from 1% to 2% yr^{-1} (Table 2, main text). Because, the protein consumption in the basal year 2015 was low, doubling the rate of increase of animal-sourced protein consumption turned out to be modest; total net protein intake $capita^{-1}$ increased from 17.6 to 24.9 $kg{\cdot}yr^{-1}$, and the overall mean animal-sourced protein intake increased from 14% to 19% (also because the animal-sourced protein intake in the rural areas was not doubled). Other parameters were as in the URBAN scenario.

The technology scenario (TECH) builds on the UPALP scenario. We assumed that the population growth in the urban areas was halved and that technological measures were taken (1) to increase livestock productivity per animal (a doubling of the amount of feed protein converted into milk, meat, and egg protein), (2) to decrease N losses from manures and wastes during storage, and (3) to increase the N use efficiency in crop production, relative to the UPALP scenario (Table 2, main text). A slowing down of population growth in developing countries is possible, as shown by the Chinese case[33], but not easy. It requires economic growth and various governmental incentives.

Ethiopia has a relatively large number of livestock, but its productivity is relatively low[4]. Feed availability and quality are major constraints, but the genetic potential of the herd and, the herd and disease management provide also opportunities for improvement. In the TECH scenario, we explored the effects of doubling of livestock productivity, i.e., the amounts of milk, meat and egg produced per unit of feed protein intake per

head was increased by a factor of two. Thus, the feed protein conversion by dairy cattle, sheep, goat and poultry was doubled; it increased to levels which are considered to be close to current averages in China but are still below the performance of the best performing countries[17,34].

Next, we assumed that the N losses from wastes and manures during storages was halved from 50% to 25% by technical measures (leak-tight and covered storages), and that the collection of manures and wastes was increased from 50% to 75% (i.e., 75% of the collectable waste and manures were indeed collected). These estimates were largely based on Bittman et al.[35].

Further, we assumed that the overall N use efficiency in crop production was increased from a base compound level of 40% to a compound average efficiency of 60%. Nitrogen use efficiency (NUE) was defined as the ratio between harvested output and total N input. The world-average NUE was 42% in 2010, while the average for Sub-Saharan Africa was 72% in 2010[36]. The latter value reflects low input and soil N mining. It has been suggested that the world-average NUE should increase close of 70% by 2050 (including Sub-Saharan Africa) to be able to produce sufficient food and stay within the proposed planetary boundaries[36]. Our suggested increases for NUE in Jimma are within the suggested ranges.

Evidently, the TECH scenario is the most demanding scenario. It provides a dot on the horizon; it may indicate the needed future direction.

We made a number of additional sensitivity analyses, in addition to the aforementioned four main scenarios. These sensitivity analyses provided insight in the most sensitive indicators, and helped to define the main scenarios. Results of these sensitivity analyses are not shown here, but are available on request.

C. Supplementary figures of the scenario analysis (including 2 figures)

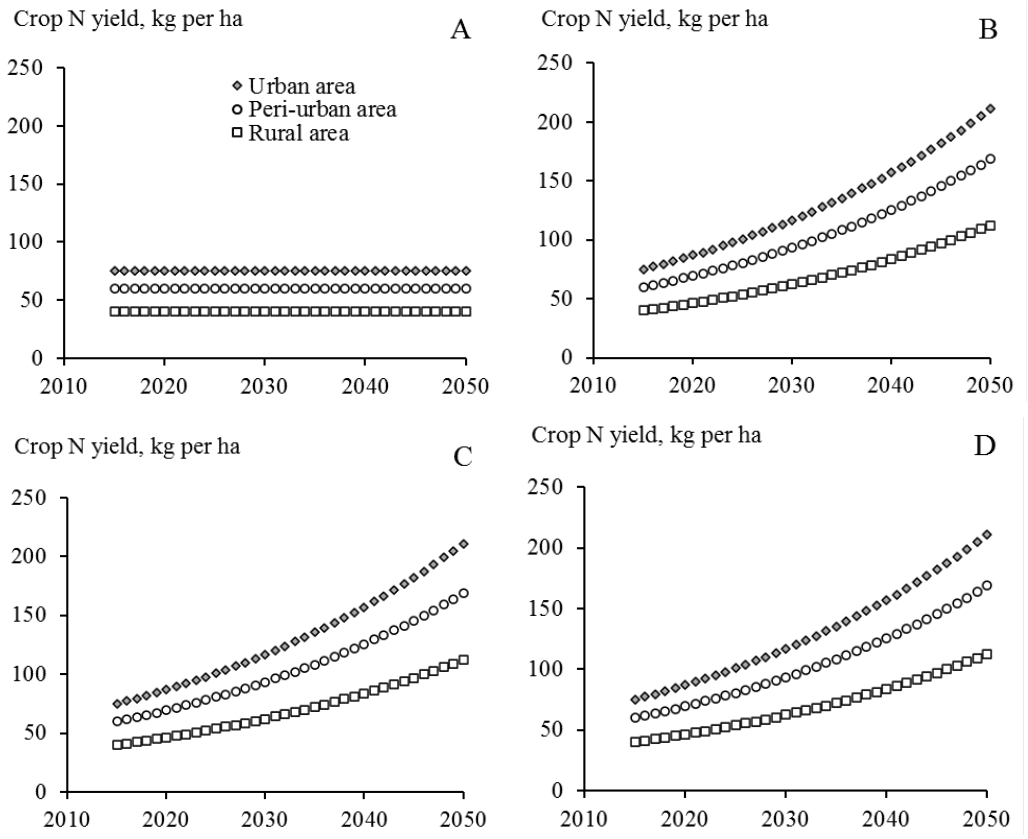

Fig. S1 Simulated changes in the crop N yields in different zones of Jimma in the period 2015 to 2050, for four scenarios: (A) BAU, (B) URBAN, (C) UPALP, and (D) TECH (see Table 2 in the main text for assumptions).

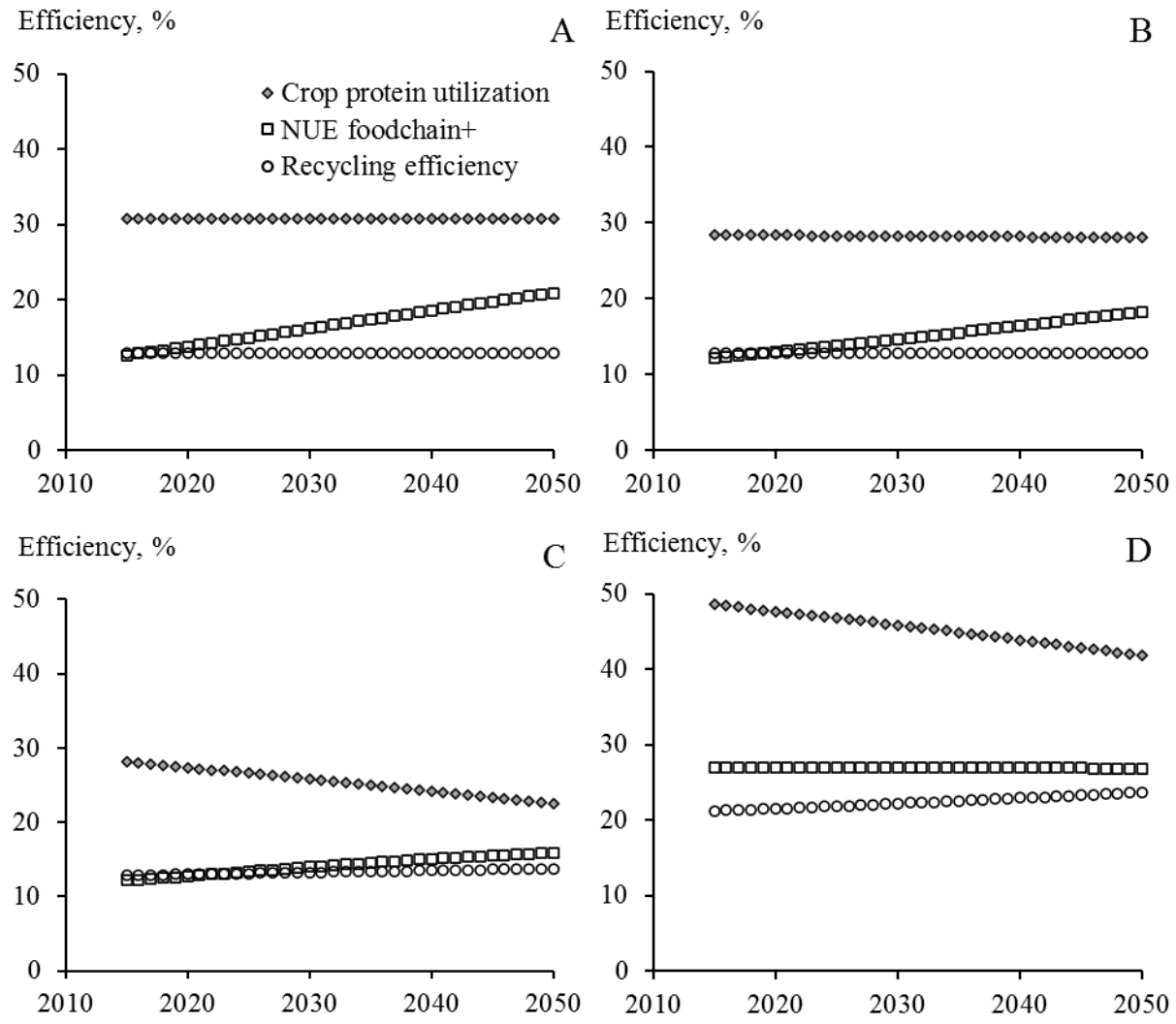

Fig. S2 Simulated changes in crop protein utilization (ratio of protein intake and crop protein needed for plant food and animal feed), whole food chain N use efficiency (ratio of protein N intake and 'new' N input needed), and recycling efficiency (the fraction of waste and manure N produced that is utilized as compost N) averaged over the different zones of Jimma in the period 2015 to 2050, for four scenarios: (A) BAU, (B) URBAN, (C) UPLP, and (D) TECH (see Table 2 for assumptions) (see Table 2 in the main text for assumptions as regards scenarios).

D. Description and detailed results of the field experiment

Design and execution of the experiments

The experiment was conducted at Jimma University research station for two years (2015 and 2016). The site is located at 7°40′N, 36°50′E, at an altitude of 1780 m.a.s.l. and 350 km away from Addis Ababa in South-west Ethiopia. The annual mean rainfall is 1800–2300 mm, of which 85% falls in June to September and the rest in January to May. The annual mean temperature is 15–22°C. The site has a gentle slope < 5% and a well-drained Nitisol soil type. The soil has a clay loam texture (65% clay, 16% sand, and 19% silt), a pH (H_2O) of about 5.7, organic matter content of 50 $g \cdot kg^{-1}$, a total nitrogen content of 25 $g \cdot kg^{-1}$, a P-Olsen of 4.5 $mg \cdot kg^{-1}$, and an exchangeable K content of 196 $mg \cdot kg^{-1}$[37]. The site was previously cropped with maize for the study of maize resistance to stalk borer.

Before the field experiment, we prepared the composts and measured their N and P contents to determine the required application rates[38]. Urban manures (chicken manure, cattle manure (cow dung), pig manure, farm yard manure) and kitchen wastes were identified as the main organic wastes, and were collected from Jimma urban areas. Human excrements were not included because of cultural barriers. The composts (Table S2) were prepared using the standard procedures[39]. Accordingly, the manures and kitchen wastes were composted in heaps (static composting) for three months, and mixed regularly. Compost maturity was assessed on the basis of the reduction in volume, C/N ratio and pH value[40]. The C/N ratio of the final composts ranged from 8.7 to 15.6 (Table S1). A low C/N ratio reflects in part accumulation of mineral N. The C/N ratio usually decreases during the composting process due to greater carbon losses via CO_2 emissions than N losses via NH_3, N_2O and N_2 volatilization (not measured), and stabilizes in the range of 10–15[41].

Table S2 Chemical properties of the five composts used for the field experiments

Type of compost	pH	TC ($g \cdot kg^{-1}$)	TP ($g \cdot kg^{-1}$)	AP ($g \cdot kg^{-1}$)	TN ($g \cdot kg^{-1}$)	NH^+_4 ($mg \cdot kg^{-1}$)	NO^-_3 ($mg \cdot kg^{-1}$)	C/N ratio
CMC	6.9	270	28	21	31	1860	1240	8.7
CDC	9.0	308	16	12	26	1560	1040	11.8
FMC	8.8	256	13	10	18	1080	720	14.2
KWC	8.6	255	11	8	22	1320	880	11.6
PMC	7.4	374	20	15	24	1440	960	15.6

Note: CMC = chicken manure compost, CDC = cow dung compost, FMC = farm yard manure compost, KWC = kitchen waste compost, PMC = pig manure compost, TC = Total carbon, TN = total nitrogen, TP = total phosphorus, AP = available phosphorus.

Samples were collected from different parts of the five types of compost heaps, oven-dried at 70°C, homogenized, ground and sieved (⩽ 2 mm) before analysis. Then, the samples were analyzed using standard laboratory procedures. Total organic C was determined by dichromate-oxidation[42]. To determine total N (TN) and total P (TP), composts samples were digested in a mixture of sulfuric and salicylic acid and selenium (Se) to which hydrogen peroxide (H_2O_2) was added according to the standard working instruction E1009. TN and TP were measured with segmented flow analyzer (SFA) using the standard working instruction E1408. TN was measured based on Berthelot reaction (measuring at 660 nm), by indophenol blue method[43], and TP was measured as phospho-molybdenum complex (measuring at 880 nm)[44]. Composts were extracted with 0.01 $mol \cdot L^{-1}$ $CaCl_2$ in 1:10 (mass: volume) ratio, shaken for 2 h, centrifuged at 48,000 g and NH_4^+ and NO_3^- were measured in the supernatant using the standard auto-analyzer techniques. Extractable P was determined by measuring orthophosphate as a phospho-molybdenum complex in $CaCl_2$ extracts. The pH of composts was measured in a 1: 2.5 (weight: weight) 1 $mol \cdot L^{-1}$ KCl extract, using digital pH meter[45]. The nutrient contents of the composts (Table S2) were close to the values reported for chicken manure, pig manure and kitchen waste composts by others[38,46–50].

The field experiment was conducted as randomized complete block design with 13 treatments (Table S3). Treatments included three references (i.e., a nil control (T1), half the recommended N and P dose (T2) and the

full recommended N and P dose (T3) via DAP/UREA), and five types of composts applied at two rates (Table S3).

Table S3 Description of treatments used for the experiments (2015 and 2016) and their nutrient supply

No.	Description of treatments	Nutrient supply (kg·ha^{-1})		
		N	P	K
T1	0 kg DAP + 0 kg·ha^{-1} UREA	0	0	0
T2	50 kg DAP + 50 kg·ha^{-1} UREA	32	11	0
T3	100 kg DAP + 100 kg·ha^{-1} UREA	64	21	0
T4	75 kg·ha^{-1} total nitrogen (TN) as chicken manure compost (CMC)	75	32	22
T5	75 kg·ha^{-1} TN as cow dung (cattle manure) compost (CDC)	75	12	18
T6	75 kg·ha^{-1} TN as farm yard manure compost (FMC)	75	16	18
T7	75 kg·ha^{-1} TN as kitchen waste compost (KWC)	75	15	23
T8	75 kg·ha^{-1} TN as pig manure compost (PMC)	75	18	28
T9	150 kg·ha^{-1} TN as CMC	150	64	44
T10	150 kg·ha^{-1} TN as CDC	150	23	35
T11	150 kg·ha^{-1} TN as FMC	150	32	35
T12	150 kg·ha^{-1} TN as KWC	150	29	46
T13	150 kg·ha^{-1} TN as PMC	150	35	55

Each treatment was replicated four times. DAP fertilizer contained 18% N and 46% P_2O_5 (20% P) and UREA contained 46% N. In both years, the experimental field was ploughed using oxen-drawn implements and manually prepared for sowing. In July, 10 planting rows were made per plot (4 m × 3 m) at 0.3 m row spacing, recommended for sowing of the HAR 3116 wheat variety. Composts and fertilizers were applied in rows a day before sowing. Improved wheat variety HAR 3116 (locally called Digalu) is high yielding and widely grown in the highlands of Ethiopia[51]. It has a yield potential of 4000 kg·ha^{-1} on research and 3100 kg·ha^{-1} on farmers' fields[52]. Seed rate was 150 kg·ha^{-1}, as recommended[53]. Urea was applied in split with half at planting and the other half 42 days after planting, at tillering stage.

In 2016, whole plant samples were collected at boot stage (stage 10 of the Feekes development scale) from 50 randomly selected plants per plot. The samples were put in an oven at 30°C until a constant weight was attained, ground and sieved (⩽ 2 mm) before analysis. Samples were analyzed for total N, P and K contents, at Eurofins-Agro (http://eurofinsagro.com) using standard procedures. After wheat harvest, soil samples (0–20 cm) were collected from each plot randomly from six spots per plot and bulked as a composite sample per plot. Samples were oven-dried at 70°C, homogenized, ground and sieved (⩽ 2 mm) before analyses. Samples were extracted with 0.01 mol·L^{-1} $CaCl_2$ in 1:10 (mass: volume) ratio and N, P, K, and pH were determined in the extract using standard laboratory procedures at Eurofins-Agro (http://eurofinsagro.com).

Wheat grain and straw yields were recorded at maturity. Yield data and results of soil and plant analyses were analyzed using MonQIt (Monitoring for Quality Improvement toolbox) model. MonQIt is a toolbox that offers data processing software (www.monqit.com). MonQIt produces farm performance indicators including NPK flows, uptake and balances and gross margins (GM) per treatment[54].

For the quantification of NPK in input and output flows, the mass of inputs (e.g., fertilizsers and the composts treatments) and outputs (wheat grain and straw yields) were multiplied by their dry matter and NPK contents[55,56] (Eq. (1)).

$$\mathrm{F} = \sum_{i=1}^{n} \mathrm{Q}i\mathrm{D}i\mathrm{C}i \qquad \text{Eq. (1)}$$

where F is the total input or output of N or P or K, in kg·ha^{-1}·yr^{-1}; *n* is the number of different nutrient inputs and outputs in a year; Q is the quantity of each input or output, in kg per ha; D is the dry matter content of the inputs or outputs, in %; C is the N or P or K contents of the inputs or outputs, in g·kg^{-1}. Therefore, nutrient (NPK) balances were calculated per plot as the difference between total inputs and outputs (Eq. (2)):

$$\mathrm{NB} = [(\mathrm{IN1} + \cdots + \mathrm{IN4}) - (\mathrm{OUT1} + \cdots + \mathrm{OUT5})] \qquad \text{Eq. (2)}$$

where NB is the nutrient balance (N or P or K); IN1 and IN2 are inputs (fertilizers and composts applied in each treatment per plot), IN3 and IN4 are atmospheric deposition and biological N fixation, respectively, and OUT1 and OUT2 are outputs (grain and straw yields obtained from each treatmet per plot) in harvested wheat and OUT3, OUT4 and OUT5 are leaching, gaseous losses and erosion, respectively[54].

GM is an indicator of profitability, and accounts for the intrinsic values of all inputs and all outputs (Eq. (3)).

$$\mathrm{GM} = \mathrm{GV} - \mathrm{VC} \quad \text{Eq. (3)}$$

where GV (gross value) is the values of an output of the harvested crop and VC (variable costs) are the value of all inputs (costs of seed, labor, DAP/UREA fertilizers and composts, in Ethiopian Birr (ETB) $ha^{-1}{\cdot}yr^{-1}$ (1 ETB is about 0.03 Euro).

The harvest index (HI, %) was calculated as the grain dry matter divided by the total aboveground biomass[57]:

$$\mathrm{HI} = \frac{\mathrm{GDM}}{\mathrm{TAB}} \times 100 \quad \text{Eq. (4)}$$

where GDM is grain dry matter ($kg{\cdot}ha^{-1}$) and TAB is total above ground biomass ($kg{\cdot}ha^{-1}$).

Apparent agronomic efficiency (AAE, $kg{\cdot}kg^{-1}$) of N, P and K was calculated according to:

$$\mathrm{AAE} = \frac{\mathrm{YF} - \mathrm{Y0}}{\mathrm{F}} \quad \text{Eq. (5)}$$

where YF is the grain yield of a fertilized plot ($kg{\cdot}ha^{-1}$), Y0 is the grain yield of the control plot ($kg{\cdot}ha^{-1}$), and F is the amount of N, P or K applied ($kg{\cdot}ha^{-1}$).

Apparent N, P or K Recovery Efficiency (ARE-N, ARE-P, ARE-K, %) was calculated as:

$$\mathrm{ARE} = \frac{\mathrm{UF} - \mathrm{U0}}{\mathrm{F}} \times 100 \quad \text{Eq. (6)}$$

where UF is nutrient (N, P or K) uptake in above ground biomass of fertilized plots ($kg{\cdot}ha^{-1}$). U0 is nutrient (N, P or K) uptake in above ground biomass of the control plot ($kg{\cdot}ha^{-1}$), and F is the amount of N or P or K applied ($kg{\cdot}ha^{-1}$).

Partial factor productivity (Pfp) was defined as ratio of grain yield to the sum of N, P and K applied ha^{-1}:

$$\mathrm{Pfp} = \frac{\mathrm{YF}}{\mathrm{F\,(N + P + K)}} \quad \text{Eq. (7)}$$

The fertilizer replacement value (FRV, %) of composts was defined as the ratio of the apparent recovery efficiency (ARE) of compost treatments and the apparent recovery efficiency (ARE) of the fertilized control treatment (T3)[58].

$$\mathrm{FRV} = \frac{\text{ARE of composts}}{\text{ARE of control treatment T3}} \times 100 \quad \text{Eq. (8)}$$

All data on wheat grain and straw yields, harvest index, nutrient uptake and nutrient recovery efficiencies, fertilizer replacement values and nutrient balances and GM were subjected to ANOVA. Means were compared using the LSD value at 5% level of significance. SPSS version 23 (IBM) was used for all statistical data analyses.

Results of the experiment

Nutrients (N, P and K) of wheat plants at boot stage during the second growing seasons (2016) were significantly ($P < 0.05$) affected by compost applications (Table S4). Composts increased the N content in the plants by 2%–18%, the P content by 10%–38% and the K content by 1.3%–26% compared to the nil treatment (T1). Chicken manure compost (CMC) was most effective in enhancing the N, P and K contents at boot stage. Increased N content (22%) was reported in wheat at boot stage from 16 $g{\cdot}kg^{-1}$, where no manure had been

added to 19.5 g·kg^{-1} when 150 kg·ha^{-1} organic N was added as manure [59]. The N contents of wheat plants at boot stage due to the compost treatments (Table S4) is close to the normal agronomic sufficiency range of 20.0–30.0 g·kg^{-1} N and the P and K contents are within the normal agronomic sufficiency range of 2.0–5.0 g·kg^{-1} P and 15.0–30.0 g·kg^{-1} K for wheat[59]. There was a relatively large within-treatment variation in N, P and K contents. In addition to the compost treatments, there was a significant block effect in N and K contents (Table S5). This indicated the importance of blocking, which was likely the result of spatial variations in natural soil fertility.

Table S4 Mean N, P and K contents in wheat plants at boot stage, in response to inorganic fertilizer (T2, T3) and composts applications (T4–T13) in 2016

Treatments	Nutrient Supply per treatment (kg·ha^{-1})			Nutrients in wheat plants (g·kg^{-1})		
	N	P	K	N	P	K
T1	0	0	0	17.3^{bc}	2.1 ^{f}	23.4 ^{bc}
T2	32	11	0	17.8 ^{bc}	2.3 ^{ef}	23.1 ^{bc}
T3	64	21	0	16.7 ^{c}	2.5 ^{cde}	22.6 ^{c}
T4	75	32	22	18.9 ^{ab}	2.4 ^{cde}	24.8 ^{bc}
T5	75	12	18	17.6 ^{bc}	2.3 ^{def}	23.4 ^{bc}
T6	75	16	18	17.7 ^{bc}	2.5 ^{cde}	22.7 ^{c}
T7	75	15	23	16.6 ^{c}	2.3 ^{cdef}	22.6 ^{c}
T8	75	18	28	18.7 ^{b}	2.5 ^{bcd}	24.0 ^{bc}
T9	150	64	44	20.5 ^{a}	2.9 ^{a}	29.5 ^{a}
T10	150	23	35	18.6 ^{b}	2.4 ^{cde}	23.7 ^{bc}
T11	150	32	35	18.0 ^{bc}	2.8 ^{ab}	25.2 ^{b}
T12	150	29	46	18.4 ^{b}	2.6 ^{bc}	24.9 ^{bc}
T13	150	35	55	18.8 ^{b}	2.9 ^{a}	25.0 ^{bc}
LSD	-	-	-	1.7	0.3	2.5
P value	-	-	-	***	***	***

Note: ANOVA was used to compare treatment means. Means with different letters within columns are statistically different using LSD test at $P < 0.05$. *** denotes significant difference.

Table S5 Summary of significant P values for nutrient content in wheat green plants (WGP) at boot stage, nutrient uptake and wheat yield across 13 treatments and 4 blocks in 2016

Source	DF	Nutrients in WGP (g·kg^{-1})			Nutrient uptake (kg·ha^{-1})			Wheat yield (kg·ha^{-1})	
		N	P	K	N	P	K	Grain	Straw
Block	3	0.0001	0.1397	0.0001	0.0097	0.0089	0.0088	0.0088	0.0177
Treatment	12	0.0031	0.0001	0.0002	0.0001	0.0002	0.0002	0.0005	0.0002

Note: ANOVA was used to compare 13 treatments replicated in 4 blocks using LSD test at $P < 0.05$.

Grain and straw yields and N uptake of wheat were significantly ($P < 0.05$) affected by compost applications (Table S6). Compost applications (T4–T13) increased grain yield by 45%–248% and straw yield by 36%–297% over the nil treatment (T1). Compost applications increased N uptake by 42%–287%, P uptake by 40%–240%, and K uptake by 40%–260% compared to the nil treatment. Only chicken manure compost (T9) increased the N uptake, P uptake, and K uptake as well as the grain and straw yields of wheat, relative to the reference treatment T3. There was significant block effect on N, P and K uptake and on grain and straw yields of wheat.

Nutrient balances and nutrient use efficiencies were significantly affected by compost and fertilizer applications (Table S7). Compost applications reversed the negative N and K balances under T1–T3 to positive N and K balances. The apparent agronomic efficiency (AAE) was on average lower in compost treatments (T4–T13) than in the DAP + UREA reference treatments T2 and T3, for both N and P. The apparent recovery (ARE) was on average also lower in compost treatments (T4–T13) than in the DAP + UREA reference treatments T2 and T3, especially for N.

The partial factor productivity (Pfp) was also lower in compost treatments (T4–T13) than in the DAP + UREA reference treatments, indicating that the composts were less effective in enhancing grain yield than the inorganic fertilizers, per applied nutrients. The fertilizer replacement value (FRV) of composts was on average only half of that of DAP + UREA for N but two times for P (Table S7). Chicken manure compost (CMC) had

a relatively high and cow dung (CDC) a relatively low FRV-N. Pig manure compost (PMC) had a relatively high and CMC a relatively low FRV-P.

Table S6 Wheat grain and straw nutrient uptake, yields and harvest index in response to urban manures and kitchen waste composts and inorganic fertilizer treatments in 2015

Treatments	Nutrient uptake (kg·ha^{-1})			Wheat yield (kg·ha^{-1})		Harvest index (HI)
	N	P	K	Grain	Straw	(%)
T1	33^{e}	5^{e}	5^{e}	1125^{e}	1825^{e}	38^{a}
T2	51de	7de	8de	1650^{cde}	3075^{cde}	34^{a}
T3	84^{bc}	12^{bc}	13^{bc}	2685^{bc}	5100^{bc}	34^{a}
T4	73^{bcd}	11^{bcd}	11^{bcd}	2488^{bcd}	4175^{cd}	36^{a}
T5	53^{cde}	8^{cde}	8^{cde}	1773^{cde}	3100^{cde}	37^{a}
T6	53^{cde}	8^{cde}	8^{cde}	1830^{cde}	2950de	38^{a}
T7	55^{cde}	8^{cde}	8^{cde}	1875^{cde}	3075^{cde}	36^{a}
T8	67^{cd}	10^{cd}	10^{cd}	2208^{cd}	3975^{cd}	35^{a}
T9	121^{a}	17^{a}	18^{a}	3920^{a}	7250^{a}	35^{a}
T10	46de	7de	7de	1628de	2475de	40^{a}
T11	68^{cd}	9^{cd}	10^{cd}	2100^{cde}	4250^{bcd}	36^{a}
T12	74^{bcd}	11^{bcd}	11^{bcd}	2493^{bcd}	4325^{bcd}	35^{a}
T13	102^{ab}	14^{ab}	15^{ab}	3278^{ab}	6250^{ab}	35^{a}
LSD	32	4	3	1056	2061	7
P value	***	***	***	***	***	NS

Note: ANOVA was used to compare treatment means. Means with different letters within columns are statistically different using LSD test at $P < 0.05$. *** denotes a significant difference, and NS denotes a non-significant difference between means.

Table S7 Partial nutrient balances, apparent agronomic efficiency (AAE), apparent recovery efficiency (ARE), partial factor productivity (PFP), and fertilizer replacement values (FRV) of inorganic fertilizers (T2, T3) and compost (T4–T13) applications in 2015

Treatments	Partial nutrient Balances (kg·ha^{-1})			Nutrient Use Efficiency indices [a]							FRV (%) [b]		
				AAE (kg grain kg^{-1} N or P or K)			ARE (%)			PFP (kg grain kg^{-1} N + P + K applied)			
	N	P	K	N	P	K	N	P	K		N	P	K
T1	–33	–5	–5	na [c]	na	na	na	na	na	Na	na	na	na
T2	–19	4	–8	16	48	na	56	18	na	38	na	na	na
T3	–20	9	–13	24	74	na	80	33	na	32	na	na	na
T4	2	21	11	18	43	62	53	19	27	19	67	57	na
T5	22	4	10	9	54	36	27	25	17	17	33	76	na
T6	22	8	10	9	44	39	27	19	17	17	33	57	na
T7	20	7	15	10	50	33	29	20	13	17	37	61	na
T8	8	8	18	14	60	39	45	28	18	18	57	84	na
T9	29	47	26	19	44	64	59	19	30	15	73	57	na
T10	104	16	28	3	22	14	9	9	6	8	11	26	na
T11	82	23	25	7	30	28	23	13	14	10	29	38	na
T12	76	18	35	9	47	30	27	21	13	11	34	63	na
T13	48	21	40	14	62	39	46	26	18	14	58	78	na

Note: [a] See Eq. (2–4), [b] See Eq. (5), [c] na = not applicable.

Gross margin (GM) was significantly ($P < 0.05$) affected by the compost treatments (Fig. S3). Compost treatments T3, T4, T9 and T13 increased the GM compared to the control treatment (T1). However, there were no statistically significant differences for the other compost treatments, indicating that compost application was only marginally profitable.

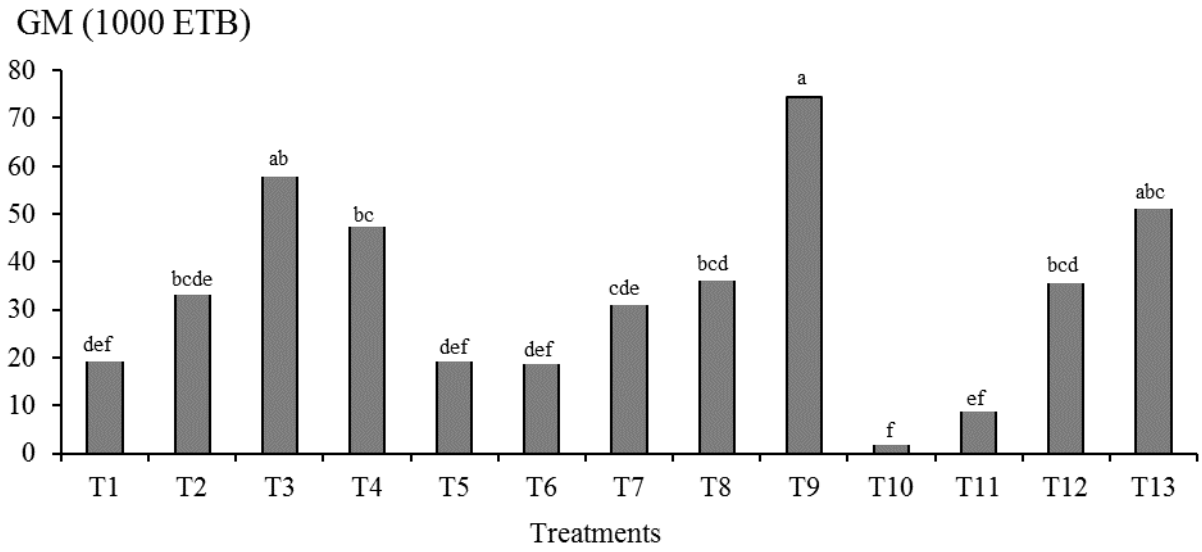

Fig. S3 Gross margin as affected by compost (T4–T13) and DAP + UREA fertilizer (T1–T3) applications. Data for 2015.

Discussion of the results of the field experiment

Grain and straw yields of the control treatment were low, indicating that the site has low inherent soil fertility. Grain yields were lower than straw yield, across all compost treatments (Fig. S4). The DAP-UREA fertilizer combinations applied at recommended rates more than doubled the grain and straw yields of the control (Table S6) and increased the N and P contents of the above ground biomass at booting stage (Table S4), which indicates that the soil was responsive to N and/or P applications. An increase in crop performances following fertilizer use could be attributed to the low inherent soil fertility of the experimental plots that leads to positive responses following N, P and/or K applications[60]. The apparent agronomic efficiency to fertilizer N (AAE-N) ranged from 16 to 24 kg·kg^{-1}, is modest[61]. The apparent agronomic efficiency to fertilizer P (AAE-P) ranged from 48 to 74 kg grain kg^{-1} P (Table S7) which, is relatively large, compared to the range of 15–40 kg grain kg^{-1} P for cereals (mainly, maize, rice, and wheat)[62]. Compost applications also increased the grain and straw yields compared to the nil control treatment (Table S6) and the N and P contents of the aboveground biomass at booting stage. The yield responses to compost applications were variable but roughly of the same order of magnitude as the responses to DAP-UREA applications (Table S6). The variable response is related to the variability within treatments, which were the result of small-scale spatial variations in soil fertility and the heterogeneity of the composts. The small-scale spatial variations in soil fertility were probably exaggerated by the relative drought during the growing season; rainfall during the growing season was 230 mm below average. As a result, maximum grain yields were less than the potential attainable grain yield of 4000 kg·ha^{-1}[52]. Wheat yield responses to compost applications may be attributed to the N and P in the applied composts, although only a fraction of the N and P in composts was readily available N and P (Table S2). The composts also supplied organic matter, potassium (K) and very likely other essential (micro) nutrients to the soil, which may have been beneficial to the wheat crop[63]. Chicken manure compost gave the highest average yield response (Table S6). This may be related to its relatively high N and P contents (Table S2) but also to the acid-neutralizing capacity of chicken manure.

Chicken manure commonly has relatively high calcium (Ca) and magnesium (Mg) contents[64], which acts as lime[65]. Cow dung gave the lowest yield, which is congruent to its relatively low N and P contents (Table S2), but also due to its relatively low acid-neutralizing capacity. Higher N and P in dried chicken manure than in dried cow dung was reported[66]. Likewise, there is a report that higher P, K, Ca and Mg contents in chicken manure compost than in cow dung compost[67]. The mean apparent agronomic efficiency (AAE) ranged from 5 to 20 kg grain kg^{-1} for N, from 35 to 65 for P and from 25 to 65 for K (Table S7; Fig. S5).

Compost applications had a positive effect on N, P and K balances (Table S7), indicating that the recycling of composts, derived from urban livestock manures and kitchen wastes, may reverse current practices of soil mining in rural areas.

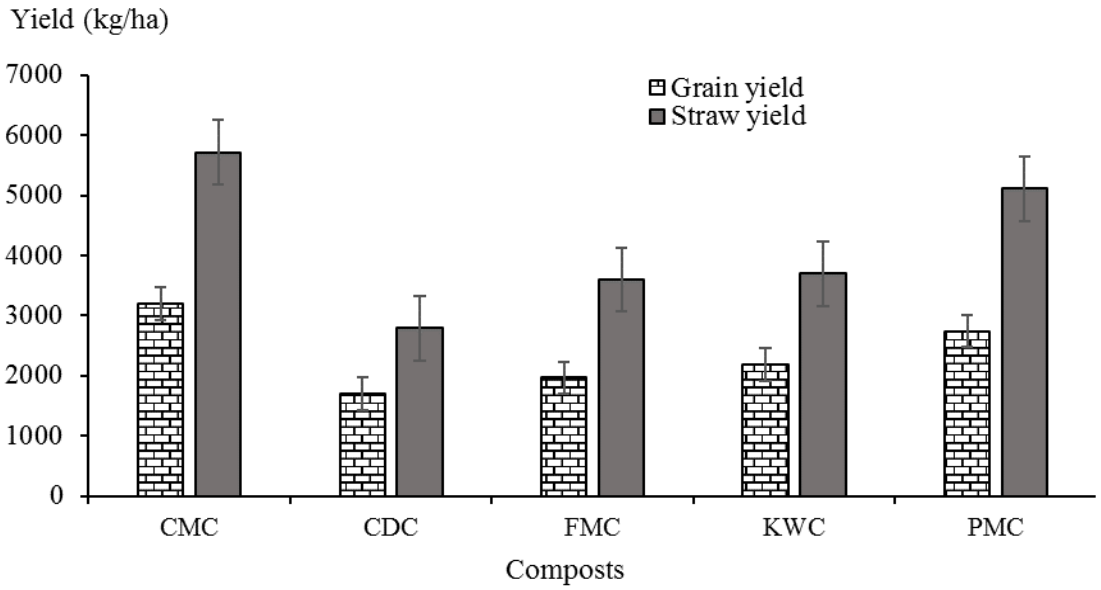

Fig. S4 Mean grain and straw yields of compost treatments (means of two applications doses).

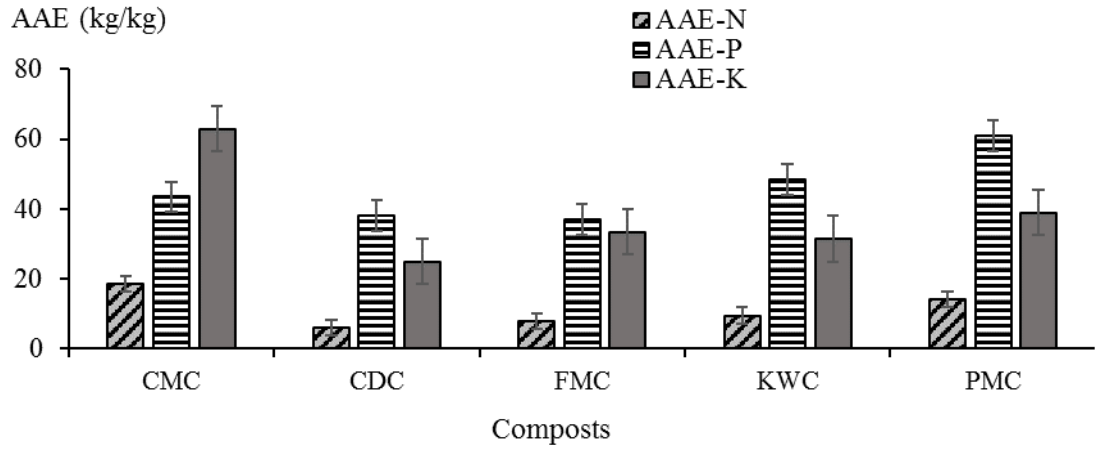

Fig. S5 Mean apparent agronomic efficiencies (AAE) of applied nitrogen (N), phosphorus (P) and potassium (K) via composts (means of two application doses).

Recycling of manures and wastes from urban areas in rural areas will decrease the environmental burden of current dumping and discharge practices in urban areas, increase crop yields, stop soil nutrient depletion, save synthetic fertilizers, and improve soil fertility in rural areas at the same time[1]. The use of agricultural wastes reduced depletion rates of soil N, reversed the soil P balance and brought a positive outcome[68]. Higher plant P and K contents was reported in treatments with organic fertilizers than in treatments with inorganic N fertilizers, likely because the organic fertilizers supplied also P and K, and because the organic fertilizers may have increased soil organic carbon content, cation exchange capacity (CEC), and pH[69]. There is an argument that crop responses to manure applications depend on the availability of N, and hence on the quality of the manure[70]. It is stated that the N and P availability in manure depends on the organic matter content of the manure, because mineralization is a major biochemical pathway through which organically bound N and P become plant available[63]. It is also indicated that manure application influenced soil organic matter content

and P Olsen[63]. Surprisingly, they reported the greatest yield benefit of organic amendments in soils with neutral pH values (6.6–7.3), suggesting that the liming effect of organic amendments is not much beneficial.

The mean apparent recovery efficiencies (ARE) of applied compost nutrients ranged from 15% to 60% for N, from 15% to 30% for P, and from 10 to 30 for K (Fig. S6). Clearly, CMC and PMC had the highest mean ARE-N, and CDC and FMC had the lowest mean ARE-N. The cow dung compost (CDC) had also a low ARE-P and ARE-K (Fig. S6). Other researcher[71] also reported the highest nutrient use efficiency at the lower part of the yield response curve.

Results of our experiment do not (yet) show clear indications of 'diminishing returns' of the high compost application rates (Table S6); this allowed us to average the results of the two compost application rates. A recent review of worldwide data on N use efficiency for cereal crops reported a mean fertilizer N recovery efficiency of 57% for wheat and a mean fertilizer nutrient efficiency of about 50% for N, 10% for P, and 40% for K[72]. These studies dealt with single-nutrient, synthetic and soluble fertilizers. In contrast, compost contains multi-nutrients, which are partly organically bound and only become available following mineralization. As a result, the recovery efficiencies of nutrients from composts cannot be estimated easily and accurately. It has been indicated that only 20% of the N in composted manure would become plant available in the 1st, 20% in the 2nd, 10% in the 3rd and 5% in the 4th year after application[73]. Thus, the resulting efficiencies are often relatively low, especially in the year of application. Similarly, it was reported that solid manures release relatively little N during the season after application, and that there is a huge variation between different types of manures[66].

The nutrient supply from organic amendments to crops is commonly expressed in the so-called Fertiliser Replacement Value (FRV), which can be determined by comparing the nutrient uptake in composts amended plots against mineral fertiliser-only plots. A proper comparison per nutrient element requires that other essential nutrients are not limiting crop yield and nutrient uptake, following the ceteris paribus principle[74].

The apparent FRV-N and FRV-P of our compost treatments (T4–T13) ranged from 11% to 73% and from 26% to 78%, respectively, and were related to compost type and application rate (Table S6). According to other researchers[74], FRV-N of FYM and other types of organic amendments was higher at high N supply than at low N supply. In contrast, we observed that type of compost was more important than the rate of application in determining the FRV of composts (Table S7).

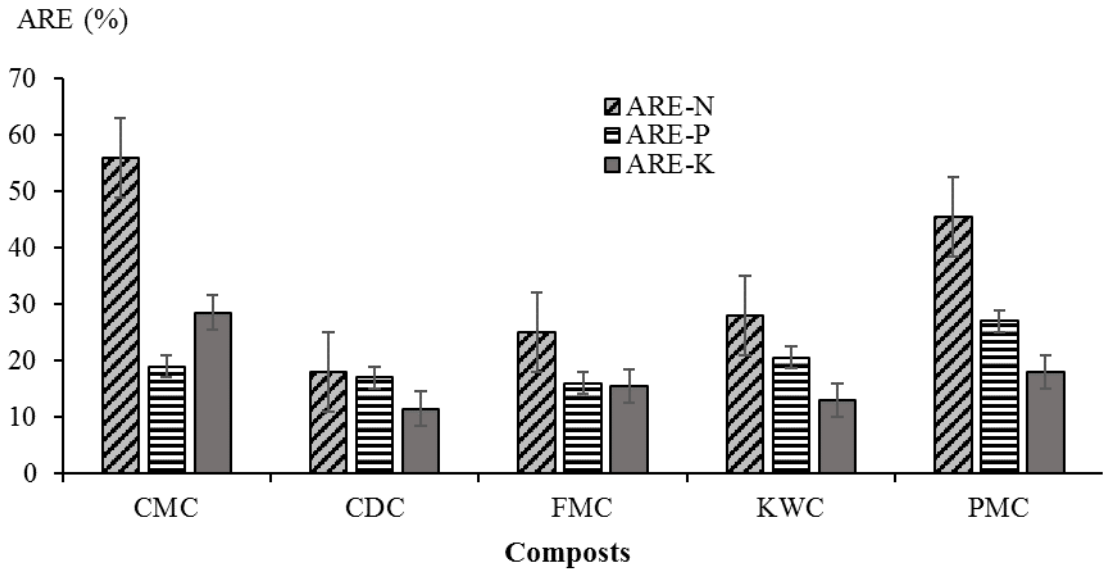

Fig. S6 Mean apparent recovery efficiencies (ARE) of applied nitrogen (N), phosphorus (P) and potassium (K) via composts (means of two applications doses).

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