Network analysis of N flows and food self-sufficiency: a comparative study of crop-livestock systems of the highlands of East and southern Africa

M.C. Rufino, Pablo Tittonell, P. Reidsma, Santiago Lopez Ridaura, H. Hengsdijk, K.E. Giller, A. Verhagen

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ORIGINAL ARTICLE

Network analysis of N flows and food self-sufficiency—a comparative study of crop-livestock systems of the highlands of East and southern Africa

M. C. Rufino · P. Tittonell · P. Reidsma · S. López-Ridaura · H. Hengsdijk · K. E. Giller · A. Verhagen

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Abstract Smallholder farming systems in sub-Saharan Africa are often nutrient-limited, and therefore imports must be increased to compensate exports and losses. To explore whether the properties of nutrient cycling networks relate to the systems' capability to sustain rural families, we investigated N flows within contrasting crop-livestock systems in Ethiopia, Kenya and Zimbabwe applying concepts from ecological network analysis. Farm households were conceptualised as networks, the compartments were the household and their farming activities which were connected by the N flows. Indicators assessing network size, activity and cycling, and the organisation and diversity of the N flows were compared with system productivity and food self-sufficiency. Results showed that organisation and diversity of N flows to, from and within the farm households differed more between farms of different resource endowments than across sites. The amount of N cycled per household was small and comparable across sites: less than 25 kg N year^{-1}, and for the poor households less than 5 kg N year^{-1}. Poor households with soil N stocks that were 50–60% smaller than wealthier households depended more on external inputs (e.g. a dependence of 65% vs. 45% in Zimbabwe). Productivity was positively related to network size, its organisation and N cycling, but utilisation efficiencies were different across sites in relation to soil N stock and the importance of livestock for N flows. Greater size of the N flow network and its organisation led to increased productivity and food self-sufficiency, reducing dependence, which may increase the adaptability and reliability of smallholder crop-livestock systems.

Keywords Diversity · Intensification · Integration · Farming system analysis · Dependence

M. C. Rufino (✉) · P. Tittonell · P. Reidsma · K. E. Giller
Plant Production Systems Group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands
e-mail: mariana.rufino@wur.nl

M. C. Rufino · H. Hengsdijk · A. Verhagen
Plant Research International, Wageningen University and Research Centre, P.O. Box 16, 6700 AA Wageningen, The Netherlands

S. López-Ridaura
INRA UMR Innovation, 2 Place Viala, 34060 Montpellier, France

Present Address:
P. Tittonell
Unité de Recherche Systèmes de Culture Annuels, CIRAD-Persyst, TA B 102/02 Avenue Agropolis, 34398 Montpellier cedex 5, France

Introduction

Beyond the diversity of livelihood strategies among rural households in sub-Saharan Africa, their subsistence relies largely on the use of natural resources.

Nutrients often limit productivity of smallholder farming systems. Although it is broadly recognised that the input of nutrients to the farming systems in sub-Saharan Africa should be increased to compensate for exports and losses (e.g. Nandwa 2001; Okalebo et al. 2006; Zingore et al. 2008), the efficiency of nutrient use depends largely on the recycling capacity of the system (Van Noordwijk 1999). This is particularly the case for N, which is used in large amounts by crops, animals and humans and is prone to loss from the agro-ecosystem (Giller et al. 1997). In environments where supply of external inputs is uncertain, conservation and recycling of nutrients may help to sustain food production (Ruben et al. 2006). When food markets are missing or failing as is often the case in poor policy environments, food self-sufficiency becomes a sensible strategy to secure food. Food self-sufficiency needs to be achieved with rather scarce (nutrient) resources that need to be used efficiently.

In this study we explore whether the properties of nutrient cycling networks relate to the capacity of the systems to sustain rural families. The study focuses on crop-livestock systems because (1) they support the largest number of resource poor-people in sub-Saharan African (Thomas and Rangnekar 2004) (2) they are diverse in farming activities, which may allow recycling of nutrients within the system, and the analysis of nutrient use efficiencies, and (3) the degree of integration of their cropping and livestock activities gives an indication of their position along an evolutionary line towards increasing intensification and decreasing dependence on (communal) natural resources (McIntire et al. 1992; Powell et al. 1996; Baltenweck et al. 2004). Nutrients enter the farm system mostly through livestock grazing in communal areas or through agricultural inputs, and transfers take place among the different compartments of the farm household system, such as the different cropping and livestock units and the household (Rufino et al. 2009a). The diversity in system compartments (or activities), their integration, and the magnitude of the nutrient transfer flows are largely the result of management (Ruben and Pender 2004).

We investigated the characteristics of N flows and cycling in contrasting African crop-livestock systems using concepts from ecological network analysis (Fath and Patten 1999; Ulanowicz 2001), and related them to farm system performance. Network analysis (NA) is an input-output analysis in which systems are conceptualised as networks of interacting compartments exchanging inputs and outputs representing different resource flows (Fath and Patten 1999). Based on the size and organisation of resource flows a series of indicators can be calculated to assess the integration and diversity of systems. Rufino et al. (2009a) showed that concepts of NA can also be used to study nutrient flows in agro-ecosystems. The main guiding question of this study was to know the extent at which indicators applied to nutrient cycling networks relate to the capacity of smallholder crop-livestock systems to sustain rural families. Our objective was to study the network size, integration, organisation and diversity of N flows within contrasting crop-livestock systems and their relation to system productivity, and to household food self-sufficiency. Smallholder crop-livestock farming systems from Ethiopia, Zimbabwe and Kenya were used as case studies.

Methods

Network analysis

Conceptualisation of the system

A farm household is conceptualised as a network in which the nodes are compartments defined to represent resource allocation by the household, and include the different crop fields (cropping activities), the livestock units (livestock activities), the organic resource management activities (composting activity), and the household (including the family members). A system is then defined by its compartments (H_i), the change in their stock ($\dot{x}_i$), the inflows (z_{i0}) and outflows (y_{0i}) between the compartments and the external environment, and the internal flows between compartments (e.g. f_{ij} represents an internal flow from H_j to H_i). Figure 1 illustrates the simplest network, a system with two compartments, H_1 and H_2, for which the stock x_1 and x_2, and the flows y_{01}, z_{01}, f_{12}, f_{21}, y_{02} and z_{20} may be identified. In this analysis we expressed flows in kg N year^{-1}, and stock and compartmental size in kg N. For N flows from one compartment ($j = 0,\ldots, n$) to another ($i = 1,\ldots, n, n+1, n+2$), $n+1$ accounts for usable exports (e.g. grain, milk) and $n+2$ accounts for unusable exports or dissipations (e.g. animal excreta

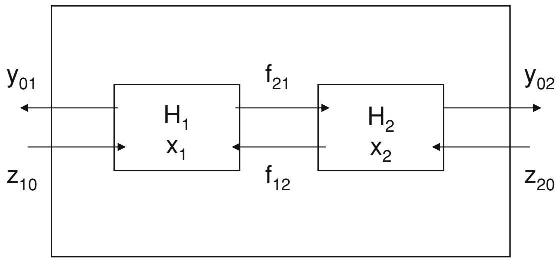


Fig. 1 System representing a network with two compartments H_1 and H_2, and their respective stock x_1 and x_2, the internal flows f_{12} and f_{21}, and exchanges from (z_{10} and z_{20}) and to the external environment (y_{01} and y_{02}). The *rectangular box* defines the system boundaries. Source: Finn (1980)

left in the communal grasslands). A compartment $j = 0$ was defined to keep track of the imports. Stock in livestock compartments is an estimation of the amount of N contained in the animal mass (kg N), while for crop field compartments stock is an estimation of the amount of N contained in the 0.3 m top soil layer (in kg N). We selected a number of NA indicators to characterise the size, integration, diversity and organisation of the networks of N flows (Table 1), as discussed in detail Rufino et al. (2009a).

Indicators of network size, activity and integration

Indicators to assess network size, activity and integration in agro-ecosystems were derived from the flow analysis in ecosystems by Finn (1980) (Table 1). Imports (IN) is the amount of N that is imported from the external environment into the farm household system (Eq. 1). Total inflow (TIN) into the system is the sum of N flows from external inputs (z) into all compartments ($H_{i,\ldots,n}$) plus the amount of N contributed to the system total flows by the stock of all compartments $(\dot{x}_i)_-$, i.e. the negative changes in the stock (Eq. 2). The compartmental throughflow (T_i) is

Table 1 Indicators used in the network analysis of N flows in agro-ecosystems and their calculation

Indicator	Calculation		Reference
Indicators of network size, activity and integration			
Imports	$\mathrm{IN} = \sum_{i=1}^{n} z_{i0}$	(Eq. 1)	
Total inflow	$\mathrm{TIN} = \sum_{i=1}^{n} z_{i0} - \sum_{i=1}^{n} (\dot{x}_i)_-$	(Eq. 2)	Finn (1980)
Compartmental throughflow	$T_i = \sum_{j=1}^{n} f_{ij} + z_{i0} - (\dot{x}_i)_-$	(Eq. 3)	
Total system throughflow	$\mathrm{TST} = \sum_{i=1}^{n} T_i$	(Eq. 4)	
Total system throughput	$T_{..} = \sum_{i,j=1}^{n} T_{ij}$	(Eq. 5)	Patten and Higashi (1984)
Finn's cycling index	$\mathrm{FCI} = \frac{\mathrm{TST_c}}{\mathrm{TST}}$	(Eq. 6)	Finn (1980)
Dependence	$D = \mathrm{IN}/\mathrm{TST}$	(Eq. 7)	
Indicators of organisation and diversity			
Average mutual information	$\mathrm{AMI} = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T_{..}} \log_2 \frac{T_{ij} T_{..}}{T_{i.} T_{.j}}$	(Eq. 8)	Ulanowicz (2001), Latham and Scully (2002)
Statistical uncertainty (diversity)	$H_R = -\sum_{j=0}^{n} \frac{T_{.j}}{T_{..}} \log_2 \frac{T_{.j}}{T_{..}}$	(Eq. 9)	
Indicators of productivity and efficiency			
Biomass production	$B = \sum_{i=1}^{n} \frac{\mathrm{Yield}}{\mathrm{HI}}$	(Eq. 13)	
Apparent conversion efficiency	$\mathrm{CE} = \frac{\mathrm{B}}{\mathrm{IN}}$	(Eq. 14)	
Food self-sufficiency ratio	$\mathrm{FSSR} = \frac{\sum_{i=1}^{n} \mathrm{EY}_i}{\mathrm{ER\_household}}$	(Eq. 15)	

Notation: z_{i0} are N inflows to each system compartment (H_i) from the external environment, $\dot{x}_i$ represents the change in stock of a compartment and f_{ij} represents internal flows between compartments (e.g. from H_j to H_i), HI is the crop specific harvest index, EY is the edible yield converted into energy units, and ER_household is the energy requirement of the household the sum of all flows coming into compartment H_i from other compartments (f_{ij}) and from the exterior (z), minus the N outflows from compartment H_i (the negative changes in stock $\dot{x}_i$) (Eq. 3). The total system throughflow (TST) is the sum of all compartmental throughflows (T_i) in the system (Eq. 4), and it represents the mobile N pool in the system associated with the system's actual production (activity). The total system throughput ($T_{..}$) is the sum of all inflows and outflows of N to and from all the compartments of the system (Eq. 5), representing the total size of N flows. The Finn's cycling index (FCI) is the proportion of TST that is recycled within the system (Eq. 6), and was proposed to be used to assess the degree of integration in agro-ecosystem (Rufino et al. 2009a). To calculate FCI, it is first necessary to estimate the relative cycling efficiency for each compartment, which is the ratio between internal inflows:outflows to and from all system compartments. The sum of all the weighted relative cycling efficiencies in the system is the total cycled system throughflow (TST_c). Dividing TST_c by TST gives the FCI. The FCI takes values between 0 and 1 (or 0–100%), with these extremes indicating either no recycling or complete recycling. The dependence of the system on external inputs (D) is calculated as the ratio IN/TST (Eq. 7). A value of D close to 1 means that the system activity largely depends on external inputs, a value close to 0 means that the stocks support the system activity.

Indicators of organisation and diversity

Two measures are used to assess the organisation and diversity of the network connections (Table 1). These measures that come from communication theory are the average mutual information (AMI) and the statistical uncertainly (H_R) (Latham and Scully 2002). AMI quantifies the organisation of the flows in the network (Eq. 8), measuring the information associated with the exchange of material, in this case N, within the system. The log term of Eq. 8 calculates the conditional probability that a flow entering H_i came from H_j. That probability is the fraction of the flow f_{ij} to all flows that enter H_i, divided by the product of the fractions of T_i and of T_j to the total system throughput $T_{..}$. Each of these conditional probabilities are weighted by the joint probability of that flow ($T_{ij}/T_{..}$), and these weighted 'constraints' are summed over all combinations of i and j in the network. In a system where the total flow is divided equally among all the compartments, and all the compartments are connected, AMI will be 0 or very close to 0. If a few flows, which are a large proportion of $T_{..}$, connect a few compartments, the value of AMI will approach its upper boundary. In natural ecosystems for which it has been estimated AMI typically takes on a narrow range of values, from 0 to ca. 6 (Patten 1995). H_R is the upper bound for AMI, and represents the diversity of flows given a certain amount of throughput ($T_{..}$) (Eq. 9). When the contribution of the flow out of a compartment (represented by $T_{.j}$ in Eq. 9) to total throughput ($T_{..}$) is small and different across compartments, diversity increases, i.e. the pattern of flows in the network deviates from being equally sized flows. H_R increases when $T_{..}$ is partitioned among a greater number of flows. Both AMI and H_R are measured in bits, which relates to the concept of binary decisions; one bit represents one binary decision. For more detail on AMI and its derivation we refer to Latham and Scully (2002).

Indicators of productivity and efficiency

Total biomass production (kg DM per farm) was calculated as the sum of aboveground biomass (yield of harvestable parts/harvest index) measured at each field cropped by the household (i.e. including food, fodder and cash crops but not communal grasslands) (Eq. 13). The ratio between total biomass production and IN (Eq. 14) was calculated as a rough measure of the capacity of the system to convert N inputs into biomass (CE = conversion efficiency). Food self-sufficiency was calculated as the food self-sufficiency ratio (FSSR) between energy in the food produced on-farm (including animal products) and energy requirements by the household (Eq. 15). We converted the harvested product destined to self-consumption into energy equivalents using standard values of energy content in food products (USDA Nutrient Data Laboratory 2007), and estimated household energy needs using an average of 9 MJ day^{-1} capita^{-1} (Bender 1997).

Case studies

The analysis included smallholder crop-livestock systems from three case study sites in highland areas of sub-Saharan Africa: Teghane village (13°45′N, 39°41′E) in Tigray, northern Ethiopia; Chiwara village (17°51′S, 31°49′E) in Murewa, north eastern

Zimbabwe; and Mutsulio village (0°12′N, 34°48′E) in Kakamega, western Kenya (Table 2). In the three sites smallholder subsistence crop-livestock systems predominate (0.5–3.0 ha in size), with cereals as staple food. The sites differ in population density, agro-ecological potential (rainfall and soils) and the relative importance of livestock, with Kakamega at one extreme having the highest annual rainfall, the highest population density, and the smallest number of livestock per household, and Tigray at the other extreme with the lowest annual rainfall, the largest herds and a population density comparable to that of Murewa. Whereas the relatively rich soils and good climate of Kakamega allow growing cash crops such as tea and coffee, steep slopes, stony soils, frost risk and rainfall limited to a short period of the year constrain agricultural production in Tigray. A major difference between sites resides also in the type of livestock feeding system, which is based on grazing of communal pastures in Tigray and Murewa and a cut-and-carry system (zero grazing) in Kakamega. In all cases livestock are fed crop residues and their manure is used to fertilise crops.

Household surveys were conducted at the three sites to collect information on family composition, land use and resource endowment (in 2002 at Tigray, 2002/2003 at Murewa, and 2002 at Kakamega). Households at the three sites were categorised according to their resource endowment into poor, medium and wealthier households using site-specific criteria and thresholds, such as area farmed, livestock owned, food security, labour availability, market orientation or access to off-farm income. At each site, a sub-sample of farms was selected to represent each of the three wealth categories identified. These farms were characterised in detail, through delineation of resource flow maps (input use, resource allocation, production and marketing), soil sampling and laboratory analysis, crop yield and livestock production estimations and labour calendars. The detailed information obtained allowed us to quantify N stocks (in soils and animals) and flows to, from and within the systems to conduct the network analysis. We focused on the flows that are managed by the household. Detailed information on the household surveys, typologies and methodologies for detailed characterisation can be found for Tigray in Abegaz et al. (2007) and in Mulder (2003); for Murewa in Zingore et al. (2007) and Tittonell et al. (2005) for Kakamega.

Approach

We constructed the N flow networks for nine selected farms, representative of each wealth class at each site, and calculated the indicators described in Table 1. The resource flows obtained from the field assessments were converted into the common currency 'kg N' by using conversion coefficients from literature (e.g. N content in different crops and crop parts, in manure, in food) as explained in detail in Rufino et al. (2009a). Four types of flows were defined: internal transfers, inflows and outflows from and to the external environment (imports and exports), and dissipations (i.e. amounts of material that cannot be re-used such as N lost through burning of crop residues). In NA of natural ecosystems (e.g. forest, marine estuaries) indicators are usually expressed as amounts of matter (e.g. g or kg) per unit of time (e.g. year) and per unit of area (e.g. m^2). Here, we normalised the measures of flow size organisation on a per capita basis (kg N $capita^{-1}$ $year^{-1}$) considering the number of family members per household. We chose not to normalise per area to avoid comparing measures that would be out of proportion across household wealth classes and environments. For instance, inflows of N by a head of livestock would yield widely different normalised indexes for a farm of 0.3 ha versus one of 1 ha.

The intake of N from grazing on communal lands was considered as an inflow to the farm household system, and the excreted N off-farm was considered an outflow. Intake and excretion of the livestock was estimated for Tigray using a simple livestock model from the NUTMON toolbox (Vlaming et al. 2001) that uses as inputs animal type, animal size, grazing time and feed availability in the pasture, and feed supplemented on-farm. Because complementary and more detailed information on livestock feeding, and livestock management was available for the case studies at Murewa (Dury 2007) and western Kenya (Castellanos-Navarrete 2007), estimations of livestock intake and excreta were made using the LIVestock SIMulator (LIVSIM) model (Rufino et al. 2009b). For the cropping activities, N flows were derived from measured yields, and from biomass estimates using harvest indices. We included a compartment representing the management unit used to recycle animal manure and to compost other organic residues. Based on the farm survey data, the household consumption and selling of

Table 2 Main biophysical and socioeconomic characteristics of the crop-livestock systems analysed

	Tigray (N Ethiopia)	Murewa (NE Zimbabwe)	Kakamega (W Kenya)
Altitude (m.a.s.l)	2,700–2,900	900–1,400	1,400–2,000
Average annual temperature (°C)	18–21	18–23	18–22
Rainfall (mm)	540 (270–810)	830 (750–1,000)	1,990 (1,750–2,100)
Rainy season(s)	Unimodal (3 months)	Unimodal (5 months)	Bimodal (10 months)
Topography	Very undulating (escarpments)	Gently undulating	Moderately to very undulating
Soils (FAO)	Leptosols, Luvisols and Cambisols	Lixisols and Luvisols	Nitosols, Ferrasols and Acrisols
Percentage clay + silt in soils	35–90	8–15	60–80
Area of land holdings (ha)	0.3–2.4	0.5–4.2	0.5–2.2
Population density (Inhabitants km^{-2})	128	104	650
Distribution of household wealth classes[a]	Poor 60%; medium 29%; wealthier 11%	Poor 56%; medium 28%; wealthier 16%	Poor 55%; medium 35%; wealthier 10%
Livestock heads per household	2–10	1–5	1–2
Main crops	Barley, wheat, field peas, faba beans, buckwheat, teff and prickly pears	Maize, groundnut, sweet potato, sunflower and vegetables	Maize, sorghum, beans, cowpea, tea, coffee, sugarcane, sweet potato, cassava, fruit trees and vegetables
Livestock system and composition	Free ranging and herded in communal grasslands; Zebu cattle (mainly Boran), sheep, donkeys, mules and chicken	Free ranging and herded in communal grasslands; Zebu cattle (Mashona, Africander), goats, sheep and chicken	Stalled or tethered on farm (cut and carry); Zebu cattle (mainly Boran), and crossbred Holstein, goats, sheep, chicken

[a] Based on location specific criteria

own produced food items was estimated, including those purchased on the market. Soil N stocks were calculated for the top layer (0.3 m) using measurements of total soil N and bulk density.

The analysis focused on N flows associated with management decisions and controlled by farmers, such as the imports of N through fertilisers or food and the exports to the market in harvested products. Due to lack of information, and to avoid introducing errors by using generic pedo-transfer functions (e.g. Van den Bosch et al. 1998), we did not estimate the size of indirect flows such as N leaching, volatilisation, runoff, wet deposition, N_2-fixation or redistribution of sediments in the landscape. Omission of these flows will affect the contribution from and to the soil N stocks, and the N loss to the environment. Estimates for these indirect N inflows and outflows using pedo-transfer functions for Kakamega yielded a net partial balance (=indirect inputs−indirect outputs) of about −10 kg N ha year^{-1} on average (Tittonell et al. 2006).

System boundaries and assumptions

We assumed that each individual field that farmers manage was a different farming activity, i.e. each field is a different network compartment, with clearly delimited spatial boundaries and relatively uniform soil properties in the arable layer. These fields included single crops, intercrops or combinations of annual and perennial crops. The livestock compartments consisted of individual or groups of animals that were managed as a unit. The definition of the system under study (i.e. number and type of compartments to be considered and their interactions) has a decisive impact on the configuration of the network and the value of some of the indicators calculated (Table 1). For example, defining each field as a system compartment, or defining each crop type as a system compartment, yields different results (Rufino et al. 2009a). Here, we use each field as a system compartment since it represents best the management units. Further, when the amount of food indicated by farmers as produced plus purchased was not sufficient to cover the average energy needs per capita, we assumed the difference to be fulfilled by additional amounts of the staple cereal at each site. This energy deficit may have been covered with purchased food, received donations, food aid or other sort of assistance by the family, community or other organisations.

Results

Characteristics of the systems and their N flows

The smallholder crop-livestock systems analysed differed in the area of land cropped per household and in their land:labour ratio, with Murewa (Zimbabwe) exhibiting larger areas of land available per family member (Table 3). Livestock densities (i.e. the ratio of number of heads to cropped area), were the largest in

Table 3 Characteristics of the crop-livestock systems analysed and the major N inflows and soil N stock

Site/wealth class	Family size (#)	Cropped area (ha)	Land/labour (ha capita^{-1})	Livestock owned (TLUs)	Fertiliser N (kg ha^{-1})	Feed N (kg TLU^{-1})	Food N (kg capita^{-1})	Soil N stock (kg ha^{-1})
Tigray								
Poor	5	0.3	0.06	1.2	23.3	70.2	3.2	8,990
Medium	9	0.7	0.08	7.1	3.7	50.4	3.1	5,330
Wealthier	10	2.4	0.24	10.0	10.2	56.6	0	5,470
Murewa								
Poor	4	0.9	0.23	0.3	20.9	0	2.1	1,750
Medium	6	2.1	0.37	4.8	33.7	15.4	0.3	2,186
Wealthier	6	2.5	0.42	5.4	33.4	18.1	0.3	2,874
Kakamega								
Poor	6	1.0	0.17	0	4.9	0	1.9	4,880
Medium	5	2.4	0.48	2.0	4.3	3.6	0.4	6,490
Wealthier	9	2.9	0.32	3.5	6.1	3.9	1.4	6,180

Soil N stock calculated for the top 0.3 m soil layer

Tigray (Ethiopia) and the smallest in Kakamega (Kenya). The size and the main type of N imports differed contrastingly between wealth classes and across sites. In Tigray, the main source of N import was feed, and this was largest for the wealthier farm household with most animals, but the amount imported N per animal (Tropical Livestock Unit, TLU) was larger for the farm household with less land as it used less on-farm produced fodder (crop residues). In Murewa, feed and fertiliser N both contributed equally to the total N imports for the wealthier farm households and only fertiliser N for the poorer households. The fertiliser N use was the highest in Murewa as compared with the other two sites. In Kakamega, the size of the imports was much smaller than in the other two sites, and the relative contribution of fertiliser N (expressed on a per capita basis) was as important as food N for the three types of farm households. Soil N stocks differed widely across sites, with the largest stocks on a per hectare basis in the systems at Tigray, followed by Kakamega and Murewa.

The configuration of the networks of N flows for the nine case study farms is illustrated in Figs. 2, 3 and 4, where the actual structure of the networks was simplified for clarity. Food crops were grouped separately from fodder crops, and all animal compartments were grouped together to show the main internal flows in the farm household. In the calculations, however, we kept individual flows from and to each of the compartments. The number of flows was

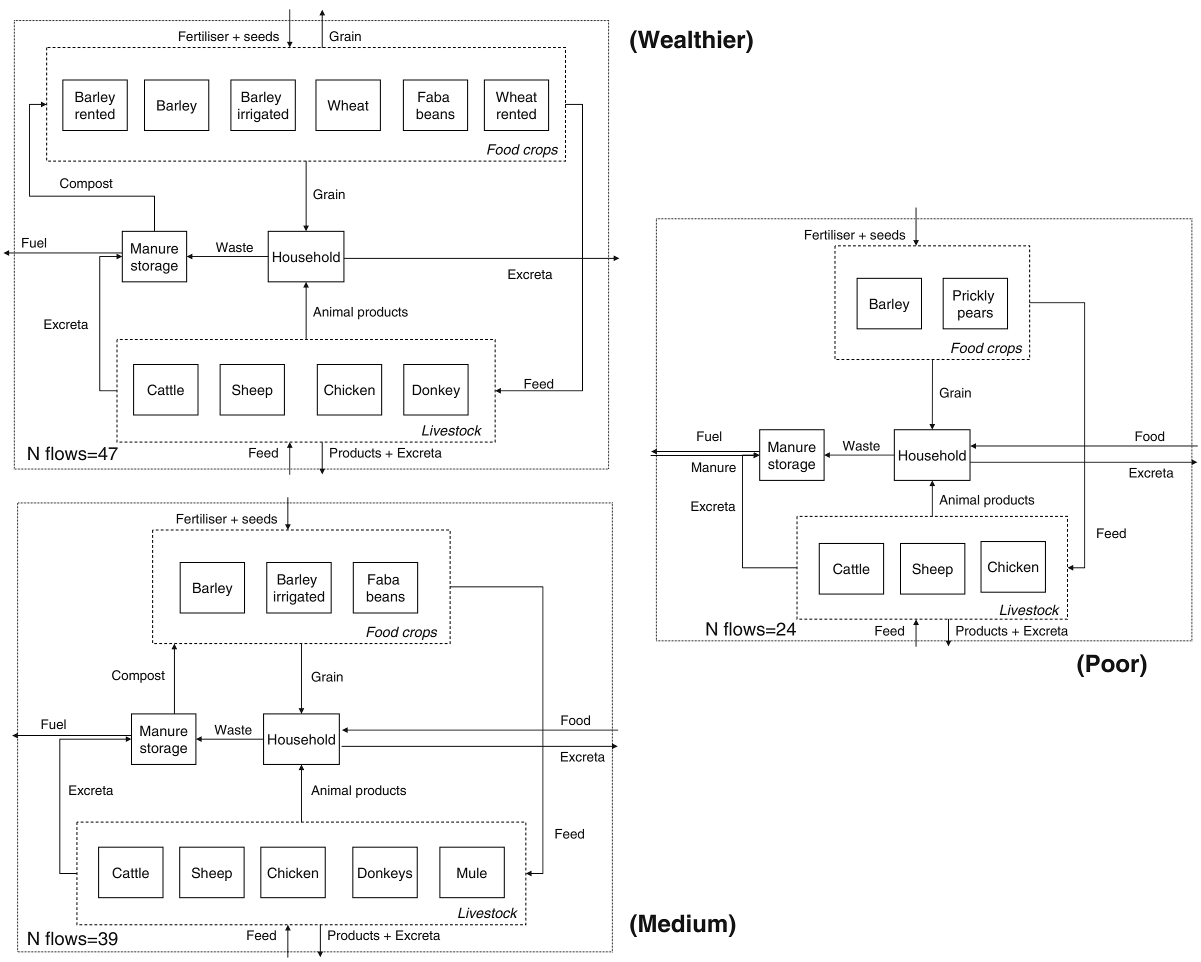


Fig. 2 Schematic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Teghane, Tigray in the Northern highlands of Ethiopia. The *boxes* represent compartments conceptualised as farming activities or management units. The N flows are represented by the *arrows* between compartments and with the exterior and were simplified for clarity of the diagram

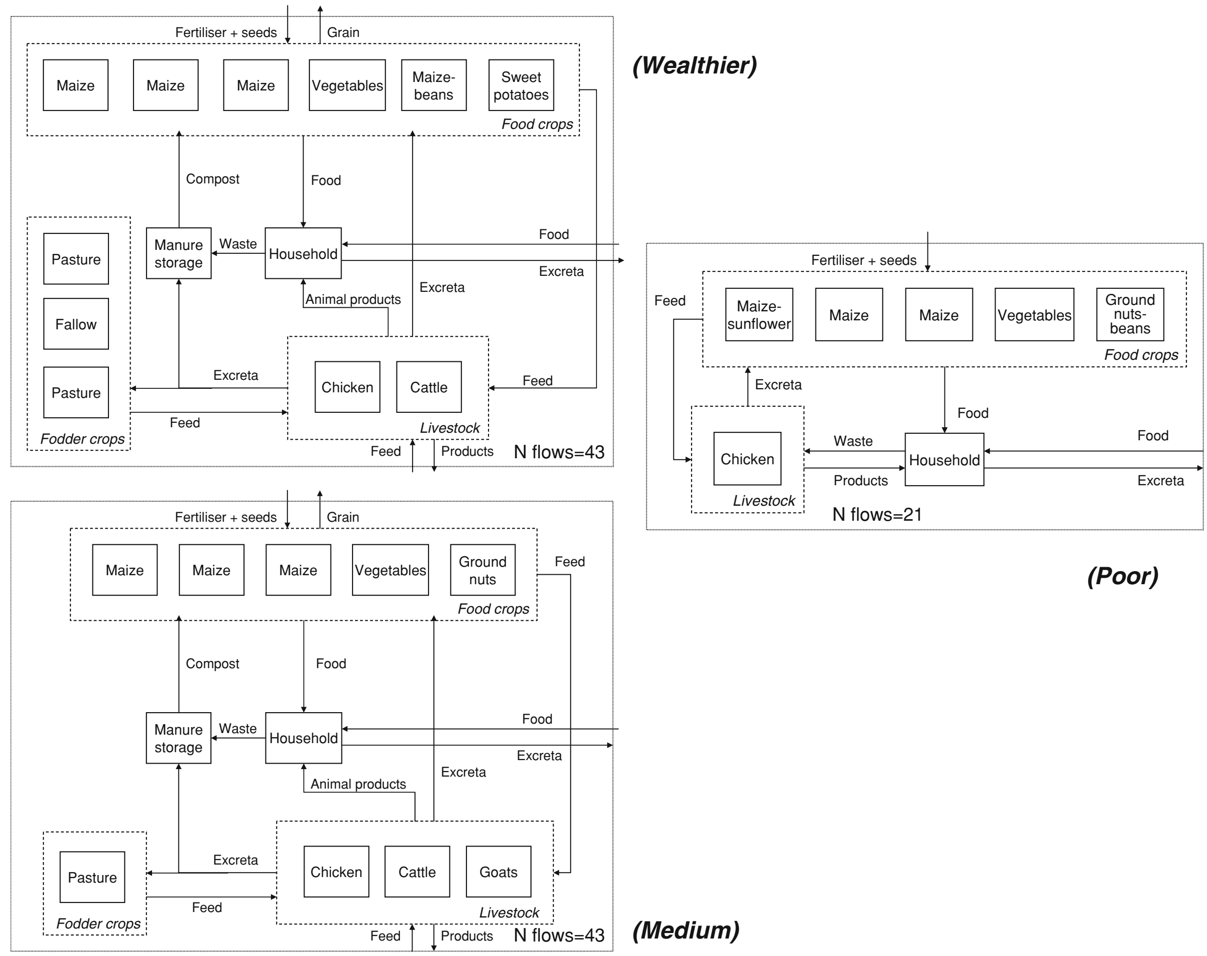


Fig. 3 Schematic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Chiwara, Murewa, NE Zimbabwe. The *boxes* represent compartments conceptualised as farming activities or management units (see "Case studies" for more detail). The N flows are represented by the *arrows* between compartments and with the exterior and were simplified for clarity of the diagram

24, 39 and 47, for poor, medium and wealthier farm households at Tigray, 21, 43 and 43 for poor, medium and wealthier farm households at Murewa, and 40, 54 and 65 for poor, medium and wealthier farm households at Kakamega. In all cases, the main sinks for internal N flows were the household and the livestock: food products from cropping and livestock activities were mainly consumed by the household and the residues of crops after harvest were fed to the livestock. Not all compartments could in practise be linked through N flows because not all farming activities produce outputs that can be recycled. For some farming activities, outputs were sold and therefore exported from the system, with only a small proportion consumed by the household (e.g. tea and vegetables). Farmers usually selected their most fertile fields to produce the crops that contributed the most to their total farm production, and concentrated most inputs in these few good fields. The number of compartments increased from poorer to wealthier households, and the systems in Kakamega had a larger number of compartments than the other sites, due to the more diverse farming activities.

Size, integration, diversity and organisation of N flows

The N imports (IN), TIN, TST and $T_{..}$ calculated for the nine case study farms indicate that the systems in Tigray used about three times more N per capita than

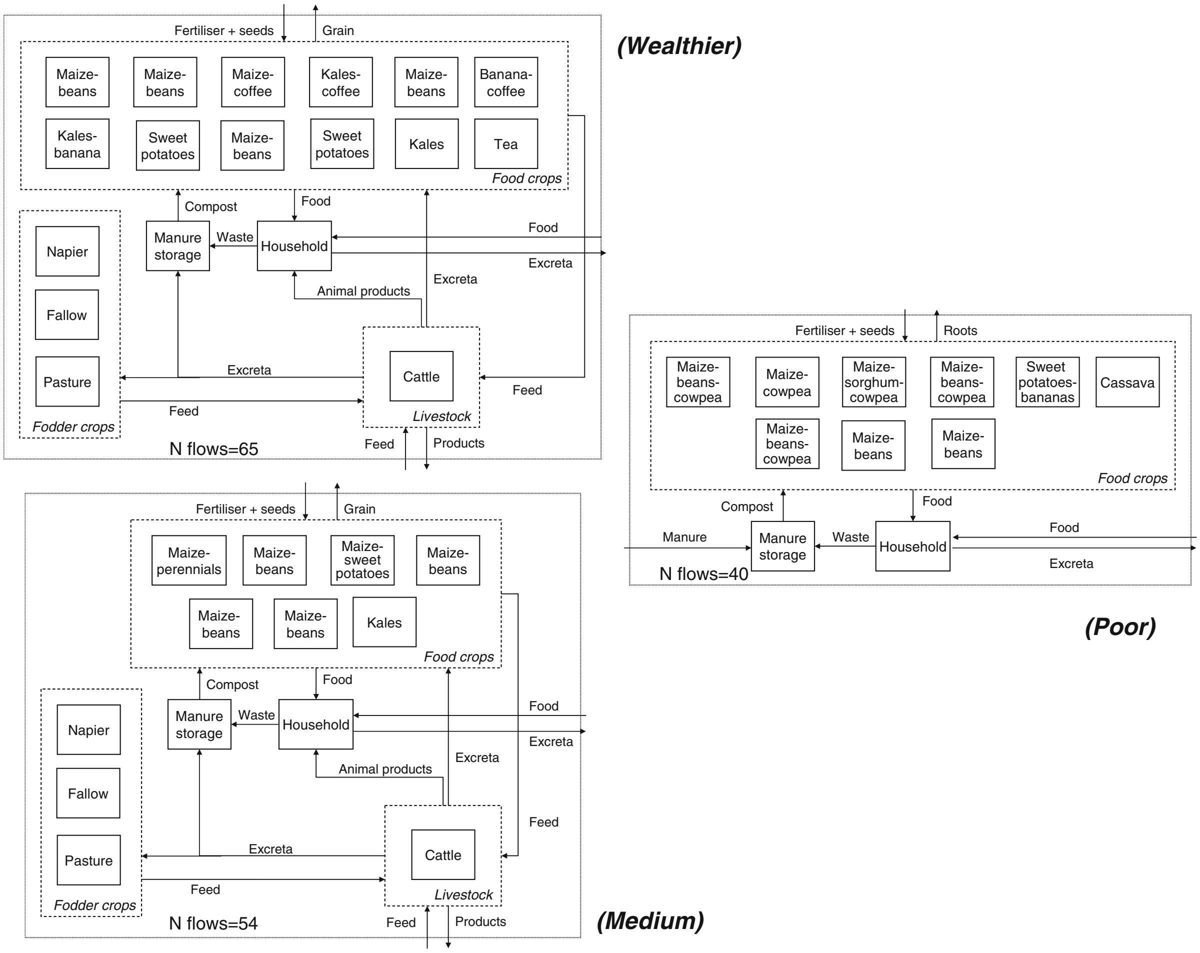


Fig. 4 Schematic representation of the network of N flows for three different farm household types (wealthier, medium and poor) in Mutsulio, Kakamega, western Kenya. The *boxes* represent compartments conceptualised as farming activities or management units (see "Case studies" for more detail). The N flows are represented by the *arrows* between compartments and with the exterior and were simplified for clarity of the diagram

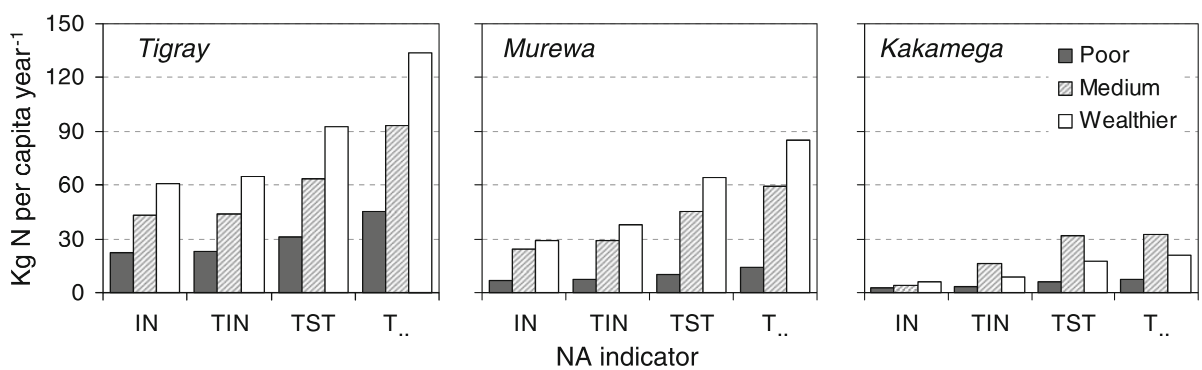


Fig. 5 Network indicators [Imports (*IN*), Total inflow (*TIN*), Throughflow (*TST*), and Throughput (*T*..)], calculated for different types of farm households at three sites: Tigray in the Northern Highlands of Ethiopia, Murewa in NE Zimbawe, and Kakamega in western Kenya. See text in "Indicators of network size, activity and integration" and Table 1 for details

the systems in Kakamega, and one and half times more than Murewa (Fig. 5). N imports and total inflow were on average larger in Tigray, leading also to larger differences between TST and $T_{..}$ values. Large differences between TST and $T_{..}$ are observed when the system is in a equilibrium (when N imports equal N exports); small differences mean that the stock of the various compartments contributes to N exports, balancing out the system activity. A change in stock implies, for example, the loss or accumulation of nutrients in a certain compartment. In Kakamega there was almost no difference between TST and $T_{..}$ implying that most N came from the soils. This can also be seen from the difference between IN and TIN (i.e. TIN = IN + nutrients taken from the stock).

At the three sites the relative importance of IN to TST, or dependence (*D*), was greater for the poorer than for the wealthier farm households (Table 4). Most of the total N inflows in the systems consisted of N imports, as revealed by the IN to TIN ratios, with greater values in Tigray and Murewa than in Kakamega. The amounts of N cycled were small and comparable at all sites (less than 2.5 kg N capita^{-1} year^{-1}). The differences between farm types within sites were larger than those across sites: wealthier farm households recycled between 2 and 3 kg N capita^{-1} year^{-1}, while the poorest less than 1 kg N capita^{-1} year^{-1}. The degree of integration, measured with the FCI was relatively larger for the medium and wealthier farm households at Kakamega (9–11%), due partly to the smaller values of TST as compared with Tigray and Murewa. Wealthier farm households had larger soil stocks of N per capita than the poorer ones, and this together with more livestock explains the larger total system size and activity. The TST represented 7–15% of the total soil N stock per capita in Tigray, 2–6% in Murewa and barely 0.7–1% in Kakamega.

The values of the AMI calculated for the nine case study farms indicated that the poor farm households have less organised networks of N flows compared with the wealthier farms at the three sites (Fig. 6). The values calculated for the statistical uncertainty (H_R) (the upper bound of AMI and a measure of the diversity of flows) indicate a greater diversity in network connections for the wealthier than for the poorer farms. The systems in Kakamega had a greater diversity of N flows compared with the other sites, indicating more options for N flows—i.e. the actual N flows were associated with a more organised pattern than in the other two sites (Fig. 4).

Systems productivity and efficiency

Biomass production per capita was comparable across sites, with the poorest households producing less than the wealthier (Table 5). The productivity (expressed in biomass) of the systems per unit of N imported, or the apparent N conversion efficiency, was the largest in Kakamega (2–30 times larger than at the other sites). This is also evidenced by the steeper relationships between N imports and biomass production for the Kakamega systems in Fig. 7a, with slopes of 15, 83 and 242 kg DM per kg of imported N

Table 4 Indicators of dependence on external N imports, N cycling and size of N stock expressed per capita

Site/Wealth class	*D* (IN/TST)	IN/TIN	TST_{cycled} (kg capita^{-1})	FCI (%)	Soil N stock (kg capita^{-1})
Tigray					
Poor	0.72	0.97	0.9	2.9	470
Medium	0.68	0.99	1.4	2.2	414
Wealthier	0.66	0.94	2.5	2.6	1,312
Murewa					
Poor	0.65	0.90	0.1	0.9	393
Medium	0.54	0.83	1.6	3.5	765
Wealthier	0.45	0.77	3.4	5.5	1,197
Kakamega					
Poor	0.45	0.78	0.1	2.2	814
Medium	0.12	0.24	3.0	9.3	3,115
Wealthier	0.34	0.67	1.9	11.0	1,991

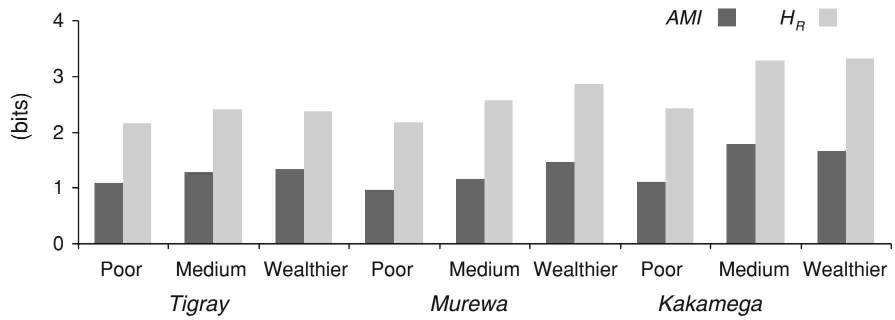


Fig. 6 Indicators of organisation, average mutual information (*AMI*) and, diversity (*HR*) for three different household types (wealthier, medium and poorer) at three different sites: Tigray in Northern Ethiopia, Murewa in NE Zimbabwe and Kakamega in western Kenya. See "Indicators of organisation and diversity" and Table 1 for details

Table 5 Indicators of system productivity and household food self-sufficiency

Site/wealth class	Biomass production (t capita^{-1} year^{-1})	N conversion efficiency (kg dm kg N^{-1})	Food produced (GJ capita^{-1} year^{-1})	Food self-consumed (GJ capita^{-1} year^{-1})	FSSR[a]
Tigray					
Poor	0.5	23	1.4	1.4	0.4
Medium	0.5	12	2.0	2.0	0.6
Wealthier	1.1	18	5.6	3.4	1.7
Murewa					
Poor	0.3	44	1.5	1.4	0.5
Medium	1.6	66	8.4	3.9	2.2
Wealthier	2.5	86	11.2	2.9	3.4
Kakamega					
Poor	0.2	74	1.0	0.9	0.3
Medium	1.4	368	4.4	3.4	1.2
Wealthier	1.3	217	3.1	2.4	0.8

[a] FSSR, energy in food produced per capita/energy needs per capita (on average 3 GJ year^{-1})

for Tigray, Murewa and Kakamega, respectively. The systems at Murewa produced, on average, more edible energy per capita than at the other two sites (Table 5). The poorest households did not achieve food self-sufficiency in any of the three sites. The medium class at Tigray and the wealthier at Kakamega did not produce enough food on their farms to fulfil the family energy requirement, but accessed cash through selling farm products that was used to cover the food deficit.

Comparing indicators of NA with system performance, we observed that the larger the value of the FCI the greater the production of biomass per capita. The relationship differed across sites, with less biomass produced per unit FCI at Kakamega (Fig. 7b). This, together with the greater apparent conversion efficiency of imported N (Fig. 7a), indicates that more internal cycling (including mobilisation from the soil stock) sustained biomass production in the systems at Kakamega. The systems at Tigray and Murewa cycled less N and required larger N imports per unit of biomass produced.

Next, we compared the relationships between the size of the network of N flows ($T_{..}$) and their organisation AMI with the food self sufficiency ratio FSSR across the three sites. The wealthier households at Tigray met their energy demand (FSSR > 1) with larger N flows than at the other sites (Fig. 7c). The relationships between network organisation and FSSR (Fig. 7d) were comparable with those observed between FCI and biomass production, with the

Fig. 7 Biomass production plotted against **a** N imports and **b** Finn's cycling index for farm households of different type at three different sites: Tigray (Ethiopia), Murewa (Zimbabwe) and Kakamega (Kenya); and food self-sufficiency (calculated as the ratio of food produced on farm per capita divided by the average energy needs of the farm household member) plotted against **c** total system throughput ($T_{..}$) and **d** average mutual information (*AMI*), for the same farm households. See "Network analysis" and Table 1 for details

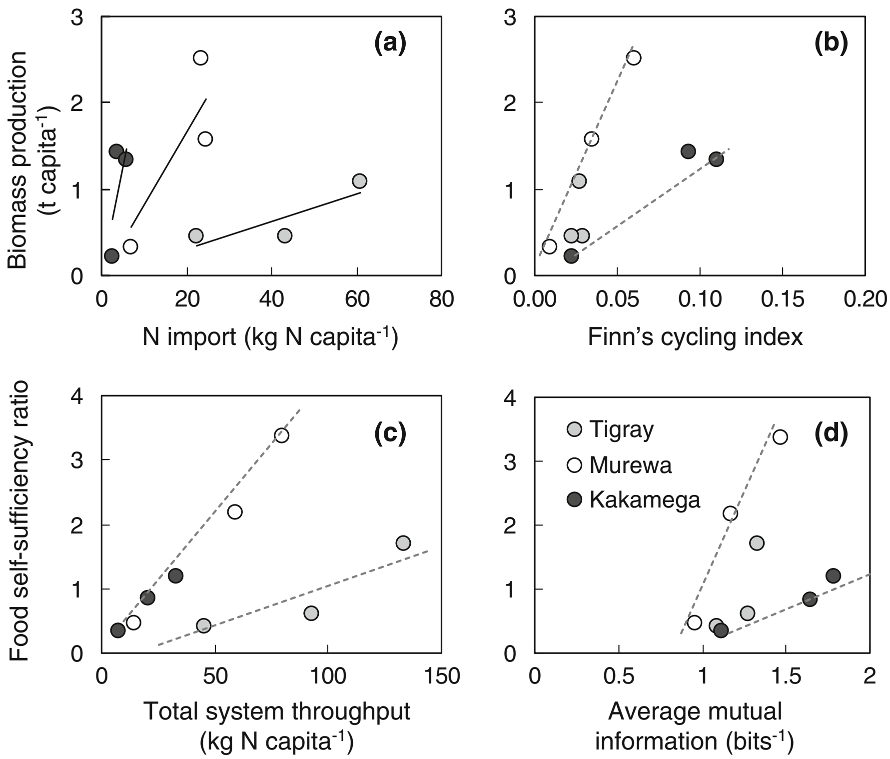
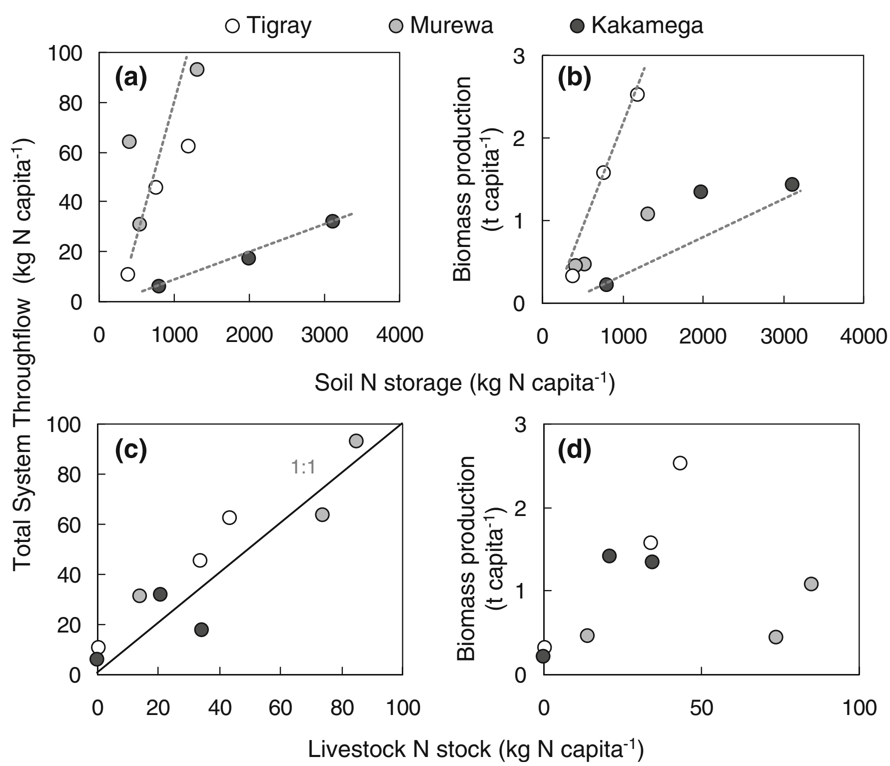


Fig. 8 Total system throughflow (TST) plotted against **a** soil N stock per capita and **c** Livestock stock per capita; Biomass production plotted against **b** soil N stock per capita, and **d** Livestock stock per capita, for farm households of different type at three different sites: Tigray (Ethiopia), Murewa (Zimbabwe) and Kakamega (Kenya)



systems at Kakamega exhibiting a more complex organisation of N flows.

The intensity of utilisation of N resources and the flow patterns differed across systems (Fig. 8a). The systems at Tigray, and particularly those at Murewa, utilised larger N throughputs ($T_{..}$), and sustained production on smaller soil N stocks than at Kakamega. The systems in Kakagema largely relied on soil N stock (as small amounts of N were imported), and less biomass was produced per unit of N in the soil stock (Fig. 8b). The differences in $T_{..}$ across sites were related to differences in the size of the livestock N stock (an estimation of the N in the body mass of the herd), and the relation between both was approximately 1:1 across sites (Fig. 8c). Larger herds in Tigray depending on communal grazing resulted in larger N imports to the farm that were used (partly) to sustain crop production, with consequently less biomass produced per unit of N stored in livestock, and presumably larger losses of the imported N.

Discussion

The size and the main type of N flows differed between farm household types and across sites. At all the sites, the poor farm households used much smaller amounts of N per capita (Fig. 5), had lower cycling indices indicating that these farms were less integrated, had a less organised network of N flows, and were more dependent on N import to sustain the system activity (TST). Less organisation here means that N was not applied to the compartments that contribute to cycling and productivity of the system. As also shown by Van Beek et al. (2009), opportunities for recycling of N in these type of farm household systems are mainly created by livestock. Without livestock farmers are often not able to collect the equivalent amount of N in plant materials to mulch their crops or produce compost. Low effective N cycling is often caused by poor feeding management. Crop residues and the N contained in them are removed from the fields, and because manure or crop residues are applied to other fields—closer to the homestead—than those where cattle feed, there is little or no return of N in manure (Mtambanengwe and Mapfumo 2005). Making use of organic resources like manure and crop residues, results in high labour costs and competition with other farm activities which may be the causes that discourage farmers from making use of recycling to sustain crop production (Ruben et al. 2006). Most farm households in our study had both livestock and cropping activities; nevertheless recycling was poor: less than 25 kg N year^{-1} farm^{-1}, and the poor households less than 5 kg N year^{-1} farm^{-1}. Farmers need to perceive the benefits of their investments in soil fertility. Intensifying crop-livestock systems requires skilled farmers, and technical assistance (Waithaka et al. 2007). The lack of these may limit the success of promising technical interventions considerably.

Animal products did not contribute much to consumption of the household members as the main role of livestock in these farming systems is the provision of draught power for soil tillage and savings for times of cash shortage (Dercon 2002; Moll 2005). The large system size (measured with $T_{..}$ was not reflected in a large increase in food self-sufficiency nor in biomass production in Tigray (Fig. 7c). Increases in the size of N flows ($T_{..}$) and N imports led to increases in production and food self-sufficiency in all three sites, although with different conversion efficiencies (Table 5). The systems with small size ($T_{..}$), and low organisation in network of flows (AMI) were less productive and less food self-sufficient than the systems with large $T_{..}$ and AMI (Fig. 7c, d). But, at large values of $T_{..}$ and AMI, food self-sufficiency and productivity were different at each of the sites. Increasing $T_{..}$ had a relatively smaller effect on food self sufficiency in Tigray than in the other two sites. The farm households that we studied use relatively large amounts of N from the surrounding environment that did not directly contribute to produce food, probably because the poor manure management. The high $T_{..}$ in Tigray was mainly caused by the large size of the N inflows due to feeding management, while the contribution of the organisation of the flows was not as important in this site as in Kakamega. It appears that in Tigray there is more scope to increase the N recycling given the actual diversity in flows for this system (Abegaz et al. 2007). Higher diversity (H_R) in flows may be positive if the N flows are organised (i.e. high AMI) to increase recycling and there is integration between the system compartments (i.e. high FCI).

The impact of recycling of N on food self-sufficiency depends on how the flows are managed, the N conversion efficiency, and whether the inflows that contribute to cycling can be sustained in the longer term to build soil fertility. The importance of these factors differs per environment; there may be trade-offs between current productivity and reliability in the long term. Reliability is understood as the capacity of the system to remain close to its stable equilibrium when facing normal perturbations, while adaptability refers to the capacity of the system to adapt its functioning to new conditions (Lopez-Ridaura et al. 2005). Reliability can be assessed through the changes in food-self sufficiency of the farm household in time, or across farm households. It appears that increasing the size of the network of N flows increases food self-sufficiency. Increases in organisation of the flows, and increased recycling may contribute partially to increase the size of the network flows, but the amount of nutrients that can be recycled is limited by the size of the inflows and of the outflows (marketed products), and from the nutrient in the soil stock. Cycling reduces dependence on external inputs, and increases the efficiency of nutrient use at the farm scale. The reduced dependence on external inputs, associated with more recycling, and supported by larger soil stocks per capita in Kakamega, may be indicative of the adaptability of the systems to different stresses (e.g. in the case of an increase in fertiliser prices). However, when outflows exceed inflows, this capacity will not be sustained in the long term. The measures of size ($T_{..}$) and the measure of activity (TST) in contrast, give an estimation of the amount of N that is used to achieve current production, and are useful to compare different farm types in terms of performance and efficiencies.

The resilience of mature ecosystems is sustained on a structure that supports a diversity of flow paths that allows buffering of external shocks and the increased efficiency of few of their flow paths that are not affected by external stressors (Odum 1969). Agro-ecosystems have, in contrast, to fulfil the goals and aspirations of the farmers, for which they need to be productive, reliable [i.e. production should be stable, with small fluctuations, or increase in the longer term (Conway 1987), and adaptable to match opportunistic decision making. In smallholder crop-livestock systems finding a balance between these properties is a challenge as farm household systems that are diverse in activities may be able to cope with risk, and contribute to reliability, but may compromise productivity.

Farmers' management decisions, together with the context in which farming takes place (i.e. agro-ecology, demography, markets), have a strong influence on the agro-ecosystems productivity (Beyene et al. 2006) and its capacity to support rural families. A more organised pattern of nutrient flows, and more recycling should lead to less reliance on external inputs. However, internal recycling may not suffice to sustain food production in poor soils, which means that the dependence on external inputs can only be relaxed when the soil nutrient stocks are large enough to produce sufficient food per capita (cf. Table 4). A farming system with few external inputs may be reliable and stable, but is often also poorly productive as the system productivity (i.e. biomass production per farm) is limited by a combination of resource availability and resource management. An alternative system more dependent on external inputs, is usually more productive, but may be less reliable because of fluctuations caused by external and sometimes internal stressors such as market failure, leading to lack of inputs, or climatic extremes that lead to relatively large losses in crop yields. To achieve food self-sufficiency, the poor farm households need to increase their nutrient imports and hence productivity. Integration and diversity may play a role in sustaining production in the long term.

The opportunities to increase system size may be different for each crop-livestock systems and related to the degree of intensification. In Tigray, relatively large inflows from grasslands through livestock, small inflows as fertilisers, and relatively poor internal cycling, characterised and explained the actual productivity. Internal cycling was less important than in the other two sites (Tables 4, 5). In Kakamega, the inflows into the systems were relatively small, and the production was sustained on internal cycling including the contribution from the soil nutrient stock. Murewa represented an intermediate situation where N inflows from grasslands, and fertilisers contributed to food production more than internal cycling and were more important than in Tigray.

Agro-ecosystems have to be productive to sustain rural families. However, in smallholder farming systems, farmers often manage their nutrient resources to spread risk, and therefore measures of productivity do not always suffice to evaluate farm performance. Cycling, diversity and internal organisation, may contribute to adaptability and reliability, sometimes at the expense of resource use efficiency, as is the case when inflows to the systems are mediated through livestock, due to inevitable losses through nutrient cycling (Rufino et al. 2006). The lower dependence on external inputs, high diversity and cycling at Kakamega is associated to relatively better conditions for agricultural production in terms of soils and climate (Tittonell et al. 2005; Vanlauwe et al. 2006). Agricultural production in Tigray is probably more water-limited than in the other sites (Hengsdijk et al. 2005). This, in combination with the unfavourable land/labour ratios in Tigray, explains much of the differences in N conversion efficiency. The organisation of the system can change to meet different goals: simpler structures may support productive systems, but those may be more vulnerable to environmental stress.

This study represents a snapshot of the systems in time, and results should be interpreted taking into account that these systems are dynamic. In agroecosystems the marketing of products may facilitate the acquisition of inputs that may increase productivity, if farmers reinvest in farming. But when this is not the case, large exports may feedback negatively leading to declining food self-sufficiency in the long term. In farming systems, marketing of produce is critical for generation of cash for needs other than food, and also to purchase key inputs for production, so nutrient export from the farms is unavoidable. The challenge is to find a balance between productivity, reliability and adaptability, which can be met by a technical change in which reconfigurations allow higher productivity to be achieved without much increase in dependence. The indicators of network analysis could be complemented with farm-scale dynamic modelling to evaluate the effects of different nutrient resource allocation on system performance indicators (i.e. food production, income) over time.

Conclusions

In the crop-livestock systems of the highlands of East and southern Africa analysed, organisation and diversity of the flows of N to, from and within the farm households, differed more between farms of different resource endowment than across sites. Differences in system productivity within and between sites were explained by differences in the size of the N inflows, and in the organisation of internal N flows and cycling. The systems operate in contrasting conditions in terms of agro-ecological potential (rainfall and soils), population density and market accessibility and in the relative importance of livestock in the system. This leads to differences in the type and amount of N inflows (e.g. fertilisers, feed), and in the structure and functioning of the systems (flow diversity, cycling). More conducive agroecological conditions allowed a more efficient use of N inflows within the system, and larger soil stocks of N rendered the systems less dependent on external N. Increases in the size (amounts of N that circulate within the network) and organisation of the flows led to increases in productivity and food self-sufficiency. As these strategies also reduce dependence, combination of both strategies may benefit not only productivity but also adaptability and reliability of smallholder crop-livestock systems.

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