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Operationalizing the concept of robustness of nitrogen networks in mixed smallholder systems: A pilot study in the mid-hills and lowlands of Nepal

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A B S T R A C T

Nitrogen (N) is often the most limiting nutrient to productivity in smallholder mixed crop-livestock systems such as commonly found in the mid-hills and lowland (Terai) of Nepal. Identifying current bottlenecks constraining agroecosystem functioning in terms of N flows and associated improvement options in these systems is paramount. Here, we explore variations in robustness, a concept from ecological network analysis (ENA) which represents the balance of system's degree of order between organization (order/constraint) and adaptive flexibility (freedom/resilience) of N flows. Robustness can provide a detailed assessment of N flows and assist in evaluation of measures to reduce nutrient losses. In this study, the FarmDESIGN model was employed to quantify nitrogen flows, generate ENA indicators of integration, diversity and robustness, and to explore the impact of crop intensification options on N networks across farm types in the mid-hills and lowland (Terai) of Nepal. Results revealed that the farms in the different agroecosystems recycled only a small portion of the total N inputs (< 15%), and had therefore high rates of N losses (63–1135 kg N per ha per year) and high dependency on N imports in the form of fodder (feed self-reliance 11–43%). The farm N networks were organised (high productivity) but inflexible (poorly resilient) and consequently unbalanced (low robustness). Scenarios of improved management (improved seed, intercropping, use of fertilizers, better timing of activities) resulted in improved crop production, leading to reduced fodder imports and less N losses. Consequently, the N networks increased in flexibility which resulted in greater robustness of the N flow network in the farm systems. Increasing on-farm biomass production by improved farm management could be an important element on the way to sustainably intensify smallholder farms, especially when dependency on external resources can be reduced. We conclude that a detailed analysis of nutrient flows and their robustness is a suitable instrument for targeted improvement of nutrient use in smallholder crop-livestock systems.

1. Introduction

Economic, political and climatic changes continuously challenge farmers to adjust their farm systems in a quest to thrive or often merely just to survive (Eakin and Lemos, 2006). This is particularly true for smallholder farming systems, which are generally highly complex mixed systems characterised by limited economic and also human resources (Descheemaeker et al., 2018). Smallholder farming systems are commonly situated in adverse fragile environments where natural resources are limited (Van Keulen, 2006). As a result, many of these systems can be described as 'low-input-low-output" relying greatly on: i) on-farm resource cycling which involves mutual dependency between crop and livestock; ii) off-farm organic resource inputs by importing resources from open areas such as forests and grazing areas mainly for feed; and iii) biological inputs such as symbiotic fixation of atmospheric N_2 by leguminous crops (Basnyat, 1995). Increasing the productive outputs of these systems based on improved use of natural resources could considerably enhance livelihood outcomes, including better nu-

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trition and more income, in a sustainable way. Crop production is the largest cause of human alteration of the global nitrogen cycle, and N fertilizers are the main source of N in cropland, followed by N-fixation and N input from manures (Liu et al., 2010; Elrys et al., 2019). Soil N depletion occurs mainly in regions with high extensive cropping production such as rice production in Southeast Asia; and with low mineral fertilizer application rates such as in Sub-Saharan Africa (Rufino et al., 2009a; Liu et al., 2010). High values of N output to soil erosion occur in regions of heavy rainfall, areas of steep slopes and high-relief topography such as the Tibetan Plateau (Liu et al., 2010).

In smallholder farm systems, artificial fertilizers and other external inputs that are available in intensified agriculture such as concentrate feed and fuel are often difficult to obtain. Therefore, improving nutrient cycling and nutrient use efficiency (NUE) is considered as one of the most effective means of increasing crop productivity while decreasing environmental degradation (Zhang et al., 2015) and the dependency on external resources (Rufino et al., 2009a; Stark et al., 2018). Farm NUE is defined as the ratio between the output of N in farm products and the input of N into the farm, for instance imported feeds and fertilizers (Huxley, 1999; Rowe et al., 2005; van Noordwijk and Brussaard, 2014). NUE depends largely on the recycling capacity within the farm and it is high if there is no waste and all residues and by-products are recycled (van Noordwijk and Brussaard, 2014). However, an analysis of NUE at farm level or at the level of farm components (e.g. soil, crop, livestock, manure) does not necessarily provide enough insight into the system structure, processes and flows to understand inefficiencies and losses. A systems-oriented analysis at farm-level and of nutrient cycles is needed to construct a coherent long-term strategy of mitigation of nutrient losses and negative system impacts in the long run (Shah et al., 2013).

Ecological network analysis (ENA) is a tool to quantify nutrient flows into, within and out of systems, that can provide additional insights into agroecosystem functioning (Groot et al., 2003; Rufino et al., 2009a; Alvarez et al., 2014). ENA can determine the degree of nutrient cycling within the system and more advanced ENA indicators quantify system properties such as integration (i.e. the degree to which nutrients cycle between compartments within the system), organization (i.e. distribution of flows connecting the compartments) and diversity (i.e. the diversity of flows of a certain amount of throughput). ENA offers novelty in understanding efficiency at system level, in contrast to single efficiency ratios field and farm levels. It provides insights on what happens with N that enters the farm system, how it is used/recycled, what the amount of productive output is, where losses occur, etc. In this study, ENA is used to assess indicators of integration and diversity and to quantify robustness which is defined as the equilibrium of the systems degree of order between organization (order/constraint) and flexibility (freedom/resilience) (Patzek, 2008; Ulanowicz et al., 2009). It was hypothesized that sustainable, self-organising systems with a high degree of robustness would maintain a balance between order and disorder to be productive but also to provide buffering and allow reconfiguration when adaptation to changes or perturbations is needed. Order relates here to organised flows leading to efficient functioning and production, while disorder relates to diversity, redundancy and flexibility, resulting in system resilience. These information theory-based concepts and metrics derived from network analysis can thus provide indicators of system robustness (Fath et al., 2007; Ulanowicz et al., 2011). To our knowledge, the quantification of N networks robustness in smallholder farms has not been studied before.

In this paper, we explore the concept of robustness for nutrient flows in complex mixed smallholder farm systems as a way to: i) identify current bottlenecks constraining agroecosystems functioning in terms of N flows, and ii) explore changes in agroecosystems under an intensification scenario. We do this using representative farms as a pilot to test the operationalization of the concept of robustness by employing ecological network analysis (ENA) at farm level focusing on the on-farm N cycle. We focus our study on diverse smallholder faming systems in the lowlands and mid-hills of Nepal.

2. Robustness and ecological network analysis in agroecosystems

To operationalize the concept of robustness of N networks, we quantify the concept using ENA. Here we introduce and describe the ENA indicators on which the concept of robustness is based. ENA is an input-output analysis that quantifies relationships within ecosystems in terms of energy, resources or specific nutrients (Leontief, 1951; Fath and Patten, 1999). It allows studying objects as part of a connected system and identifying and quantifying their effects (direct and indirect) in the system (Fath and Patten, 1999).

Ecological networks can be represented as directed graphs that consist of nodes and edges. The nodes denote compartments that store and convert biomass or nutrients. Edges represent the flows between the compartments and the exchanges with the environment (comprising inflows, outflows and dissipations). Compartments can represent biomass of species or functional types in a food web, or components of an agroecosystem such as different types of crops and animals, soils, and manures.

ENA allows analysis of structural and functional properties of nutrient flow networks, with the aim to explore the characteristics of system compartments and their interactions (Fath et al., 2007). The nutrient network properties can be associated to agroecosystem properties such as productivity, adaptability and reliability of smallholder crop-livestock systems (Rufino et al., 2009b). In order to explore the properties of N networks, three categories of ENA indicators can be calculated for activity and integration (Section 2.1), organisation and diversity (Section 2.2) and degree of order (Section 2.3). The relationships between farm structure and ENA indicators are illustrated with a simplified example in Box S1 in the Supplementary Material.

2.1. Indicators of activity and integration

The indicators of ecosystem activity and integration quantify the amount of nutrients that flow into, through and out of the system, and among the compartments of the system. These indicators have been derived from the flow analysis of Finn (1980). The equations used for the calculation of the flow metric indicators are listed in Table S1 of the Supplementary Material.

Imports from the environment are captured by the sum of inflows into the system (IN). Compartmental throughflows T_i are defined as the total flow from other compartments and the environment to compartment *i*, minus the outflow associated with a change in stock within the compartment. The total system throughflow (TST) is calculated by summing the T_i of all compartments, and it represents the mobile N pool within the system and the activity of the network. TSTc is the total cycled system throughflow. The Finn cycling index (FCI) is the fraction of TST that is recycled within the system. It is calculated by dividing the cycling flows (TSTc) of all the compartments by the total TST. It has values between 0 and 1, indicating no recycling and total recycling, respectively.

The total system throughput (T) represents the total size of N flows in the system and exchanges with the environment. T is the sum of all the inflows and outflows to and from all the compartments in the system. It is also considered as the 'power' generated by the system. Dependence (D) represents the dependence of the system to external inputs. It is calculated as the ratio between the IN in the system and the activity TST. The link density (LD) is the quotient between the number of flows and the number of compartments, and is a measure of the connectivity of the network. The average path length (APL) is the average number of compartments visited by a unit of N input before leaving the system.

2.2. Indicators of organization and diversity

The indicators of organization and diversity are derived from communication theory (Latham and Scully, 2002). Organization reflects the tendency for the total system to act in a coherent manner, i.e. as an integral unit, in contrast to a collection of independent parts (Ulanowicz, 1980). The average mutual information (AMI) quantifies the organization of the flows in the network (Latham and Scully, 2002). AMI assesses the probability that a flow entering a compartment is coming from a specific compartment. It indicates to what extent the flows of N in the systems are homogeneously distributed. Statistical uncertainty (H_R) is defined in communication theory as the statistical measure of the uncertainty of a message source. It expresses the diversity of flows given a certain amount of throughput. It is the upper boundary for AMI, and the AMI/H_R ratio signifies the degree of organisation of the network. Both AMI and H_R have no physical dimensions.

2.3. Indicators of systems degree of order

Ascendency (A) and overhead (Φ) indicators give dimensions to AMI and $H_{R.}$ Latham and Scully (2002) formulated the concept of ascendency as the product of the total activity or power generated by the system (T), with its organization in the context of how effectively component processes are linked (AMI) (Table S1). Ulanowicz et al. (2011) described A as the "organized power" because it represents how power is channelled within a system, which could lead to productivity. It is a "natural descriptor of the combined processes of growth and development" (Ulanowicz, 1980).

System overhead (Φ) is the result of H_R multiplied by T (Ulanowicz and Norden, 1990) and represents the freedom of the network to adapt to changes and disturbances. Ulanowicz et al. (2009) call the sum of A and Φ the system development capacity (C), as any increase in ascendency usually comes at the expense of overhead (Φ). This highlights the importance of these two indicators and of the ratio $A/C = a$ that quantifies the degree of system order and the ability to self-organise. Highly ordered systems with high A that retain little overhead (hence a high A/C ratio) are "rigidly linked and vulnerable to collapse" (Holling, 1986). The vulnerability is a result of the lack of sufficient freedom and flexibility resulting in low system resilience (Ulanowicz et al., 2011). On the other hand, in systems with too little order (low A/C ratio), the randomness inherent in Φ provides opportunities for constraints to appear, which hampers organisation to emerge and results in lack of efficiency (Ulanowicz et al., 2011; Fath, 2015). Robustness is a normalized measure for an ecosystem to persist, it is defined as $R_N = -ea \ln(a)$. In order for an ecosystem to persist the value of a should be close to a value of a where the maximum R_N of $\frac{1}{e}$ is reached (Fig. 1; Box S1 in

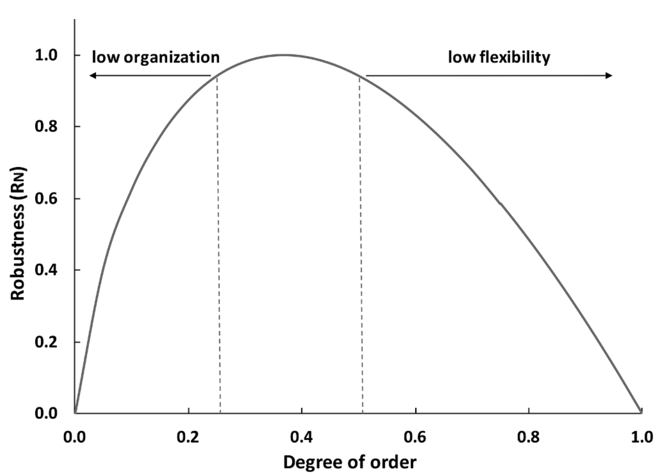

Fig. 1. Fitness curve showing the robustness (R_N) as the balance between system flexibility and organization (Ulanowicz et al., 2009). The degree of system order represents the ratio A/C, with A denoting the ascendency and C indicating the capacity of the system. A simplified example of different types of agroecosystems and its robustness are described in Box S1 in the Supplementary Material.

Supplementary Material) (Ulanowicz et al., 2011; Fath, 2015). Networks distant from this maximum are not robust as they either have too little organization or are too inflexible (Fig. 1) (Ulanowicz et al., 2011).

In this paper we test the following hypothesises. 1) In agroecosystems with more exchanges among compartments, which are usually more diverse in farm activities, ENA metrics can capture that the activity of the network enhances, the dependency decreases, and cycling increases compared to less diversified systems. 2) Agroecosystems with more complex N flows among compartments will be closer to the maximum value of robustness (Fig. B2 in Box S1 in Supplementary Material). 3) Increasing on-farm productivity will reduce external fodder import, increase flows among compartments and increase the robustness of N networks.

3. Materials and methods

3.1. Study sites

The research was carried out in three districts in the mid-hills and low-lands (Terai) of Nepal, namely Palpa, Dadeldhura and Nawalparasi. Palpa and Dadeldhura are located in the mid-hills in the Western and Far-Western regions, respectively. Nawalparasi is located in the low-lands in the Western developmental region (Fig. 2).

There are strong ecological differences between low-lands and mid-hills shaped by large differences in climate and topography. Nawalparasi consists of flat land at low altitude (105 m above sea level) in contrast to the two mid-hill regions that are situated at higher altitudes; Dadeldhura at 1500 m.a.s.l. and Palpa at 1300 m.a.s.l. Overall, the soils in both mid-hill districts are chromic cambiosols; while in Nawalparasi eutrict and ferralic cambiosol are dominant (Dijkshoorn and Huting, 2009). The soil texture in Palpa is predominantly loam, and loam to silty in Dadeldhura and Nawalparasi.

The climate as described by the Koppen classification in the low-lands is tropical to subtropical and in the mid-hills mostly subtropical to temperate (Department of Hydrology and Meteorology of Nepal, 2015). The three regions have a dry winter and summer monsoon. The wet summers (June-September) have an average precipitation of 990 mm in Dadeldhura and 1052 mm in Palpa, and 1200 mm in Nawalparasi, while in the dry winters (December-March) the precipitation is slightly higher in Dadeldhura (349 mm) than Palpa (228 mm) and Nawalparasi (120 mm) (Department of Hydrology and Meteorology of Nepal, 2015).

Large differences between the low-land and mid-hill regions are also seen in farm orientation and access to inputs (Table 1). The access to inputs, irrigation and markets in the low-lands is good due to its flat terrain and road infrastructure and the proximity to markets in India, whereas in the mid-hills connectivity to markets is limited as a result of remoteness and because agriculture is practiced on terraces.

In Nawalparasi, albeit the main cropping season is concentrated in

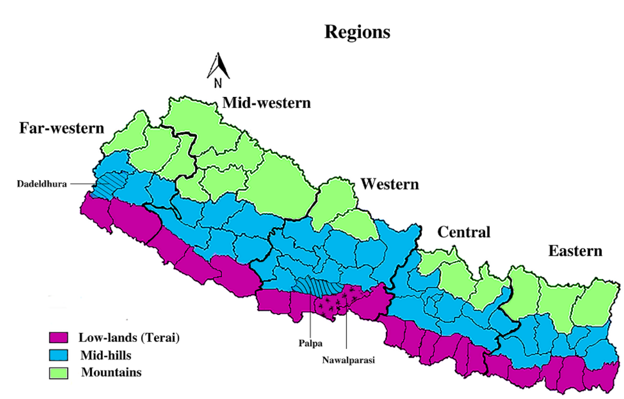

Fig. 2. Map of the geographical and developmental regions in Nepal. Dadeldhura, Palpa and Nawalparasi districts, where the study sites were located, are indicated.

Table 1
Characterization of the agroecosystems of lowlands (*Terai*) and mid-hill regions of Nepal (Westendorp, 2012).

Characteristic	Lowlands	Mid-hills
Farm main orientation	Both market oriented and self-subsistence	Most farms are self-subsistence, production on small fields
Main cereals	Paddy rice, wheat, maize, fodder crops	Maize, millet, wheat, upland rice
Cash crops	Lentils, chickpeas, sugarcane, vegetables	Potato, Mustard and soybean (oil), vegetables
Livestock	Buffalo, cattle, goats, poultry, fish	Buffalo, cattle, goats, poultry
Farm management practices	Artificial fertilisers and pesticides, mechanization widely spread	Terraces, farm yard manure, no or limited artificial fertilizers and pesticides, oxen as animal traction and labour exchanges
Water availability	Irrigation	Rain-fed
Labour	Hired labour readily available	Exchange of labour
Market access	Good. More entrepreneurial farms	Good when close to roads, low when more remote

the monsoon (summer), three cropping seasons are commonly practiced due to the access to irrigation (spring, summer and winter). The main crop in the summer is paddy rice (*Oryza sativa*), and wheat (*Triticum. aestivum*), mustard (*Brassica juncea*) and chickpea (*Cicer arietinum*) in the winter. Maize (*Zea mays*) and vegetables e.g. bitter gourd (*Mordica charantia*), eggplant (*Solanum melongena*), cabbage (*Brassica oleracea*), potato (*Solaum tuberosum*), among others are the main crops in spring. In contrast, in the mid-hills there are two cropping seasons. In Palpa the main crop grown in summer is maize, usually mixed with legumes, finger millet (*Eleusine coracana*) and/or cucurbits, while in winter mustard mixed with chickpea (*Cicer arietinum*) or lentils (*Lens culinaris*) is prevalent. In Dadeldhura, maize (mixed with legumes, cucurbits and finger millet) and upland rice are alternated in the fields each year during the summer. In the winter, wheat is the main crop. From January to April-May most of the fields are fallow. In the case of a spring season, vegetables are the main crop limited to farmers that have access to irrigation.

3.2. Data collection and farm typology

To analyze the diversity of farming systems in the three districts, we performed a rapid household survey among a total of 140 households in Palpa (n = 50), Dadeldhura (n = 50) and Nawalparasi (n = 40) from September until December 2013, just after the monsoon season. Households were selected in each site using a Y-shaped sampling method (Tittonell et al., 2010). We applied five Y-shaped sampling frames in three different VDC (Village Development Committee) in each of the mid-hill districts and four Y-shaped sampling frames in the four VDC in the low lands. With each Y-frame 10 farms were selected within 1200 m diameter. The survey covered biophysical and socio-economic components: i) crops and livestock characteristics; ii) land size, and farm management; and, iii) socio-economic characteristics as age, household size, income, ethnicity, labour availability, proximity to main roads, months of food self-sufficiency.

We used the survey data to construct farm typologies in order to capture farm diversity in terms of resource endowment. For each district, we built a farm typology using multivariate analysis: a principal component analysis (PCA) was performed to identify non-correlated explanatory variables, followed by a hierarchical clustering (HC) to group the farms. The clustering algorithm finds the most homogeneous groups possible, minimizing the intra-group heterogeneity and maximizing inter-group heterogeneity (Alvarez et al., 2018). The software R was used for the statistical analysis (version 3.4.0, R Development Core Team, 2017; *ade4* package) (Dray and Dulfur, 2007). Each district was characterized independently due to differences in endowment and farming orientation (Table 2). The variables used for the construction of the typologies were: number of household members, yearly income, productive land holding, labour, number of tropical livestock units (TLU) and months of food self-sufficiency.

Our study focused on smallholder mixed farms which represented the majority of farms in all three sites. After the analysis of the survey data, seven farms (2, 2 and 3, respectively in Palpa, Dadeldhura and Nawalparasi) were omitted from the typology construction and subsequent analysis, as they represented commercial highly specialized farms and did not fit the focus of our study.

Three farms per resource endowment type were selected in each of the three districts to be used in the ecological network analysis (ENA) study. For these nine farms, we collected detailed data to compile a comprehensive set of biophysical and socio-economic information. The data collected was used as input for the calibration of whole-farm model FarmDESIGN (Groot et al., 2012); see Section 3.3.

In addition to the on-farm surveys, we performed on-farm measurements to quantify imports, e.g. counting the number of straw bunches or baskets (*dokos*) imported per day and measuring the dry weight of the imported biomass. Similarly, the amount of manure applied to each field was determined by estimating the number of manure baskets applied per season in each field and measuring the weight and dry matter content of the manure. Crop yields were estimated through the number of grain baskets harvested in each field and measuring the grain dry weight. Maize and soybean yields were also estimated in on-farm experiments (Alomia-Hinojosa et al., 2018).

When the total amount of feed stated by the farmer (i.e. feed produced on the farm plus the feed and fodder imported) was not sufficient to cover the calculated energy and protein requirements of the livestock, it was assumed that the difference was fulfilled by additional amounts of imported fodder. Energy and protein feed requirements were calculated based on the metabolic weight for each type of animal, the activity of the animals i.e. time spent grazing, and the production level (Groot et al., 2012). The amount of manure produced on the farm was calculated using as input the dry matter (DM) quantity supplied to the animals, the dry matter digestibility of the different feeds and fodders, and the amount of time spent by the animals on the farm. Nitrogen losses to the air through volatilization of ammonia were estimated using emission factors for different steps of the manure management chain: excretion (5% of inorganic N), storage (27%) and application (5%) to the field (Dämmgen and Hutchings, 2008). Total soil losses through leaching and denitrification were calculated from the difference between net inputs into the soil (manure including bedding and feed losses, fertilizers, crop residues returned to soil, deposition, non-symbiotic fixation) and outputs from the soil (crop uptake, erosion). Potential accumulation of soil nitrogen was calculated from the organic matter balance assuming a C:N ratio of 12. The estimated increase in soil N stocks associated to organic matter amounted to 10.7% (range 7.0–15.4%) of soil N loss on average. Losses were not corrected for this amount given the uncertainty of the estimate and the assumption of steady state conditions for the FarmDESIGN and network calculations. The percentage of N losses in eroded soil was fixed to 0.075, while the N deposition was assumed as 10 kg ha $year^{-1}$.

3.3. Whole farm model FarmDESIGN

FarmDESIGN is a static bio-economic farm and household model which supports evaluation and re-design of mixed farm systems in planning processes (Groot et al., 2012) used in this case for the

Table 2
Main characteristics of farm types with different resource endowment levels (LRE: low, MRE: medium; HRE: high) in Palpa, Dadeldhura and Nawalparasi districts, Nepal.

Resource endowment type*	Household members	Cultivated land (ha)	Tropical Livestock number (TLU)	Labour force (men/day)	Food self-sufficiency (months)	Annual income (USD)	Income from farm (%)	First income source
Palpa district – Mid-hills region								
HRE								
min*.	3	0.15	7.1	3	8	1320	36	livestock
av.	6	0.65	12.1	4	11	6957	71	
max.	7	1.22	16.6	5	12	10,780	100	
MRE								
min.	4	0.05	1.4	2	4	235	0	livestock,crops
av.	6	0.29	5.5	3	8	2117	33	
max.	10	0.65	11.1	5	12	5358	79	
LRE								
min.	1	0.05	0.0**	1	1	105	0	off-farm activities
av.	4	0.18	2.3	2	5	1369	25	
max.	6	0.45	4.1	2	12	3700	100	
Dadeldhura district - Mid-hills region								
HRE								
min.	3	0.20	0.4	2	5	310	1	off-farm activities
av.	5	0.72	5.0	3	10	2557	38	
max.	7	1.70	9.3	4	12	12,420	100	
MRE								
min.	2	0.08	0.0	1	1	30	0	off-farm activities
av.	4	0.33	4.5	2	5	894	24	
max.	7	0.75	10.4	3	11	3480	100	
LRE								
min.	5	0.05	1.2	2	1	45	0	off-farm activities
av.	7	0.27	4.1	3	4	703	23	
max.	9	0.56	6.6	5	9	2400	100	
Nawalparasi district - Low-lands region								
HRE								
min.	5	0.07	2.7	3	4	920	0	crops, external wages
av.	8	2.31	7.3	4	11	2997	30	
max.	10	8.60	14.0	5	12	9600	100	
MRE								
min.	2	0.13	0.0	1	5	550	0	external wages
av.	5	0.51	2.4	2	11	2799	21	
max.	9	1.00	6.6	4	12	6000	48	
LRE								
min.	4	0.03	0.0	2	5	50	0	external wages
av.	6	0.32	1.5	3	6	448	20	
max.	8	0.67	3.1	4	8	1050	68	

*min.: minimum; av.: average; max.: maximum.
** 0.0 indicates that farms have only between 2 and 5 chickens (0.01–0.05 total TLU).

calculation of nitrogen flows to, through and from a farm on an annual basis.

In the model, each farm was conceptualized as a network where its compartments were the different types of livestock, fields (including soil), crops, manure and household. The N flows between compartments were simulated. Each type of livestock was defined as a different compartment, e.g. cows, buffaloes and goats were different compartments. Every type of livestock was parameterized considering the animal body weight estimated on-farm, the average age, and the energy and protein maintenance requirements for each type. Crops were conceptualized in terms of cropping patterns, defined as the crops cultivated on a field during one year, including intercrops. For example, a combination of "maize + soybean (summer) and wheat (winter)" constituted one crop compartment. Most fields contained at least two crops per cropping pattern. In this way we assessed the complexity of the cropping systems including all the crops. The ratio of maize grain used for home consumption and animal feed was allocated following the percentage mentioned by each farmer.

The biomass exchanges between compartments within the system were represented as links, while exchanges between compartments and the external environment represent inflows, outflows and dissipations. The exchanges between compartments were calculated by the FarmDESIGN model. The input of the quantity of biomass per compartment was measured on-farm. Each studied farm was considered as an individual system. The boundaries of each farm system were the physical boundaries of the farm. External imports included purchased artificial fertilizers and fodder or wood collected from communal or open grasslands or forest (which constitute a fundamental part of the natural assets supporting the agroecosystem). The modelled time period for all the indicators was one year. The dry matter and N content of used for N flow quantifications are presented in Table S2.

The model was used to quantify i) the balance between the amount supplied in feed and the animal energy and protein requirements, ii) the nitrogen flows on the farm, and iii) the ENA indicators. For this last purpose, the model was extended with a module that constructs nitrogen flow matrices and calculates the indicators of activity, integration, organization, resilience and efficiency of the farm systems, as presented in Section 2 and Table S1 in the Supplementary Material.

3.4. Scenario of crop intensification

Increasing on-farm biomass productivity is one of the few options to intensify production in small farm systems, particularly in the case of mixed farms with low food and feed self-sufficiency. On-farm experiments in Nepal showed that maize and legume yields could significantly increase by using improved management practices, improved seeds and artificial fertilizers (Devkota et al., 2015; Alomia-Hinojosa et al., 2018). Therefore, we were interested in exploring the impact of increased on-farm biomass production on the indicators of integration, organization, diversity and efficiency of the on-farm.

The scenario explored in FarmDESIGN was based on the experiments done by Alomia-Hinojosa et al. (2018). The inputs used in these field experiments were used as input to the model with artificial fertilizer (urea) application in so as to reach 120 kg N per ha (and 60 kg phosphorus and 40 kg potassium per ha). The yields obtained from the experiments were used as input to the model at individual farm level. The yield increment used in the model was based on the average from the experiments performed during two years in different fields of individual farms in each of the regions. The yield for maize grain increased from 3 to 7 Mg ha^{-1}, the stover from 4 to 9 Mg ha^{-1}, soybean grain yield was set to 1.5 Mg ha^{-1} and soybean stover to 1.3 Mg ha^{-1}. It was assumed that maize and soybean stover was fed to the livestock, and the amount of feed supplied was rebalanced with animal requirements, leading to decreases of imported feed. The statistical significance of differences between the baseline and the intensification scenario were assessed with a paired sample *t*-test.

4. Results

4.1. Farm characterization

The typologies construction identified three farm types in each district. The three independent typologies showed similar relative differences across farm households in terms of resource endowment: a resource endowment gradient was revealed, from farms with lower (LRE), to medium (MRE) to higher (HRE) resource endowment (Table 2). Consequently, HRE farms were characterized by having a larger farming area and area of cultivated land, generating more income, having more labour available and being more food self-sufficient than the MRE and LRE farms in all three districts (Table 2). Most of the farms raised livestock. For LRE farms the herd mainly combined 1–2 chicken, 2–4 goats, and 1 buffalo, while HRE herds were comprised of up to 10 milking cows and 14 goats. Besides, HRE and MRE farms in Palpa generated a larger proportion of their income from livestock than the two other districts. There was a large gap between LRE and HRE in terms of annual income; on average HRE income was 3.6, 5.1 and 6.7 times higher than LRE income in Dadeldhura, Palpa and Nawalparasi, respectively (Table 2). Most farm types received a considerable proportion (29–80%) of their income from off-farm activities, which included wages from off-farm labour i.e. construction, small business, government, remittances and pensions. HRE farms generated the largest income from farm activities, yet the HRE farms from Dadeldhura and Nawalparasi still generated 62 and 70% of their annual income from off-farm sources, respectively. The HRE farms in Palpa had the largest contribution of on-farm activities in their income (70%) as these farms were specialized in milk production. The household food self-sufficiency followed the resource endowment gradient, with on average shorter periods of food shortage for HRE than for MRE and LRE households. Farms in Nawalparasi produced a larger quantity of on-farm feed than farms in the mid-hills (Table 2).

4.2. Nutrient flows and indicators

The networks of on-farm nitrogen flows of the 9 representative farms (three farms per farm types in each of the three districts) were complex with a multitude of N flows between farm (sub) compartments. An example is presented in Fig. 3. HRE farms in the three districts had the highest number of compartments (Table 3). Farms in Dadeldhura and Nawalparasi tended to have a larger crop diversity resulting in more sub-compartments, while in Palpa the animal density was higher, with up to 31 TLU/ha on the MRE farm in Palpa (Table 3), consequently imports and losses were also higher than in the lowlands.

The farms in the mid-hill districts of Palpa and Dadeldhura imported more N in the system than those in the low-lands region (IN; Table 3). Palpa had on average 60% more N imports than Dadeldhura and 70% more than Nawalparasi. The farm with the highest animal density (31 TLU ha^{-1}) had the highest imports of 1584 kg N ha^{-1} year^{-1}. All the representative farms presented low flexibility and a high degree of order, and consequently had low RN. Farms in Palpa showed the lowest values (Table 3).

A strong correlation between N imports and animal density was identified (Fig. 4). Imports were primarily related to off-farm fodder collection and purchase of supplementary feed. When inputs rates increased the flow network activity increased as well as losses per unit of area (Fig. 4). The fraction of nitrogen cycling within the systems as reflected in the Finn Cycling Index (FCI) was lower than 10% in most of the farms except the HRE farm in Palpa with 15% FCI, while the lowest cycling was found in the farms of Dadeldhura with less than 3%. As a consequence, the dependence (D) was high but similar for the three districts, while on average it was higher for the LRE farms than for the other farm types (27% for LRE in contrast to 25% of the MRE and 24% of the HRE farms). The MRE farm in Nawalparasi was the most efficient with low inputs, balance and dependency, and high values for the average path length and cycling index FCI (Table 3). In general, the farms in Nawalparasi had higher feed self-reliance (SR) than the farms in the mid-hills with the exception of the HRE in Palpa that produced on-farm fodder.

Correlation analysis demonstrated that increased farm intensity (higher livestock density and input rates; larger nutrient balance and losses) was positively correlated with A, Φ and C ($P < 0.05$; Table 3, Figs. 4 and S1). Farm intensity was negatively correlated ($P < 0.05$) with nutrient cycling (FCI), NUE and feed self-reliance (SR). On the other hand, increasing the path length (APL) and link density (LD) was positively related to FCI, NUE and SR, and also reduced the dependency D ($P < 0.05$; Table 3 and Fig. S1). Moreover, this was correlated with higher values of both AMI and H_R, although significant relations with the AMI/H_R and A/C ratios were not detected (Fig. S1). For AMI and D there was a relationship with the Shannon index, indicating that higher crop diversity was positively correlated with AMI and negatively related to D (Fig. 4).

4.3. Scenario of crop intensification

The scenario exploring the impacts of improving crop productivity through improved crop management showed that size and network activity of the farm systems were not affected by increasing maize and soybean yield. However, although artificial N fertilizer was used, the total N imports and losses in the system decreased slightly, as the imports of fodder declined (Fig. 5).

Significant changes in the cycling, integration, dependency and self-reliance for all the farms studied were shown when improving maize-legume yield (Table 4). The integration of N flows increased as well as the feed self-reliance. The dependence of the farms decreased in the intensification scenario (Table 4, Fig. 5). Similarly, the organization (AMI) and diversity (H_R) of N flows increased. The degree of order (A/C) of the N flows significantly decreased in the intensification scenario (Table 4). As a result, the degree of order values moved closer to the higher values of robustness (R_N; Fig. 6).

5. Discussion

The analysis of N flow networks within representative smallholder farms in the three agroecosystems in Nepal showed that N networks were relatively inflexible and unbalanced resulting in low robustness (Table 3, Fig. 6) which could make them vulnerable to collapse. The low robustness of the farm N networks is related to the unidirectional flows from inputs to losses, and hence their low N recycling capacity. These unidirectional flows were the result of high livestock densities

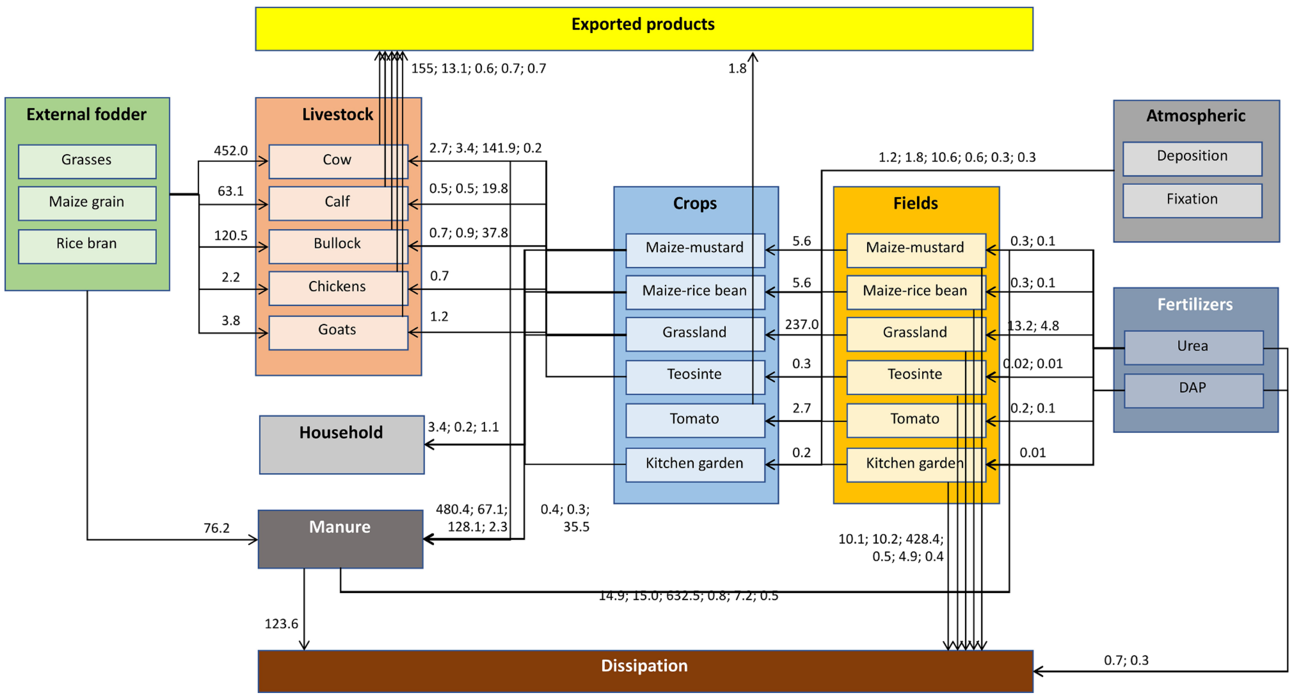

Fig. 3. Nitrogen flows diagram for the HRE farm in Palpa, expressed in kg N ha^{-1} year^{-1}. The numbers above the arrows represent the quantity (kg N ha^{-1} year^{-1}) of N that flow between components. The exported products, external fodder, fertilizers, and the N dissipation are outside of the farm system boundaries.

which caused high dependency of N imports in the form of fodder (Fig. 4), while on-farm resources such as animal manure and crop residues remained unutilized and were largely lost. In the explored scenario of increased maize and legumes yields, it was observed that although new N imports in the form of artificial fertilizer were added, total system N imports decreased as a result of the consequent reduction of N imports in the form of fodder (Fig. 5). Therefore, farm N recycling improved (FCI and TSTc), while N losses and external N dependency decreased. The system flexibility improved leading to a better balance with the system's degree of order and thus resulting in an increase in robustness (Fig. 6).

The quantification of the N flows was partly based on FarmDESIGN model and scenario assumptions (Groot et al., 2012). For instance, in the intensification scenario it was assumed that a large part of the

Table 3
Network flow indicators of selected farms representing farm types with different resource endowment (LRE: low, MRE: medium; HRE: high) in Palpa, Dadeldhura (mid-hills) and Nawalparasi (lowlands) districts, Nepal.

Indicators	Palpa			Dadeldhura			Nawalparasi		
	HRE	MRE	LRE	HRE	MRE	LRE	HRE	MRE	LRE
Farm area (ha)	1.22	0.19	0.10	0.81	0.60	0.19	0.76	0.24	0.30
*Number of fields/crops**	6/8	3/5	3/6	5/12	5/9	5/11	6/13	6/16	2/4
Animal density (TLU/ha)	12.0	30.8	10.5	5.4	6.5	17.2	5.3	5.9	2.0
IN (kg N ha^{-1} year^{-1})	756	1584	741	286	307	645	425	258	273
BAL (kg N ha^{-1} year^{-1})	580	1149	558	242	239	553	292	86	126
NUE (-)	0.23	0.28	0.25	0.15	0.22	0.14	0.31	0.67	0.54
SR (-)	0.31	0.11	0.28	0.11	0.16	0.12	0.36	0.43	0.39
N (compartments)	22	13	12	18	17	17	21	18	10
LD (links/compartment)	4.27	4.08	3.42	4.06	4.29	4.24	4.95	4.39	3.10
T (kg N ha^{-1} year^{-1})	4105	6978	3490	1320	1460	3143	2144	1603	1219
TST (kg N ha^{-1} year^{-1})	2459	5068	2377	997	1086	2329	1492	1039	889
APL	4.26	3.34	3.70	3.47	3.61	3.71	3.91	5.06	3.45
D (–)	0.22	0.29	0.27	0.27	0.26	0.25	0.24	0.19	0.29
FCI (–)	0.147	0.026	0.071	0.018	0.022	0.029	0.047	0.099	0.034
AMI (bits)	2.11	2.03	2.19	2.08	2.20	2.16	2.32	2.46	2.06
H_R (bits)	2.89	2.96	2.83	3.25	3.47	3.22	3.67	3.70	2.95
Ratio AMI/H_R (–)	0.73	0.69	0.77	0.64	0.63	0.67	0.63	0.66	0.70
A (kg N ha^{-1} year^{-1})	8671	14,176	7635	2749	3209	6787	4967	3945	2510
Φ (kg N ha^{-1} year^{-1})	7059	14,187	4752	3139	3793	6824	6008	4149	2227
C (kg N ha^{-1} year^{-1})	15,730	28,363	12,387	5888	7002	13,611	10,975	8094	4737
Ratio A/C (–)	0.55	0.50	0.62	0.47	0.46	0.50	0.45	0.49	0.53
RN (–)	0.89	0.94	0.81	0.97	0.97	0.94	0.98	0.95	0.91

* Kitchen garden and mixed vegetables are counted as one, but can have a diverse composition. Counts the number of cultivations of crops, the same crop can be cultivated on multiple fields and in different seasons or intercropped, the instances are counted separately.

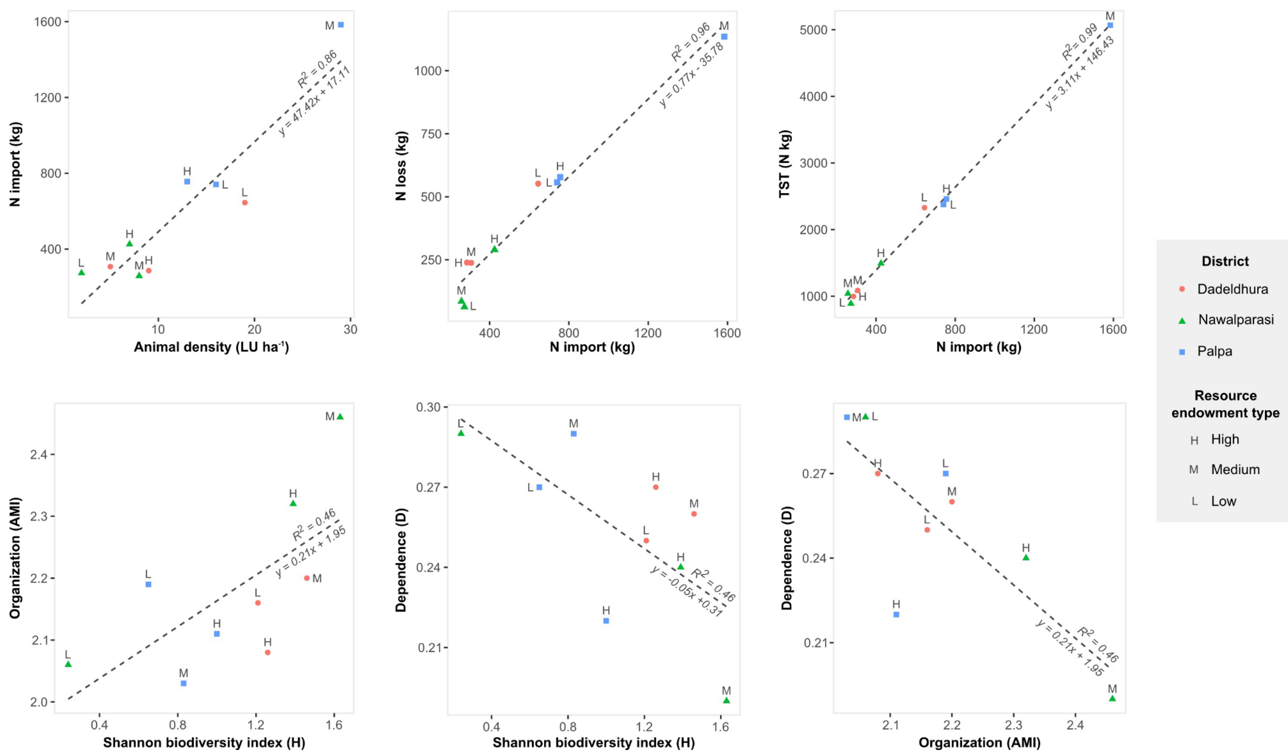

Fig. 4. Relationships between indicators of farming intensity (inputs and animal density), organization, diversity and integration.

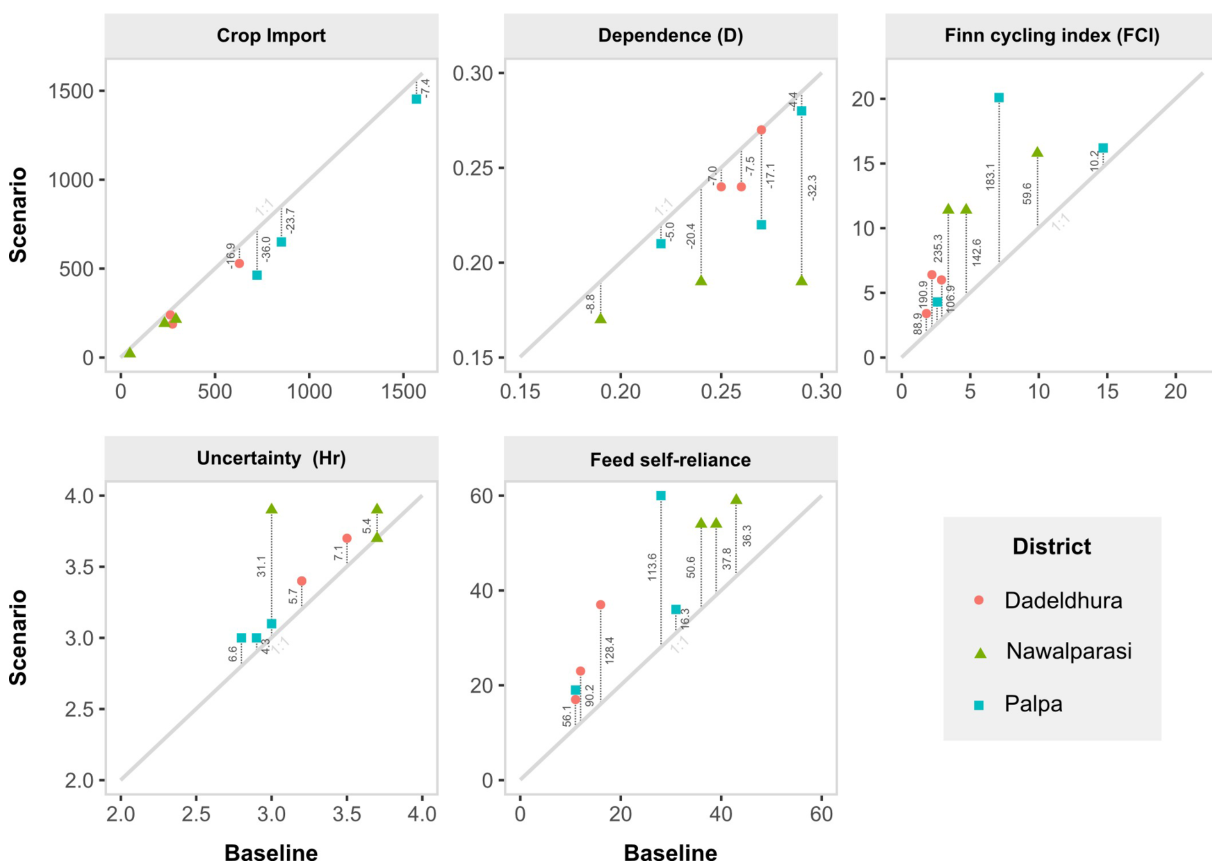

Fig. 5. Comparison between the baseline and the increase crop yield scenario with the percentage of change for the nine mixed farms in Palpa, Dadeldhura and Nawalparasi districts, Nepal.

Table 4
Main values of ENA indicators for baseline and crop intensification scenario of different resource endowed farm types in Palpa, Dadeldhura and Nawalparasi.

District	Type	NC	TST	TSTc	FCI	AMI	Hr	SR	D	Loss	Balance	FYM	A/C	ϕ	R_N
Baseline (indicators)															
PLP	H	22	3388	929	14.7	2.11	2.89	30.7	0.22	578	580	20,686	0.55	7059	0.89
PLP	M	13	5441	373	2.6	2.03	2.96	10.6	0.29	1135	1149	3115	0.50	14,187	0.94
PLP	L	12	2753	376	7.1	2.19	2.83	27.9	0.27	557	558	1350	0.62	4752	0.81
DDL	H	17	1051	55	1.8	2.08	3.25	10.7	0.27	239	242	5048	0.47	3139	0.97
DDL	M	18	1172	85	2.2	2.20	3.47	16.2	0.26	238	239	2564	0.46	3793	0.97
DDL	L	17	2537	207	2.9	2.16	3.22	12.3	0.25	552	553	3425	0.50	6824	0.94
NWP	H	21	1738	246	4.7	2.32	3.67	35.8	0.24	290	292	4422	0.45	6008	0.98
NWP	M	18	1356	317	9.9	2.46	3.70	43.0	0.19	85	86	1556	0.49	4149	0.95
NWP	L	10	949	60	3.4	2.06	2.95	39.2	0.29	63	126	125	0.53	2227	0.91
Improved yield scenario (indicators)															
District	*Type*	NC	TST	TSTc	FCI	AMI	Hr	SR	D	Loss	Balance	FYM	A/C	ϕ	R_N
PLP	H	22	3278	1042	16.2	2.13	3.01	35.7	0.21	518	519	20,484	0.53	7557	0.92
PLP	M	15	5571	241	4.3	2.05	3.08	18.7	0.28	1075	1086	2784	0.48	15,784	0.96
PLP	L	14	2196	863	20.1	2.27	3.02	59.6	0.22	301	302	1062	0.59	4253	0.85
DDL	H	20	1032	100	3.4	2.08	3.43	16.7	0.27	228	231	4709	0.43	3560	0.99
DDL	M	21	1057	214	6.4	2.23	3.72	37.0	0.24	164	165	2440	0.42	3948	0.99
DDL	L	20	2576	155	6.0	2.16	3.40	23.4	0.24	498	499	3164	0.46	7990	0.97
NWP	H	21	1823	580	11.4	2.42	3.87	54.0	0.19	187	189	4096	0.45	6474	0.98
NWP	M	20	1458	230	15.8	2.46	3.73	58.6	0.17	38	40	1349	0.48	4546	0.96
NWP	L	21	1823	580	11.4	2.42	3.87	54.0	0.19	187	189	4096	0.54	2518	0.91

Where PLP: Palpa; DDL: Dadeldhura; NWP: Nawalparasi; NC: number of compartments; TST: total system throughflow (kg N $year^{-1}$); TSTc: total cycled system throughflow (kg N $year^{-1}$); FCI: Finn's cycling index (%); AMI: average mutual information (Bits); Hr: statistical uncertainty (Bits); SR: feed self-reliance (%); D: dependency (–); Loss: N losses (kg N $year^{-1}$); Balance: N balance (kg N $year^{-1}$); FYM: farm yard manure (kg DM $year^{-1}$); A: ascendency (kg N $year^{-1}$); C:capacity (kg N $year^{-1}$); Φ: overhead (kg N $year^{-1}$); R_N: robustness (–).

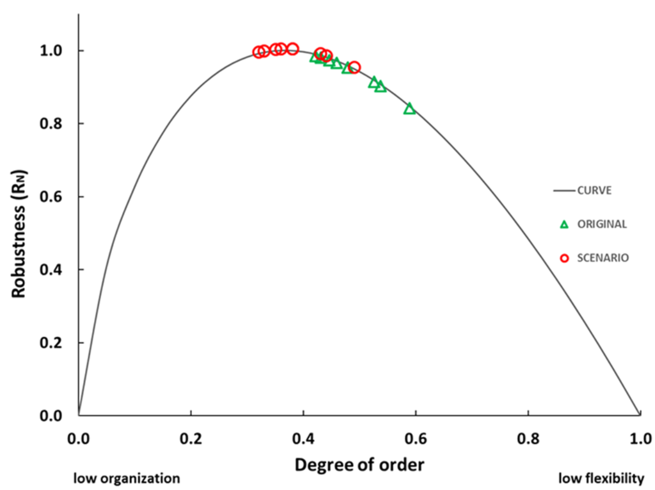

Fig. 6. Relationship between the degree of order and robustness (R_N) of the N flows of nine farms in the baseline (in green) vs the intensification scenario (in red), in Palpa, Dadeldhura and Nawalparasi districts, Nepal.

residues from maize and soybean were used as fodder, but this would not necessarily apply to all the farms. Some farmers although having enough residues prefer fresh fodder for quality reasons.

ENA allowed analyzing key system properties such as organization which represents system's directionality, but also adaptability and stability (Rufino et al., 2009a). Earlier studies using ENA showed that it can be an effective way to identify weaknesses and critical points to target interventions (Alvarez et al., 2014), while contributing to unravelling problems associated with intensive agricultural systems by providing a more holistic view of the interactions between natural systems and agriculture (Bohan et al., 2013). Network analysis can provide a good approximation to assess integration from the behaviour of system feedbacks within social-ecological systems (Bohan et al., 2013). The values of the metrics of ENA are always dependent on the delineation and conceptualisation of the system. Our approach is in line with earlier published approaches of network analysis in agroecosystems (e.g. Rufino et al., 2009a,b; Alvarez et al., 2014). However, our complementary use of the whole-farm model allowed to better decompose the farm and its nutrient dynamics, and clearly separate crops from soils (allowing including crop uptake as flows) and different manure flows (from various animal types and to separate fields). This created a larger complexity, but also a better representation of the actual flows on farms.

Our analysis demonstrated that ENA can facilitate quantifying flows organization at farm level, which could not be explored by single efficiency ratios (e.g. the N use efficiency or N productivity, calculated as the ratio between crop yield and N inputs). From a whole farm perspective, more N in the system does not necessarily mean more productivity (Table 3). System N productivity is not merely the result of the quantity of N entering the system but also of the activity, organization and diversity of the flows of N which entails the cycling and recycling of N in the system. For longer term system stability, diversity might be desired. However, for short term gains unidirectional flows towards products might be preferred.

Earlier studies of Alvarez et al. (2014) and Rufino et al. (2009b) showed that differences in ENA indicators between farm systems in Sub-Sahara Africa were related largely to differences in livestock densities. Livestock densities in the lowlands of Nepal (2 to 6 TLU ha^{-1}) were comparable to those reported by Alvarez et al. (2014) in Madagascar (1 to 3 TLU ha^{-1}) and by Rufino et al. (2009b) for mixed systems in Ethiopia, Kenya and Zimbabwe (1 to 10 TLU ha^{-1}). However, livestock densities in the mid-hills (from 5 to 31 TLU ha^{-1}) were considerably higher. Livestock densities influence the activity of the N networks (Table 3, Fig. S1) because N imports (in form of feed) significantly increase when livestock density increases. As a consequence, the N imports and losses also increase. This same pattern was observed in the case studies in both Nepal and Sub-Saharan Africa.

Farms in Nepal exhibited better integration (recycling) than the African farms analysed by Alvarez et al. (2014) and Rufino et al. (2009b). The N cycling in the farm systems in the mid hills (FCI of 1.8

to 4.7%) was lower than in the farms of the low-lands (7.1 to 14.9%), but values were higher than the values calculated in Madagascar (2.5 to 4.4%) and in Ethiopia, Zimbabwe and Kenya (0.1 to 11%) (Rufino et al., 2009b; Alvarez et al., 2014). The integration in Nepalese farms could be further improved as farms are based on cereal production which have a commonly a dual use for food and animal feed, particularly in the lowlands where three cropping seasons are possible. The organization (AMI) across the farm systems of Nepal did not vary considerably among farm types as reported in farms in Sub-Saharan Africa. In general, it was higher than in the farms in Madagascar. Although with not a big difference, low resource endowment farmers across the districts in Nepal were more dependent on N imports with 20% vs 18% of the wealthier ones. Larger differences have been observed in African farm systems where poor households have a reliance on imports of 65% in contrast to 45% of the wealthier ones (Rufino et al., 2009b). In our study, the difference in topography and climate between districts (Table 1) influenced the cropping patterns and production orientation of the farms, but farm features and performance (Table 2) and N flow metrics (Table 3) were not systematically different between districts; resource endowment had a much stronger effect on these farm characteristics.

When increasing on-fam maize and legumes productivity, the network's organization did not significantly change. However, the crop productivity lead to more diversity of flows (H_R) and overhead of the network (Φ), which means that T was partitioned among a greater number of flows (Rufino et al., 2009a). The diversity (or absence of order) makes it possible for a system to persist over the long run (Ulanowicz et al., 2011) as a result of more redundancy that strengthens system resilience in case of disturbance. TSTc increased relative to total system throughflow, and consequently FCI significantly increased showing a more recycling of N in the farm. More flow connections emerged because more crop residues were used as feed.

One of the innovative aspects of our study is the quantification of the indicators of ascendency and overhead to calculate robustness of agroecosystems as the balance between these system characteristics. This concept has been used by Patzek (2008) to study the sustainability of agroecosystem of for example, the maize production in the USA. Patzek (2008) concluded that the productive industrial maize agricultural system is unsustainable, among other reasons because it relies on external (fossil fuel) inputs and is not cyclic. Mixed farm systems in Nepal - characterized by high livestock densities - do not rely on external fossil fuel, instead they are dependent on external N mainly in the form of fodder. This causes a similar unidirectionality of N flows, creating too constrained and inflexible farm systems as observed for the USA maize systems studied by Patzek (2008). By increasing on-farm maize and legume yields in our scenario analysis the farm systems moved closer to an optimum R_N (Fig. 6), losing the organized power but becoming more flexible and less unidirectional.

Robustness to changes can be considered a precondition for sustainability (Kharrazi et al., 2013). However, the concept of robustness to assess sustainability at farm-level is incomplete, neglecting the complexity of the farm system. It fails to explore the multitude of aspects that sustainability involves. Sustainability of the farm systems requires an integrated and comprehensive assessment of ecological, social and economic aspects of the agroecosystem (López-Ridaura et al., 2002; Lichtfouse et al., 2009; Rockstrom et al., 2009). The concept of robustness has also been applied for socio-ecological systems, where it refers to the capacity of the system to continue meeting a performance objective under uncertainty and shocks (Janssen and Anderies, 2007). The quantification of robustness in our study has a biophysical focus, omitting the socio-economic aspects. Our results based on 9 representative pilot farms suggest that increasing crop yields leads to farm systems gaining in flexibility and robustness. However, the increase of N fertilizers can create the dependency on external inputs of the farms, which could increase socio-economic farm vulnerability.

For the studied farms in Nepal, negative environmental side-effects of concentrating nitrogen from imports could be reduced by improving the use of organic resources. In particular, the management of farmyard manure can be largely improved to reduce losses. Manure losses may occur from manure stored in heaps for extended periods of time (Shah et al., 2013), or during its application, when applied irregularly in the field, e.g., accumulation of manure in the fields close to the homestead (Tittonell et al., 2010). Since most of the livestock is kept on-farm (especially for the farms in the mid-hill locations), N losses are easier to control with small improvements in manure handling, e.g. covering the manure (Shah et al., 2013). However, underlying causes of poor manure management require attention. These include high labour costs in form of both the time allocated from the family labour and the financial cost for hired labour to transport and apply the manure. These constraints discourage farmers to recycle nutrients in crop production (Ruben et al., 2006). Other challenges to managing N flows and closing N cycles in the fragile environments of the mid-hills and Nepal include the hilly terrain and the lack of farmer training and extension. Moreover, despite the efforts of NGOs and research for development projects, the technology and mechanisation level are still low in farms in Nepal. As a consequence, crop and animal management are often sub-optimal (e.g., low plant density in crops, inefficient crop residue use and imbalanced animal feeding), which leads to increased risks of nutrient losses and inefficiencies in smallholder farming.

6. Conclusions

The analysis of N flow networks within representative mixed crop-livestock, smallholder farms in three contrasting agroecosystems of Nepal revealed that they were able to recycle only a small portion of the total N that flows within the network and because of high inputs of livestock feed high rates of N losses occurred. These losses were large due to the high livestock densities, which also caused high dependency on N imports in the form of fodder. Farms in the mid-hill regions imported more N than farms in the lowlands.

The N networks in the farm systems of the three districts were unbalanced (low robustness) and inflexible/constrained (poorly resilient) particularly for the farms in Palpa and for the least endowed farm types in all districts. The crop intensification scenario demonstrated that higher maize and legume yields could result in reduction of farm fodder imports. This would decrease the total N imports onto the farm system, as well as N losses, despite additional N imports in artificial fertilizer and increased the flows among compartments. Most importantly, the improved system flexibility under this scenario led to increased flexibility and greater robustness.

The outcome of this paper suggests that incrementing on-farm biomass production is a pathway to increase the robustness of farm systems. The analysis of robustness to assess sustainability at a farm-level could be complemented with an assessment of the socio-institutional complexity of the farming systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.105883.

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