

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

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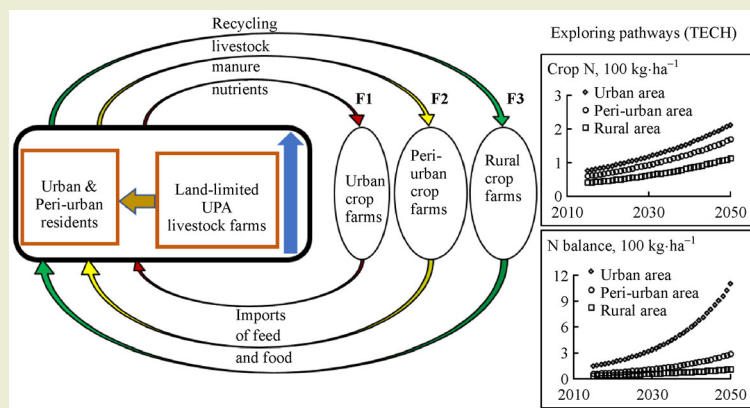
KEYWORDS

compost, food self-sufficiency, livestock production, nitrogen balance, nitrogen use efficiency, scenario analysis

HIGHLIGHTS

- Livestock manure was the main organic waste in urban and peri-urban areas.
- Manure production will increase by a factor of 3–10 between 2015–2050.
- Only 13%–38% of excreted N by livestock will be recycled in croplands.
- Intensification of urban livestock production greatly increased N surpluses.
- Reducing population growth and increasing livestock productivity needed.

GRAPHICAL ABSTRACT



ABSTRACT

Urban population growth is driving the expansion of urban and peri-urban agriculture (UPA) in developing countries. UPA is providing nutritious food to residents but the manures produced by UPA livestock farms and other wastes are not properly recycled. This paper explores the effects of four scenarios: (1) a reference scenario (business as usual), (2) increased urbanization, (3) UPA intensification, and (4) improved technology, on food-protein self-sufficiency, manure nitrogen (N) recycling and balances for four different zones in a small city (Jimma) in Ethiopia during the period 2015–2050. An N mass flow model with data from farm surveys, field experiments and literature was used. A field experiment was conducted and N use efficiency and N fertilizer replacement values differed among the five types of composts derived from urban livestock manures and kitchen wastes. The N use efficiency and N fertilizer replacement values were used in the N mass flow model.

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Livestock manures were the main organic wastes in urban areas, although only 20% to 40% of animal-sourced food consumed was produced in UPA, and only 14% to 19% of protein intake by residents was animal-based. Scenarios indicate that manure production in UPA will increase 3 to 10 times between 2015 and 2050, depending on urbanization and UPA intensification. Only 13% to 38% of manure N will be recycled in croplands. Farm-gate N balances of UPA livestock farms will increase to $> 1 \text{ t} \cdot \text{ha}^{-1}$ in 2050. Doubling livestock productivity and feed protein conversion to animal-sourced food will roughly halve manure N production.

Costs of waste recycling were high and indicate the need for government incentives. Results of these scenarios are wake-up calls for all stakeholders and indicate alternative pathways.

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1 INTRODUCTION

The urban population of Africa has increased > 16 times between 1950 and 2018, from 33 million to 548 million. During the same period the African component of the global urban population has increased from 4% to 13%. In 2050, Africa will have 22% of the global urban population with about 1.5 billion urban dwellers^[1]. This growing urban population is increasing urban food demand^[2] and is drawing food and nutrients from the proximate rural and peri-urban areas^[3]. Thereby, urbanization is aggravating soil nutrient depletion in rural areas, and this is a major constraint to agricultural production in many sub-Saharan African countries^[4,5]. Soil nutrient depletion is mainly due to nutrient removal through crop harvests and to limited nutrient replenishment via residues, manures and fertilizers^[6]. Thus, the increase in average yield of major cereal crops has been stagnating in this region; for example, it is $\sim 2 \text{ t} \cdot \text{ha}^{-1}$ in Ethiopia, while the global average is $> 3.5 \text{ t} \cdot \text{ha}^{-1}$ ^[5].

Ethiopia has a surface area of 1.1 million km^2 and had 109 million people in 2019 with a mean population density of 100 per km^2 . Most people work in agriculture ($> 80\%$) and live in the highlands in the center of the country on $< \text{half}$ of the total area, where rainfall ranges from 1000 to 2000 $\text{mm} \cdot \text{yr}^{-1}$. Ethiopian agriculture has a relatively high potential but would be considered to be largely undeveloped; as a consequence, Ethiopia has a precarious food security situation, also because of climate variability^[7,8].

In the process of urbanization, urban and peri-urban agriculture (UPA) is becoming more important in providing food mainly to urban people because increasing numbers of urban poor are engaged in diverse types of UPA systems as poverty alleviation strategies^[9,10]. Urbanization and income growth are also

deriving substantial increases in the demand for animal-sourced food and vegetables^[11,12]. Livestock farms are important among UPA farms in Ethiopia; these farms largely depend on animal feed scavenged from neighborhoods and feed imported from rural areas, as they have little or no land^[11]. The manure of the livestock, which contains 60% to 95% of the nutrients contained in the animal feed, are not used for manuring croplands, but are dumped into the urban environment, disregarded or used partly as biofuels^[11,13]. These manure disposal practices may create serious environmental^[11,14] and human health problems^[15] and are not sustainable because they waste non-renewable resources (e.g., phosphorus extracted from finite mineral deposits)^[16]. Thus, urban livestock manures and household wastes have to be seen as resources for enhancing crop yields and soil health^[13,17,18], and for realizing a circular economy^[19].

There are several reasons for not collecting and recycling urban livestock manures and household wastes, even though there is a large need for essential plant nutrients in the rural areas^[11,19,20]. First, there are cultural barriers and a poor infrastructure. Second, there is lack of data, knowledge and urgency at the policy level, and thus absence of effective policies and incentives for facilitating urban manure and waste recycling. In particular, there is lack of knowledge in urban communities and urban waste management agencies about the quantity and quality of urban livestock manures and household wastes that may be collected and recycled.

The main objective of the current study was to increase the understanding of possible development pathways for urban livestock farming and the recycling of urban livestock manures and household wastes. We selected a small city (Jimma) in Ethiopia for a case study and used survey data and a simple mass flow model to explore possible development pathways toward

2050. Our research questions were (1) how much nitrogen (N) in urban livestock manures will be excreted and household wastes produced in 2050 and how much may be collected and recycled in cropland, (2) what are the expected economic and environmental benefits of the urban manure and household waste collection and recycling, and (3) what is the fertilizer N replacement value of composts made from animal manures and kitchen wastes. Addressing this last question was based in part on a field experiment in which the effectiveness of urban livestock manures and kitchen waste composts was tested. We focused on N as key nutrient, although we acknowledge that manures and wastes contain all essential plant nutrients in various proportions as well as organic matter, which are all useful for soil fertility.

2 MATERIALS AND METHODS

2.1 Study site

In 2018, about 20% of the population in Ethiopia were living in cities, which is less than the African average. Projections indicate that the proportion of urban people will increase to 40% in 2050. The number of people in cities is expected to increase by on average 3%–4% per year^[1]. The capital, Addis Ababa, is the largest city with 3.4 million people in 2018, and there are about 20 cities with 0.1 million to 0.4 million people. One of these is Jimma with 0.2 million in the south-west of Ethiopia. It is situated at an altitude of 1780 m.a.s.l. and has a mean rainfall of 1500 mm·yr⁻¹. Wheat, barley, teff, maize, pulses and coffee are the commonest crops, and dairy cattle, goats and poultry the main farmed animal species in urban and peri-urban areas of Jimma city and the surrounding rural areas.

Urban, peri-urban and rural areas differ in population density, built-up areas, infrastructures and key economic activities^[21,22]. A city center with urban, peri-urban and rural areas were distinguished around the center^[23]. City centers and urban, peri-urban and rural areas are often an asymmetrical, uneven and multi-dimensional continuum. There are no distinct lines

separating the center from peri-urban, urban and rural settings, but often a slow zone of change exists^[24]. For the purpose of our study, we distinguished three zones around the city center of Jimma. Accordingly, Jimma consists of a circular city center surrounded by 5-km-wide urban and peri-urban zones and a 10-km-wide rural zone (Table 1), following the concepts and approaches of other researchers^[22,23,25]. We assumed that there was no agriculture in the city center^[26].

In 2015, there were about 500 urban and peri-urban livestock farms with, on average, 11.5 tropical livestock units per farm and little or no land and a few hundred crop farms with, on average, 1.5 ha (mainly vegetables, often with some animals)^[19]. Three types of livestock production were considered, namely milk (dairy cattle), meat (cattle, goats and poultry) and eggs (poultry); the relative proportions were based on farm surveys^[19]. Crop and livestock production was considered to be demand-driven; for 2015 we assumed a mean net protein intake of 17.6 kg·person⁻¹·yr⁻¹ (gross intake 22 kg·person⁻¹·yr⁻¹^[27]; 20% food losses^[28–30]), and that 14%^[28,31] of the protein intake is animal-derived. Mean net protein intake is below the recommended level but reflects the situation in Africa including Ethiopia^[27].

2.2 Scenario design

We designed exploratory scenarios^[32] and developed a simple N mass flow model (see supplementary materials) to estimate the effects of possible future developments on the amounts of N in urban livestock manures and household wastes that may be collected and recycled in cropland between 2015 and 2050, as well as the expected economic costs and environmental benefits of this recycling. Four possible development scenarios were explored: (1) a reference scenario (business as usual; BAU), (2) increased urbanization (URBAN), (3) intensification of UPA, especially livestock production (UPALP), and (4) increased technological development (TECH). The latter three scenarios (variants) were explored separately and combined (Table 2).

Table 1 Characteristics of the four circular zones of Jimma, Ethiopia in 2015 (after Tadesse et al.^[19])

Zone	Total area (km ²)	Population (million)	Population density (km ²)	Agricultural area (%)	Protein-N yield (kg·ha ⁻¹ ·yr ⁻¹)
City center	78	0.02	255	0	Not applicable
Urban zone	235	0.10	425	5	75
Peri-urban	392	0.15	382	20	60
Rural	1256	0.12	96	60	40

Table 2 Summary overview of the main variables of the scenarios (variants) explored in this study

Variable	Zones	Scenarios (variants)			
		Reference (BAU)	Increased urbanization (URBAN)	Increased UPA (UPALP)*	Enhanced technology (TECH)
Population growth (% per year)	Urban	3	5	5	2.5
	Rural	3	1	1	1
Change in protein consumption (% per year)	Urban	0	1	1	1
	Rural	0	1	1	1
Change in animal-sourced food consumption (% per year)	Urban	0	1	2	2
	Rural	0	1	1	1
Self-sufficiency animal-sourced food (%)**	Urban	20	20	40	40
	Rural	100 +	100 +	100 +	100 +
Decrease in cropland area (% per year)	Urban	0	2	2	2
	Rural	0	0	0	0
Increase in crop yield (% per year)	All	0	3	3	3
Food waste losses (%)	All	20	20	20	10
Feed scavenged from neighborhood (%)	All	20	10	10	10
Feed N conversion dairy cattle (%)	All	10	10	10	20
Feed N conversion beef cattle (%)	All	5	5	5	10
Feed N conversion poultry (%)	All	20	20	20	40
Manure & waste N losses during storage (%)	All	50	50	50	25
Manure and kitchen waste collection (%)	All	50	50	50	75
Sewage waste collection (%)	All	0	0	0	0
Composting losses (%)	All	30	30	30	30
N use efficiency of fertilizer N (%)	All	40	40	40	60
Fertilizer N effectiveness of compost (%)	All	40	40	40	60

Note: Urban zones include city center, urban and peri-urban zones (Table 1). UPA refers to urban and peri-urban agriculture. See text and supplementary materials for underpinning of the variables. *Scenario UPALP stands for an increased (doubling) of livestock production in UPA; **Shortages of animal-sourced food in urban and peri-urban areas were assumed to be covered by import from rural areas and in some cases from other areas/countries.

In BAU, the population growth was set at 3% per year in all four zones and it was assumed that protein consumption per capita, agricultural area, and crop and livestock productivity per hectare will remain constant. In URBAN, the population growth in the urban and peri-urban areas was set at 5% per year and in rural areas at 1% per year (Table 2). Urbanization was associated with a decrease in agricultural land in urban and peri-urban areas, which had implications for manure and waste disposal on agricultural land. UPALP was projected to be implemented through an increase in self-sufficiency in consumption of animal-sourced products in urban and peri-urban areas, from 20% to 40%^[28,33,34]. We assumed that 20% of the required animal feed was scavenged from the neighborhood (roadsides and open markets) and that the other 80% would come from cropland, based on data from farm surveys^[19]. The TECH

scenario assumed that the productivity and efficiency of crop and livestock production had doubled and that emission abatement measures were implemented to reduce N losses from manures and household wastes (Table 2). These measures include doubling the conversion of feed protein into animal-sourced food protein (through breeding and improved feeding), increased manure and kitchen waste collection, leak-tight and covered manure storage, and improved agronomic practices, to enhance the N use efficiency of fertilizer and compost N.

2.3 Calculations

A simple N mass flow model was developed in a Microsoft spreadsheet to explore the effects of the scenarios. Calculations

were done for the four zones of Jimma (Table 1) on an 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 NUFER model^[35,36] and followed the principles of mass flow analysis, in this case, of N. The fourth module was developed for the purpose of this study; it considered the costs of manure and waste collection, storage, composting, transport and compost delivery or marketing. Mean cost of compost production was estimated at 500 to 600 ETB·t⁻¹ of dry weight, currently equivalent to 15–20 USD·t⁻¹ of dry weight. This includes the costs for collection, transport, composting and delivery to the market. We assumed that a laborer can collect 2–4 t waste or manure per day for free, based on information from locals, labor costs of 5 USD·d⁻¹^[37], weight losses during composting of 30%–50%^[38,39], and additional transport and infrastructural costs of 1–5 USD·t⁻¹, depending on the area. The cost estimates were derived from interviews with locals; these estimates are uncertain, also because there are no existing commercial services for manure and waste collection, storage, composting, transport and delivery/marketing.

The model accounts for additional N inputs (via biological N₂ 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. One compound crop yield per zone was defined, which was either kept constant (in BAU) or increased over time (in the other scenarios; Table 2). The required additional N input via biological N₂ fixation and mineral N fertilizers (N-input_N; kg·ha⁻¹·yr⁻¹) was estimated from the following mass balance: $N\text{-input}_N = \text{crop protein-N yield} \times \text{NUE}^{-1} - (N\text{-input}_M \times \text{FRV}_M)$, 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), and NUE is the N use efficiency in crop production (%; ranging from 40% to 60%; Table 2). Farm-gate balances were derived from the difference between the inputs via imported animal feed (in UPA) and additional N (via biological N₂ fixation and mineral fertilizer), and the output of harvested crop and animal produce. A surplus on the farm-gate N balance reflects N losses via ammonia volatilization, nitrate leaching and denitrification. We assumed that the soil was not a (temporary) net source of N (there was no soil N mining), also not a net sink of N (there was no soil N sequestration).

The Microsoft spreadsheet model is available as a supplementary material.

2.4 Field experiment

Field experiments were conducted in 2015 and 2016 to estimate the fertilizer N replacement value of composts derived from cattle and poultry manure and kitchen waste. The study was conducted at Jimma University research station (see supplementary materials for research site description).

The field experiment was conducted as randomized complete block design with 13 treatments (Table S3). Treatments included three references (i.e., T1, unfertilized control; T2, half the recommended N and P application; and T3, full recommended N and P application, that is 100 kg·ha⁻¹ of diammonium phosphate (DAP) and 100 kg·ha⁻¹ of urea^[40,41]), and five types of composts (prepared from chicken manure, cattle manure, pig manure, farm yard manure and kitchen waste) applied at two rates (Table S3). Composts were collected at local farms. Each treatment was replicated four times. DAP contained 18% N and 20% P and urea contained 46% N. In both years, the experimental field was plowed using oxen-drawn implements and manually prepared for sowing. Wheat cv. HAR 3116 was the test crop and planted with 0.3 m row spacing. Plot size was 4 × 3 = 12 m². Composts and fertilizers were applied in planting rows a day before sowing. In 2015, grain and straw yields were recorded at harvest, and in 2016, whole plant samples were collected at booting stage (stage 10 of the Feekes development scale) from 50 randomly selected plants per plot for plant analysis (see supplementary materials).

Results of the field experiments were used to estimate: harvest index (%), apparent agronomic efficiency (kg·kg⁻¹), apparent N, P or K recovery efficiencies (%), partial factor productivity (kg·kg⁻¹), and the fertilizer replacement value (FRV, %) of composts (see supplementary materials).

3 RESULTS

3.1 Simulated changes in demography and food self-sufficiency

With a net population growth rate of 3% per year in the BAU scenario, Jimma will have a total population of 1.1 million in 2050 of which 70% will be living in urban and 30% in rural areas. In the URBAN scenario, with a population growth of 5% per year in urban and 1% per year in rural areas (Table 2), Jimma will have 1.7 million people in 2050, with 90% living in urban areas (Fig. 1).

The rural area produced a surplus of food in 2015 which also covered the demand by the urban dwellers. With rapid

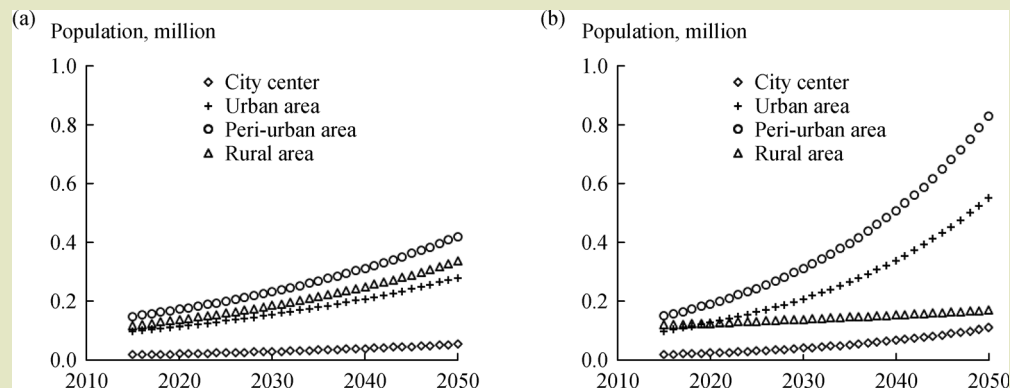


Fig. 1 Simulated changes in the number of people in the various zones in Jimma between 2015 and 2050 for (a) Reference (BAU) scenario, and (b) Urbanization (URBAN) scenario (See Table 2 for assumptions).

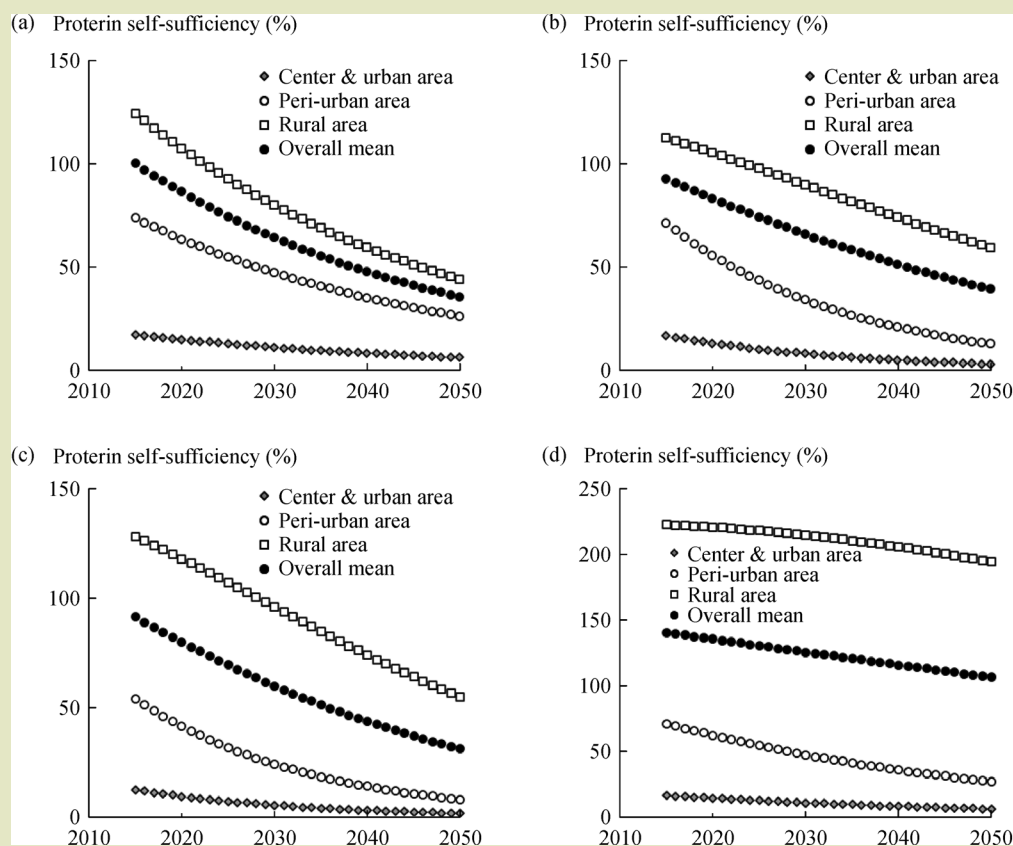


Fig. 2 Simulated changes in the self-sufficiency of crop production, to cover the demands for plant food and animal feed in the various zones in Jimma between 2015 and 2050 for four scenarios: (a) BAU, (b) URBAN, (c) UPALP, and (d) TECH (see Table 2 for assumptions). Self-sufficiency is defined here as the ratio of domestic production to total consumption (or demand); the latter is assumed to be equal to domestic production plus net imports. Self-sufficiency was 100% for the whole area in 2015, using the data presented in Table 1, and assuming a net protein intake of $17.6 \text{ kg} \cdot \text{capita}^{-1} \cdot \text{yr}^{-1}$, with 14% animal-sourced food.

population growth and stagnant yields in the BAU scenario, food self-sufficiency of the whole city area will decrease to 35% in 2050 (Fig. 2(a)). In the URBAN scenarios we assumed a steady crop yield increase of 3% per year^[42,43] (Table 2), but because of the increased population growth, food self-sufficiency will drop below 100% indicating the need to import food. To be able to remain food self-sufficient, population growth will have to be limited to 2.5% per year, crop productivity will have to increase by 3% per year^[42,43], and animal (dairy and beef cattle and poultry) productivity in terms of feed protein-N conversion (Table 2) has to double, as indicated in the TECH scenario (Fig. 2(d); Table 2). Further, animal-derived protein intake has to be limited to no more than 20%.

3.2 Waste and manure production

The modeled demographic changes had large impacts on the total mass of waste and manure N production. In the BAU scenario, total household waste N production and manure N excretion will almost triple between 2015 and 2050 (Fig. 3(a)). Animal manure N (cattle, goats and poultry) contributed 67%, kitchen waste 7% and sewage waste 26% to the total N

production. Household waste production will be greatest in the urban and peri-urban zones, while manure N excretion will be the greatest in the rural area; 18% of the manure will be produced by UPA livestock farms.

Household waste and manure N production will increase much faster in the URBAN scenario than in the BAU scenario (Fig. 3(b)). The projected increase was most notable in the urban and peri-urban areas of the UPALP scenario (Fig. 3(c)), because 37% of the total manure production will occur in the urban area (and 63% in the rural area). Animal manure will contribute 73% to the total production of waste and manure N, i.e., 6% more than in the BAU scenario because of the assumed increase in animal-sourced protein consumption (14%–19%). Total waste and manure N production will be lower in the TECH scenario than in the other scenarios (Fig. 3(d)) due to reduced population growth, halving of food wastes, and doubling of animal productivity (Table 2).

3.3 Waste and manure recycling

Only 18% of the amount of N in manures and kitchen wastes will

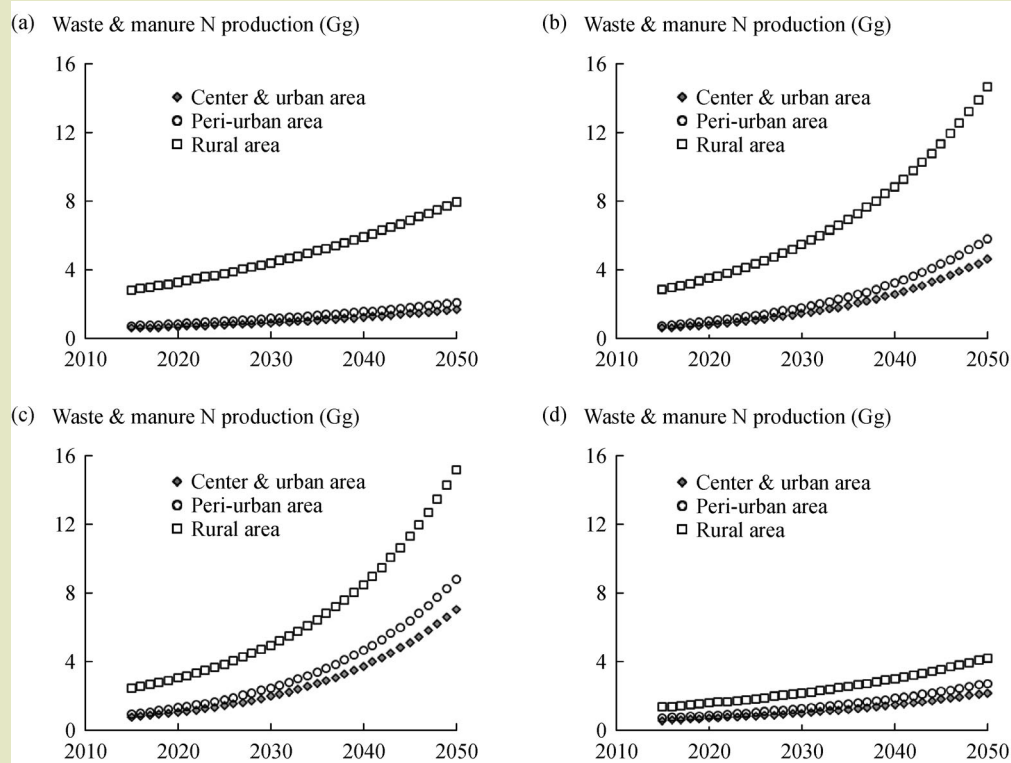


Fig. 3 Simulated changes in the total production of household wastes (kitchen and sewage) and animal manures from livestock in different zones of Jimma, Ethiopia for 2015 to 2050 in four scenarios: (a) BAU, (b) URBAN, (c) UPALP, and (d) TECH (see Table 2 for assumptions). There was no livestock production in the city center.

be recovered as compost for recycling to cropland in the BAU scenario (Fig. 4(a)). The remainder will be lost during storage and composting or not collected; we assumed that 50% will be collected (Table 2). Similar losses were assumed in the URBAN and UPALP scenarios (Fig. 4(b,c)).

No N from sewage waste is likely to be recovered because of cultural barriers. Losses of N from wastes and manures will occur during storage (estimated at 50%)^[39], during collection (estimated at 50%), mainly through neglect and disregard, and during composting (estimated at 30%), possibly through NH_3 volatilization, denitrification, leaching and runoff. In the TECH scenario we estimated that 39% of the N from kitchen wastes and manures will be recovered (Fig. 4(d)) because of improved collection and the use of emission mitigation techniques (Table 2).

The total amount of compost N available in 2050 is likely to range between 1.5 Gg (in the BAU) and 4 Gg (URBAN and UPLP) (Fig. 4). About 2 Gg N would be recovered as compost in

the TECH scenario, indicating that the reduction in waste and manure production outweighed the effects of emission mitigation and improved collection. Manures will have a share of about 90% in compost production (Fig. 4), with about 36% originating from UPA livestock farms.

The total cost of compost production will increase (Fig. 5) because the volume of compost increases but also because of assumed inflation (1% per year). The costs of compost, estimated at $500\text{--}600 \text{ ETB} \cdot \text{t}^{-1}$ of dry weight, currently equivalent to $15\text{--}20 \text{ USD} \cdot \text{t}^{-1}$ of dry weight, would lead to a competitive price when considering the amount of nutrients in the composts and the price of mineral NPK fertilizers without subsidies: $426 \text{ USD} \cdot \text{t}^{-1}$ of DAP and $355 \text{ USD} \cdot \text{t}^{-1}$ of urea.

Costs of composting were expected to increase threefold in the TECH scenario because of the investments in sheltered barns with leak-tight floors, and leak-tight and covered manure stores. These investments increased the fraction of waste and manure N recovered in compost (Fig. 5(d)), and the N content of the

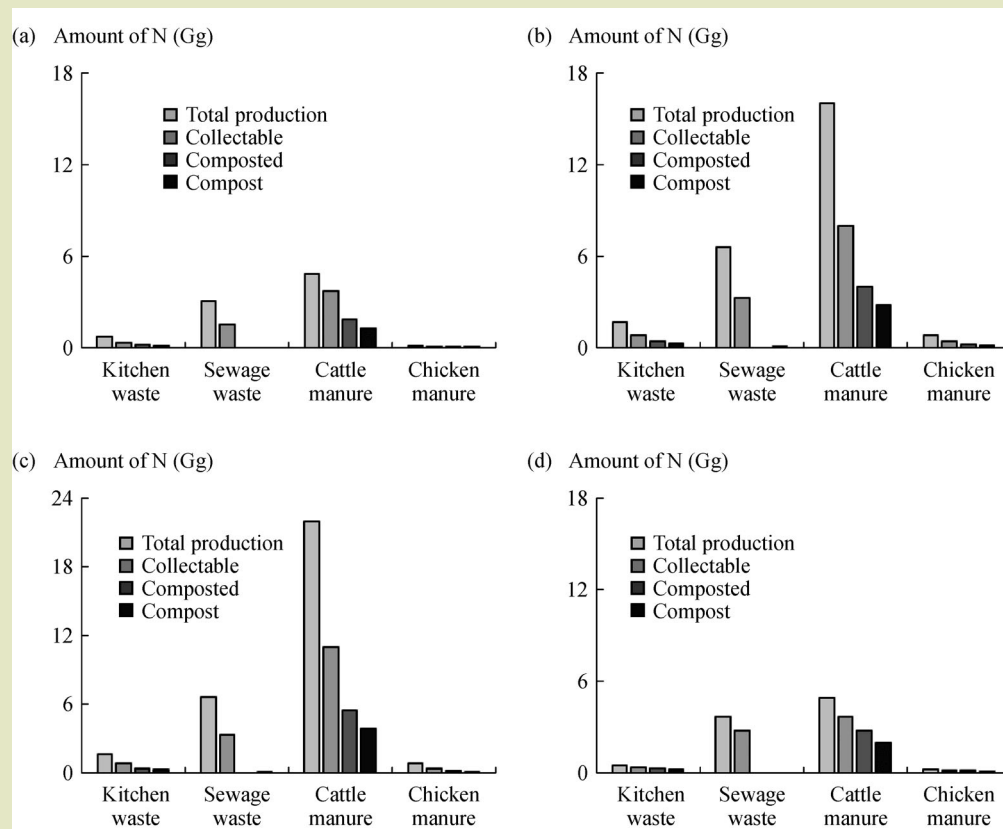


Fig. 4 Calculated amounts of nitrogen (Gg) in kitchen wastes, sewage wastes, cattle manures and chicken manures that will be produced, collected, composted, and recycled as compost in Jimma, Ethiopia in 2050 in four scenarios: (a) BAU, (b) URBAN, (c) UPALP, and (d) TECH (see Table 2 for assumptions).

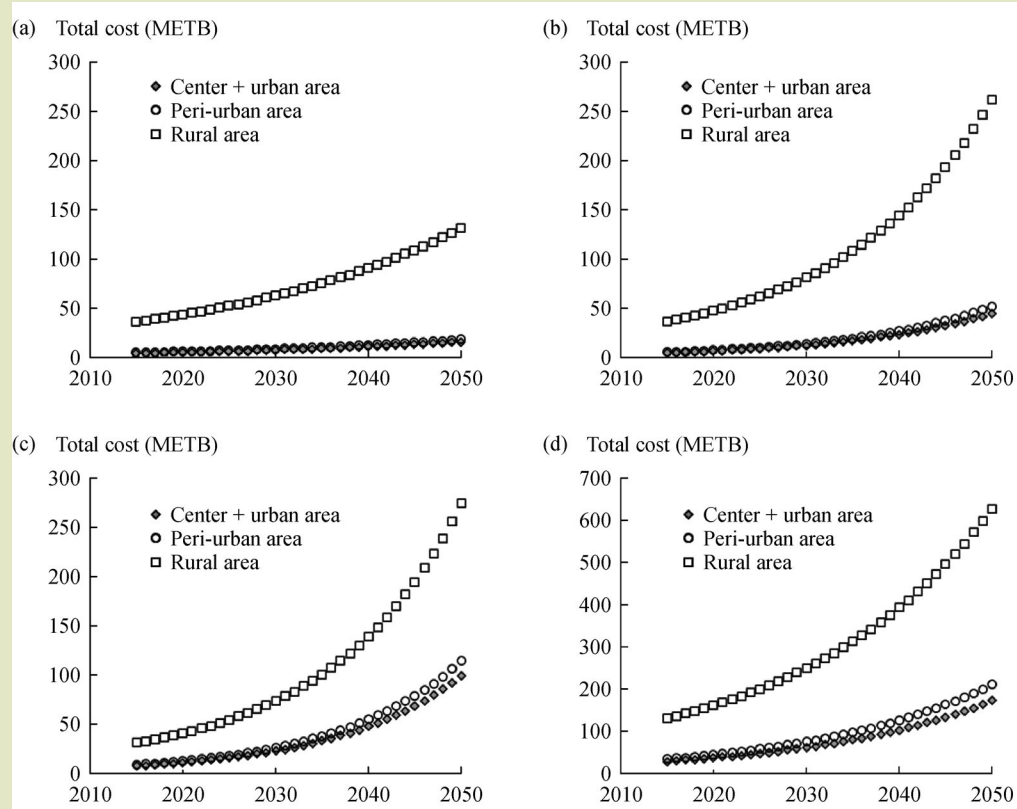


Fig. 5 Simulated changes in the total cost of collection, composting and transport of kitchen wastes and animal manures in different recycling zones of Jimma, Ethiopia for 2015 to 2050 in four scenarios: (a) BAU, (b) URBAN, (c) UPALP, and (d) TECH (see Table 2 for assumptions). METB = Million Ethiopian Birr.

compost, but made the compost less competitive relative to mineral fertilizers.

3.4 Fertilizer N replacement value of composted manures and wastes

Results of the field experiments show that nutrient (N, P, and K) contents of wheat plants at booting stage were significantly ($P < 0.05$) enhanced by most compost treatments (Table S4). Chicken manure compost was most effective in enhancing the N, P, and K contents at booting stage. The N contents of wheat plants at booting stage were close to the agronomic sufficiency range of 20–30 g·kg⁻¹ for N, 2–5 g·kg⁻¹ for P, and 15–30 g·kg⁻¹ for K^[44]. There was a relatively large within-treatment variation in N, P and K contents and a significant block effect in N and K contents (Table S5), which was likely the result of spatial variation in soil fertility. Most compost treatments increased grain and straw yields and N, P and K uptake compared to the unfertilized control (Table S6). The apparent agronomic efficiency and the apparent N recovery were on average lower

in compost treatments than in the DAP-urea reference treatments, for both N and P, indicating that the composts were less effective per unit of applied nutrient in enhancing grain yield than the synthetic fertilizers (Table S7).

The fertilizer N replacement value was about 30% for composts derived from cattle manures, farmyard manures and kitchen wastes, and about 60% for composts derived from poultry and pig manures (Fig. 6). Based on these results, we assumed a compost N efficiency value of 40% in the BAU scenario and 60% in the TECH scenario.

3.5 Nitrogen input-output balances

Simulated farm-gate N input-output balances were much higher in the UPA than in the rural area (Fig. 7). In the BAU scenario, N surplus in the UPA will increase from 240 kg·ha⁻¹ in 2015 to 480 kg·ha⁻¹ in 2050, and in the rural area from 90 to 150 kg·ha⁻¹. Farm-gate N surpluses in the UPA will increase rapidly in the URBAN and UPALP scenarios, especially in the urban areas (Fig. 7(b,c)) because of the increasing urban food demand and

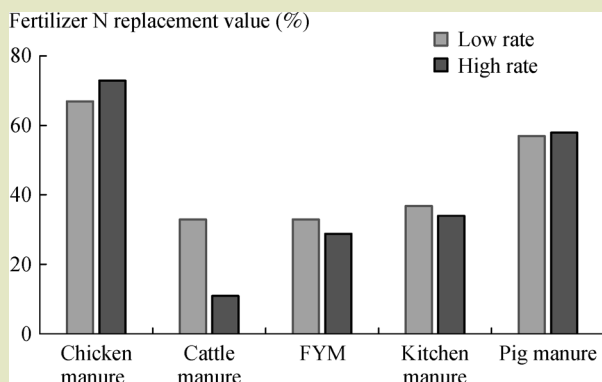


Fig. 6 Fertilizer N replacement values of composts from different sources, as derived from the results of the field experiments in Jimma, Ethiopia, in which the composts were applied at low and high application rates.

the corresponding intensification of urban livestock production. Increases will be much less in the TECH scenario (Fig. 7(d)) because of the assumed increase in food production efficiency and use of emission mitigation techniques. Calculated soil N balances (not shown) will be 1.5–5.5 times less than the farm-gate N balances in the UPA; this large difference reflects the loss of N from manures at the farmstead, i.e., from manure stores.

The N output/input ratio of the whole food production-consumption chain was 0.13 in BAU in 2015 (Fig. S2), indicating that an intake of 1 kg protein-N by Jimma residents required the input of 7.7 kg of additional N on average^[35,45]. The ratio will increase to 0.37 in BAU in 2050, reflecting an increase in the import of food from elsewhere (and hence the neglect of the N cost of producing that food). The N output/input ratio of the whole food chain will be 0.22–0.26 in the TECH scenario because of the more effective recycling of manure and waste N in crop production.

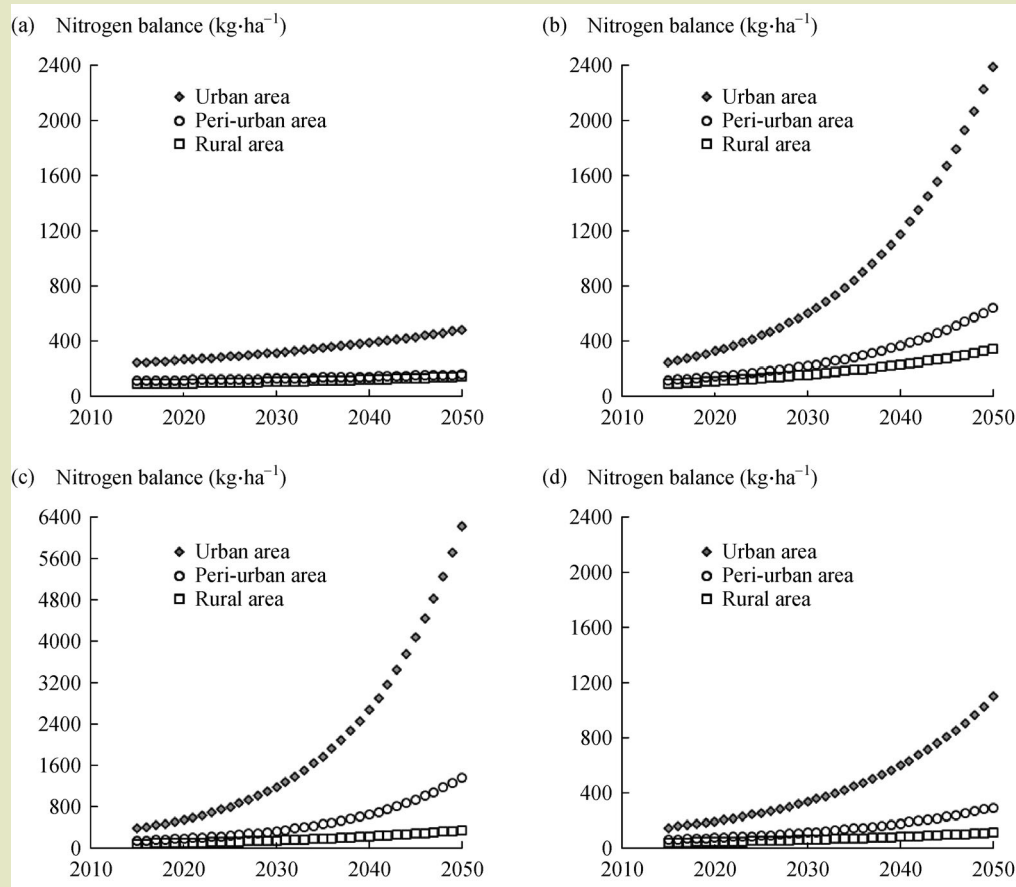


Fig. 7 Simulated changes in the N input-output balance of agriculture in different zones of Jimma, Ethiopia for 2015 to 2050 in four scenarios: (a) BAU, (b) URBAN, (c) UPALP, and (d) TECH (see Table 2 for assumptions).

4 DISCUSSION

4.1 Importance of urban livestock farming

UPA is important for nutritional security and poverty alleviation of urban households in Africa, and its importance is increasing over time^[46]. It has been suggested that the nutritional benefits of UPA livestock production outweigh the health risks involved^[47], though the latter cannot be ignored^[48]. Urban livestock farming in Africa is highly diverse in primary farming objectives including a survival strategy for poor urban residents and also increased income by established urban residents^[11], but dominated by smallholders^[49,50]. This contrasts with the increasing number of large specialized animal feeding operations in urban and peri-urban areas in countries with emerging economies such as China^[51], where the specialized pig and poultry farmers often partner with animal breeding or feeding companies (contract farmers). Basically, most UPA livestock farms around the world have a relatively high farm income from a small farm area^[11,51,52], and specialization and intensification are common trends^[53,54]. Common features of UPA livestock farms are also the need to import a large fraction of the required feed from elsewhere and the shortage of land for rational manure disposal. As a consequence, UPA livestock farms often have large manure nutrient surpluses^[11,52,55], as was the case in Jimma especially in the URBAN and UPALP scenarios (Fig. 7).

Scenario analysis is an important tool in exploring the effects of possible alternative developments for waste management during urbanization and UPA intensification^[56]. Increased recycling of organic wastes to supplement crop nutrient demand is an essential component of sustainable food systems^[57] and entails the concept of the circular economy^[58]. We built and used a simple N mass flow model for a circular city with four zones to explore possible development pathways of UPA and manure N recycling in Jimma, one of the many small but rapidly growing cities in Ethiopia (and other countries in Africa). The model was effective in examining the relationships between population growth, urbanization, UPA intensification, food production self-sufficiency and the recycling of N from manures and wastes during the next few decades. The size of the rural area around Jimma was chosen such that the overall mean population density in the four zones in 2015 was similar (200 km⁻²) to the mean population density in those areas of Ethiopia where most people live and where most of the food is produced. Thus, the cropland and rural areas may not be extended easily when population increases in Jimma; it would be at the expense of other people's needs.

Total manure N production in the urban and peri-urban areas will likely increase by 3–10 times over the next three decades.

Increases were especially large in the URBAN and UPALP scenarios (Fig. 3) as a result of the expected population growth, urbanization and UPA intensification. Manure N production had an estimated share of 56%–73% in the total waste and manure production in Jimma, even though animal-sourced protein was only a small fraction (14%–19%) of the total protein intake of residents, which is below the world average but close to the animal-sourced protein intake recommended from environmental points of view^[59,60]. Kitchen wastes had a share of 4%–7% and sewage wastes of 21%–40% in the total manure and waste N production. Manures from UPA livestock farms were the main source of organic wastes in the urban environment, and are the targeted resource for nutrient recycling. Though sewage waste was also a significant source of N (and other nutrients and organic carbon), we did not consider its recycling because of cultural barriers. Neglecting the recycling of human waste leads to a loss of plant nutrients^[61].

Urbanization and UPA intensification strongly increased the farm-gate N balance of UPA (Fig. 7). The farm-gate N balance is an indicator of the pressure of agriculture on the environment^[45,62]. Clearly, the pressure on the environment will greatly increase over time in the URBAN and UPALP scenarios to a level where the livestock farms will become major sources of environmental pollution unless drastic measures are adopted, as examined in the TECH scenario (Fig. 3(d)).

Three main changes were incorporated in the TECH scenario, i.e., a halving of the urban population growth, a doubling of animal productivity (doubling of feed protein-N conversion) and N use efficiency in crop production, and a halving of food wastes and N losses from manure stores. Reducing the population growth in the urban area from 5% to 2.5% and doubling animal productivity will be needed to achieve self-sufficiency of crop protein production and to cover the demands for plant food and animal feed (Fig. 2). Doubling animal productivity via doubling the feed protein-N conversion also halved manure N production, and combined with a 50% reduction in manure N losses greatly contributed to a reduced growth of the N surpluses (Fig. 7). Clearly, drastic improvements in productivity and N use efficiency of UPA livestock farming will greatly contribute to food self-sufficiency and environmental sustainability.

4.2 Recycling manure N from urban livestock farms

Many UPA livestock farms in Ethiopia do have some land for cropping, grazing and manure disposal^[11,52], but the area is insufficient to provide the required feed and to dispose of all the manure in an agronomically and environmentally sound

manner. Therefore, most of the feed is imported from the rural areas, but we assumed that 20% of the required feed of UPA livestock will be scavenged from the neighborhood, based on earlier surveys^[19]. Unexpectedly, the amount of manure N that may be recovered in compost in the urban area was insufficient to cover the total N demand by all cropland in the urban area according to our model calculations. The shortage of N is related to the relatively high N demand of the cropland and the poor manure N recycling efficiency; in BAU only 18% and in TECH 38% of the excreted N in manure is recovered as compost, and utilized with a fertilizer N replacement value of 40% (Table 2; Fig. 6). This poor recycling efficiency is consistent with a literature review that indicates that N losses from manure stores in Africa range roughly from 40% to 70%, depending on manure quality and storage conditions^[39]. A large fraction is not collected and recycled because of various barriers^[63]. In BAU, a total of 0.34 Gg N will be recovered as compost N in the urban and peri-urban areas by 2050. The amount of compost N will be 1.73 Gg N in the UPALP scenario, and 0.8 Gg N in the TECH scenario. These numbers compare fairly well with estimates of the manure recycling potential in other East African cities currently, e.g., Nairobi^[64] and Kampala^[65].

In addition to the large losses and poor recycling efficiency of the wastes and animal manures (Fig. S2), the fertilizer N replacement value of the composts was relatively low. The nutrient supply from organic amendments to crops is usually expressed as a fertilizer replacement value. A proper comparison per nutrient element requires that other essential nutrients are not limiting crop yield and nutrient uptake, following the *ceteris paribus* principle^[66]. However, we were interested in the overall fertilization effect of the compost; the apparent fertilizer N replacement value of the composts examined in the field experiment ranged from 11% to 73% (Fig. 6). Compost type was more important than compost application rate according to our field experiment. Grain yield of the control treatment was low, indicating that the site had low inherent soil fertility (Table S6) and thus we expected a high fertilizer N replacement value (close to 100%) because of the multiple nutrients applied in compost^[67,68]. However, the fertilizer N replacement value was on average much less than 100%, likely because a large fraction of the N was organically bound and had to be mineralized before becoming available to crops^[69,70]. A strategy with integrated application of compost and mineral fertilizer would likely lead to a higher N use efficiency. Likely, the fertilizer N replacement values of the compost will increase over time, when applications will be continued^[65]. Further, the response was variable, which was likely related to spatial variation in soil fertility and to the heterogeneity of the composts.

Compost applications did reverse the negative N, P and K balances of the control treatment to positive balances (Table S7), indicating that recycling of composts contributes to reversing soil mining, which is the current practice in rural areas^[11,71]. The possible presence of plastics, pollutants, pharmaceutical compounds and veterinary products such as hormones and antibiotics in manures and wastes are sometimes challenges for environmentally sound recycling practices^[72–74] and food safety^[75,76]. The impact of plastic waste is currently increasing in urban areas^[76,77].

4.3 Costs and benefits of recycling manures

Recycling manures may have multiple benefits including soil fertility replenishment, increasing crop yields, fertilizer savings, and diminishing environmental pollution associated with dumping and/or disregarding manures. However, the manures have to be collected, stored properly and applied to cropland at the right place and time, and in the right amounts, to be able to provide these benefits. There is also competition from alternative uses in the rural areas (building materials and biofuel). Subsidizing mineral fertilizers in Ethiopia also does not facilitate manure recycling, although there are various constraints to transporting the fertilizers to the rural areas^[78,79].

The calculated cost of recycling manures will increase over time because the amounts of manure will increase. Most costs are for the rural area because most manure is produced there, also in the UPALP scenarios (Fig. 5). The introduction of covered and leak-tight manure stores and increased manure collection efficiency in the TECH scenario (Table 2; Fig. 4(d)) will increase the cost of compost (Fig. 5(d)) threefold and make the compost less competitive relative to mineral fertilizers. The cost of covered and leak-tight manure stores was estimated to be relatively high per unit of composted manure because of the high number of smallholdings. The question is whether such investments can be made economically attractive for smallholders. Another question is whether the future is more in the direction of mixed crop-livestock farms with sufficient land for manure disposal, or in the direction of large technically-advanced and confined animal feeding operations with high manure N recovery efficiency potential.

The results of the current scenario analyses are not free of uncertainties. We made several assumptions and gross simplifications for estimating possible future developments and pathways. Uncertainties arise from the assumptions of model parameters, population growth, crop yields, cropping areas,

number of farms and animals, and the economic costs of manure and waste collection, composting and redistribution. The livestock sector responds to changes in local and global markets, availability of new technology, and government policies. Conflicts and migration may also play a role. Thus, more dynamic modeling approaches, more diverse scenarios and also consideration of long-term effects of manure and fertilizer applications on soil fertility will be needed^[80] in future studies.

5 CONCLUSIONS

Urbanization and intensification of UPA livestock production are partly entwined in Africa. Both are driven by population growth and have large effects on regional food self-sufficiency and on the potential for recycling of manures and wastes over the next few decades as indicated by our scenario analyses for Jimma, a small city in Ethiopia. Livestock manure was by far the main organic waste in the urban and peri-urban areas, even though only 20%–40% of animal-sourced food consumed was produced in those areas and only 14%–19% of the protein intake by the people was animal-sourced. Manure production in the urban and peri-urban areas is expected to increase by 3–10 times from 2015 to 2050 depending on scenario, but only about 13%–38% of the manure N will be recycled in cropland according to our model calculations.

The expected population growth of 3%–5% per year is threatening the food self-sufficiency of Jimma over the next few decades, even under the assumption of an annual increase of

3% in compound crop yields. At the same time, mean farm-gate N balances of UPA farms will increase to over $1 \text{ t} \cdot \text{ha}^{-1}$ in 2050 because of the enhanced import of animal feed, and thus are threatening the environmental sustainability of the food system.

The TECH scenario highlights three important messages for diminishing the pressures on food security and environmental sustainability: (1) the need for reduced population growth and urbanization (family planning policy and health extension to control unprecedented population growth, the related rural-urban migration and urban population growth in Ethiopia), (2) the need to substantially increase crop and livestock productivities (feed conversion efficiency and N use efficiency), and (3) the need to substantially improve manure and waste recycling through improved collection and reduced losses during storage. The first two have greater impacts on diminishing the identified pressures than the last one.

Although the costs of manure and waste recycling will increase greatly, our modeling indicates that the cost of the resulting composts will be comparable to the cost of mineral fertilizers, per unit of N and P, which suggests that the composts would be economically compatible. However, it is possible that little waste and manure from the urban and peri-urban areas will be recycled because of informational, cultural and technical barriers, which highlights the need for incentives from government. There is a need for real-world validation and further exploration using more refined models and farm survey data. There is also a need for discussions with stakeholders and policymakers.

Supplementary materials

The online version of this article at <https://doi.org/10.15302/J-FASE-2020375> contains supplementary materials.

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Compliance with ethics guidelines

Solomon Tulu Tadesse, Oene Oenema, Christy van Beek, and Fikre Lemessa Ocho declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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