FARMER PERSPECTIVES ON SUSTAINABLE CROP- LIVESTOCK INTREGRATION IN CEREAL BASED FARM SYSTEMS OF NEPAL

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Farmer perspectives on sustainable crop-livestock integration in cereal based farm systems of Nepal

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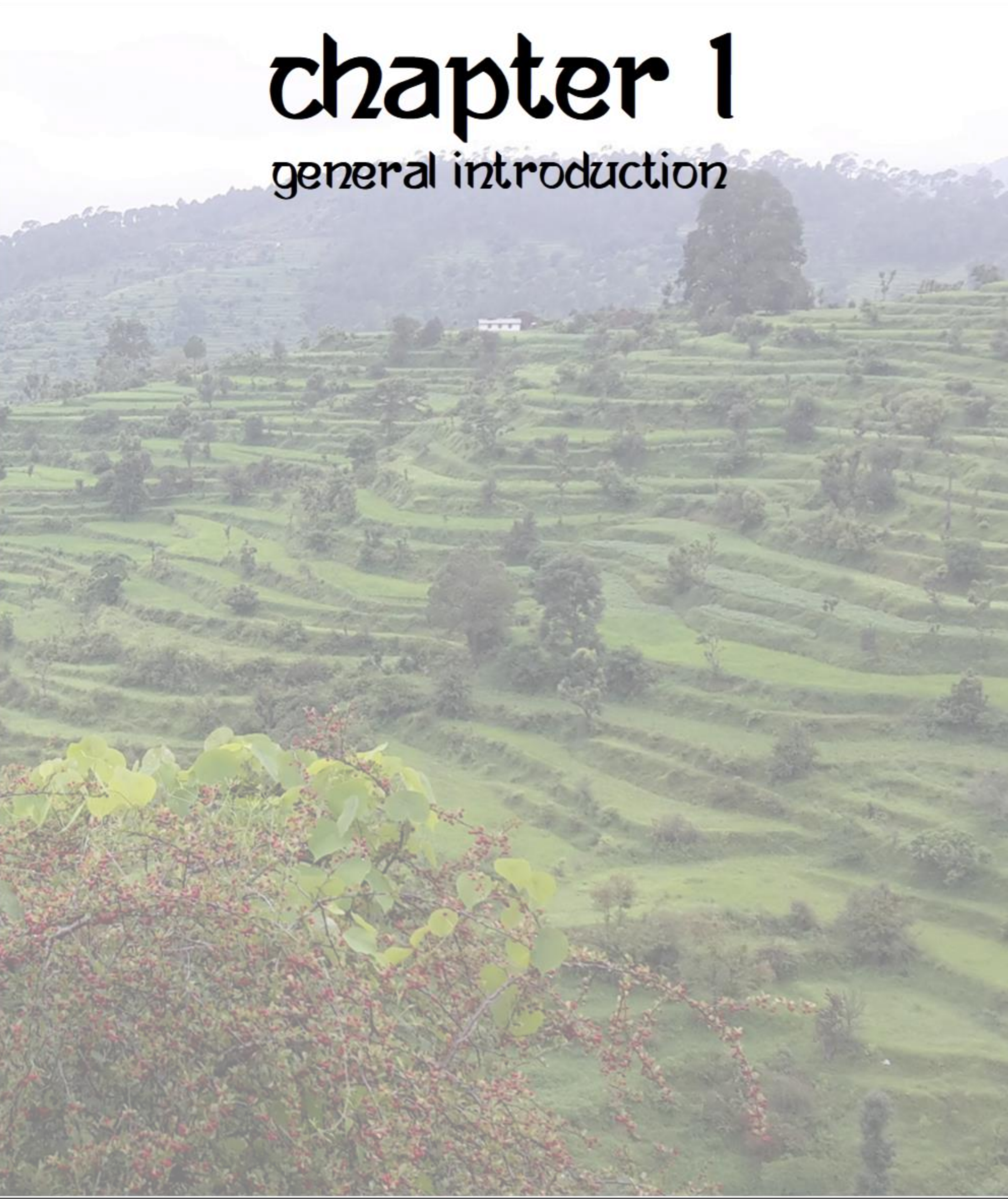
To Surya, for showing me the true reason of this thesis

A Nina, que me dio fuerza para terminarla

Table of contents

chapter 1
general introduction



1. General Introduction

1.1. Background

Many of the high-income countries have developed a system of large-scale, industrial agriculture but small-scale farmers still play an important role in feeding rural communities in low or low-middle income countries (Lowder et al., 2016). The Food and Agricultural Organization of the United Nations (FAO) estimated that 84% of farms worldwide are categorized as small-scale farming systems (FAO, 2017). Although an operational definition of the term "small-scale farmer" is still debated, it generally includes families cultivating a land area smaller than two hectares. Interestingly, even though small-scale farms operate 12% of the world's agricultural lands, the contribution of food commodities generated by small-scale farmers to communities in sub-Saharan Africa, South Asia, Southeast Asia, and China is estimated as high as 30% (Fanzo , 2017). With close to 60% of the human population living in Asia (UN, October 2019), it comes as no surprise that 74% of the world's farms are concentrated on this continent (Lowder et al., 2016). In their latest briefing on the world economic situation and prospects, the UN mentions that although "Asian economies have achieved tremendous progress in lowering extreme poverty over the past few decades, many segments of society are still being left behind" (UN, 2019). The poorest segments of the world´s communities can be commonly found in densely populated areas. It is in these areas that farm sizes have decreased by continued fragmentation, resulting in smaller farmlands per family. Although there exists a large diversity of small-scale farming systems, they are often classified as mixed agroecosystems where the production of food crops in combination with raising livestock are at a low-to-medium level of intensity. As a result, small-scale farming families in developing countries in Asia often are affected by food-insecurity, which could lead to malnourishment, even though these farms effectively produce much of the food themselves (Sibhatu and Qaim, 2017).

One of humanity's greatest challenges has always been to feed the growing global population. Current predictions indicate population growth until the end of the century, resulting in an increase in food demands. With the latest estimations forecasting a population growth of at least 2.5 billion people by the year 2050, the world is seeking solutions to increase food production. Furthermore, as the world continues to develop, the demand for animal protein will grow rapidly as more people are expected to be able to afford meat (FAO, 2009; Godfray et al., 2010). In line with the 2030 FAO agenda, this increase in productivity must be achieved in a sustainable manner, with less input of fertilizers and pesticides, more in balance with nature (FAO, 2015). In this thesis, I investigate options to achieve sustainable intensification in smallholder farm systems in Nepal.

1.2. Nepalese context

Nepal is a country that displays a mosaic of geographically and climatically diverse landscapes in the middle of the Himalaya mountain range. The higher altitude range of Nepal consists of thousands of glaciers that are the sources for more than 6000 Nepalese rivers (Alford and Armstrong, 2010). In addition to melting glacial waters, Nepal’s hydrology is surprisingly dependent on the monsoon season that brings on average 85% of the country´s annual rainfall between June and September (Bartlett et al., 2010). Nepal’s immense water supplies feed directly into the large tributaries of major downstream rivers across South Asia, including the Ganga, thereby providing water to approximately one billion people (Alford and Armstrong, 2010). With close to 2.3% of the world’s water resources, Nepal is second only to Brazil when water-wealth (Gurung et al., 2019). However, as abundant as water is in Nepal, close to a fifth of the Nepalese population lacks access to safe drinking water, predominantly due to a lack of infrastructure (UNICEF Nepal, 2018).

Nepal is locked in-between China and India, superpowers to the north and south and the two most populous countries in the world. Nepal’s current 29 million inhabitants are expected to double in the next 30 years, one of the highest growth rates observed in Asia (UN, 2019). The social stratification system of traditional “castes” is different today compared to what it was in 1950, but Nepal is still home to 125 castes or ethnic groups (UNFPA Nepal, 2017; Subedi et al., 2019). About two-thirds of the Nepali population identifies itself as Hindu, followed by Buddhist (9%), and Muslim (5%). In 2018, a quarter of the Nepali population aged 15 years and older was illiterate (UNESCO, 2019). Although the valley of the capital of Kathmandu is one of the fastest-growing metropolitan regions in South Asia, which could be interpreted as a sign of a transition towards urbanization, 4 out of 5 Nepali people still live in rural areas (Muzzini and Aparicio, 2013; FAO, 2018). Similar to other countries in South Asia, throughout its history, Nepal has always had high rates of undernutrition. However, despite several years of political instability and the massive earthquake that struck the country in early 2015, Nepal has been mentioned as a success story for the remarkably fast reduction in the undernourishment of its people (Headey and Hoddinott, 2015). In 1999, 5.2 million Nepali were estimated to be undernourished but this number more than halved over the past two decades; only approximately 8% of Nepali people were severely food-insecure in 2018 (FAO, 2018). Policies to combat severe food insecurity, malnutrition, and overall poverty remain high on the political agenda of the Nepalese Government (Bista et al., 2013).

Although Nepal is still placed among the least developed countries in the world, it´s gross domestic product (GDP) is expected to grow by 7.1% in 2019 and 6.3% in 2020, the second highest growth in South Asia (Asian Development Bank, 2019). Moreover, this growth of Nepal´s economy is also projected for the medium term, based on the prospect of private investment and consumption that is directly fueled by a steady inflow of remittances (Ezemenari and Joshi, 2019). The largest driver of the economy of Nepal is the influx of international aid and remittances, mostly comprised of the money that Nepalese migrant workers send back home to their families. Last year, migrant workers sent home an estimated $8.1 billion, which corresponded to 28% of the country's GDP (Ezemenari and Joshi, 2019).

However, agriculture is the true backbone of the Nepalese economy and the largest contributor to the GDP after migrant worker remittances. Although the contribution of agriculture, forestry, and fishing was as high as 70% in the mid-1970s, today the agricultural sector alone accounts for 26% of the GDP (UNCTAD, 2011; CIA, 2019). More importantly, it generates in-country employment to 59% of Nepali men and 80% of Nepali women (The World Bank, 2019).

Nepal can be divided into three zones that differ in climatic conditions. The first zone is comprised of the fertile plains of the Terai, whose valley parallels the lower ranges of the Himalayas and flank the border with India. The Terai valley offers a uniform tropical to sub-tropical climate with altitudes between 100 and 1000 meters above sea level (masl). These conditions allowed for the extensive cultivation of a wide range of crops including cereals, vegetables, and fruits, facilitating the development of the nation's best infrastructure and better market access. The transition from rural communities to cities is most visible in this part of Nepal and comes with livelihood changes. For example, the growing urbanization has increased the demand for livestock products in the area (Yadav and Devkota, 2005).

The second and largest zone includes the mid-hills, stretching roughly from 1000 to 2500 masl. This region has a variety of climates, starting with sub-tropical milder conditions in the foothills flanking the Terai to the south, which allows for rice cultivation and both temperate and subtropical fruit crops. Climbing toward the higher mid-hills, sub-tropical conditions change into temperate climates. The topography of the mid-hills includes many hills and mountains, creating slopes that make agricultural practices challenging when compared to the relatively flat Terai. However, the mid-hills include some of the most fertile valleys in Nepal (FAO, 2015). Depending on the altitude, steepness, and directionality of the slopes, farmers commonly cultivate main commodities like temperate fruits, maize, potatoes, and various spring/winter crops in the mid-hills region (FAO, 2015). With increased elevation, livestock such as sheep and goats become more important than arable land for farming families on isolated farms, partly due to seasonal snowfall and the production of manure (Merrey et al., 2018).

The third zone is called Mountain region (Himal), as it contains the highest parts of Nepal (>2500 masl). The Mountain regions are characterized for their severe climate with snow that prevails for a large part of the year. Although not as populated as the mid-hills and the Terai, subsistence agriculture in these high-altitude regions is dominated by traditional crops such as local beans, buckwheat, and millet, often in combination with yaks or other livestock that can persist in these rough high-altitude conditions (Merrey et al., 2018).

Interesting nationwide tendencies in current Nepalese agricultural practices are the increasing numbers of livestock, mainly cattle, buffalo, and chicken. This might be correlated to the growing demand for and average supply of animal protein, per capita, in Nepal (The World Bank, 2018).

The productivity of cereals in Nepal is significantly lower than the productivity of cereals in other South Asian countries; Nepal produces, on average, 2.8 tons of cereals/hectare (ha), whereas the average of all South Asian countries combined is 3.5 tons of cereals/ha (The World Bank, 2018).

Several factors have been shown to limit agricultural productivity in Nepal, such as low levels of soil fertility, limited access to external inputs, a lack of functioning irrigation systems, ongoing land fragmentation, and increasing soil erosion (Basnyat, 1995; Kiff et al., 1995; Pilbeam et al., 2005; Dahal et al., 2007; Tiwari et al., 2010; Das and Bauer, 2012). Moreover, larger scale socio-economic factors influence community and farm household dynamics. Seasonal off-farm jobs or permanent emigration to emerging international job markets such as in the Middle East, offer an alternative to diversify income sources (remittances), but have consequently reduced the availability of sufficient farm labour in Nepal (Dahal et al., 2007; Blake, 2012; Nepal Central Bureau of Statistics, 2012).

Due to land scarcity, the possibilities for expansion of novel arable lands suited for crop cultivation are limited in Nepal. Intensification of existing small-scale farm practices has been used as an interesting strategy aimed at increasing agricultural production levels, particularly in the densely populated lowland regions such as the Terai (Dahal et al., 2007). In contrast to the better infrastructure, favorable climatic conditions, and a better access to local markets as offered by the Terai, farmers of agroecosystems of various parts of the mid-hills encounter more difficulties due to the remote topography and poor access to infrastructure. Farmers there often cultivate their land on slopes and are therefore faced with higher levels of soil erosion. Farmers in these hills and mountains often cultivate their lands with a lower availability of external inputs due to an insufficient financial situation which does not allow them to buy fertilizers or lack mechanical help to plough fields (Wymann von Dach et al., 2013). Farmlands in the mid-hills are commonly inherited like almost all the farming systems in Nepal. Moreover, farmer households in the mid-hills are mainly based on cereal production (e.g. maize, wheat, and rice) and livestock. Both cereals and livestock are a source of income and at the same time provide a reliable buffer in times of food shortages. In fact, livestock not only provides valuable manure to fertilize crops but also delivers draught power to work the fields more efficiently, thereby strengthening the integrated nature of farming systems in the mid-hills region (Kiff et al., 2000). Pilbeam et al. (2000) estimated that approximately 80% of all nitrogen (N) supplies enter the agricultural soils of the mid-hills via the application of livestock manure. However, the productivity of Nepalese crop-livestock systems is relatively low. This low productivity could be explained by the trade-offs at both the farm and the landscape level that farmers are known to face on a day-to-day basis; managing crop-livestock intensification with the low availability of farm labour is not easy, nor is finding a balance between maintaining the low environmental impact of farming practices while also competing for natural resources. In fact, a small amount of fodder is often obtained from on-farm trees or crop residues and roadside grass, whereas tree leaves are generally gathered from communal forest areas nearby (Kiff et al., 2000; Devendra and Thomas, 2002; Lawrence and Pearson, 2002; Thorne and Tanner, 2002). Consequently, Nepal’s natural forest coverage has progressively decreased from 34% in 1990 to 25% in 2005. Until 2017, this coverage has remained constant (FAO, 2018). However, due to higher levels of climate variability, the availability of fresh fodder throughout the year is no longer reliable. This additional insecurity has resulted in higher farm labour demands to ensure sufficient fodder. In turn, this tendency has shown to lead to a larger number of wildlife-related incidents on the farms, as wild animals damaged important crops such as maize and fruits. Climate variability is expected to lead to the disruption of the normal monsoon cycle, which in-turn might lead to more frequent incidences of prolonged periods of either drought or floods. The effects of climate change on important weather events such as the monsoons might negatively impact agricultural production systems and existing infrastructure, thus destabilizing food security or poverty-reduction campaigns in Nepal (Gornall et al., 2010).

1.3. Crop-livestock integration to improve agricultural sustainability

The design of food systems that can produce sufficient and diverse food, maintaining environmental quality standards and without disrupting the socio-economic stability of rural farming families, is an on-going worldwide challenge (Godfray et al., 2010; Garnett et al., 2013; FAO, 2014; de Fries et al., 2015). Sustainable intensification can address this challenge because on one hand it enhances production of agricultural commodities without increasing farm areas, while on the other hand it reduces environmental impacts. This can be explained by the principle of sustainable intensification which focuses on a higher efficiency of external inputs by improving integration and management of ecological processes (Pretty, 1997; Reardon et al., 1999; Keating et al., 2010; Tittonell et al., 2014). Integrated crop-livestock systems contribute to this efficient design of sustainable farming systems because they promote a holistic approach aimed at synergy and balance between soil, plant, animal and atmosphere. (Gliessman, 2006; Russelle et al., 2007; Hendrickson et al., 2008a; Erenstein et al., 2015). Integrated crop-livestock systems involve temporal and spatial interactions at different scales, with both animals and crops, within a similar area, in a rotation or succession-based farming system (de Moraes et al., 2014).

Although most of the farm systems in Nepal are of a mixed nature, a growing number of farms are becoming specialized in producing income-generating commodities such as vegetables and milk. High livestock densities are rather common in Nepal due to the small farm size, resulting in high pressure on the system. Therefore, future livestock specialization would result in increasing densities to the limit of what a system can cope with. This transition poses a serious threat to the overall sustainability of Nepalese farming systems (Behera and France, 2016). In general, specialized crop or livestock systems can have negative effects on the environment. First, these systems negatively affect the agrobiodiversity because they commonly operate as mono-cropping systems (seeds with an identical genetic background). Second, they promote climate change due to increasing greenhouse gas emissions. Third, they increase levels of soil erosion due to the high livestock carrying capacity. Pushing specialized farms to the limit destabilizes a previously balanced farming system, commonly resulting in increased levels of air and water pollution in the surrounding environment, as compared to the mixed-system approach (Altieri, 2009; Soussana and Lemaire, 2014; Peyraud et al., 2014). In conclusion, efficient crop-livestock integration could help limit negative impacts of agriculture on the environment without compromising the economic situation of farm families (Dumont et al., 2013; Guillou et al. 2013; Martin et al., 2016; Ryschawy et al., 2017).

1.4. The importance of nitrogen cycling and Ecological Network Analysis

Nitrogen (N) is often considered the major macronutrient limiting the overall productivity of smallholder crop-livestock systems (Ruffino et al., 2009). Many of the smallholder systems are generally described as "*low-input-low-output*" (Van Keulen et al., 2006). In fact, it is these systems that rely greatly on an efficient on-farm nutrient cycling, which involves both crop cultivation and livestock raising (Basnyat, 1995). External inputs such as artificial fertilizers are often difficult to obtain in those systems, especially when they lack access to infrastructure or do not have the economic situation to afford them. Therefore, improving nutrient cycling and nutrient use efficiency (NUE) is considered one of the most effective instruments to increase crop productivity while decreasing environmental degradation ((Rufino et al., 2009; Stark et al., 2018). NUE has been shown to be an effective way to become less dependent on external resources (Zhang et al., 2015). However, an analysis of NUE at the farm level or at the individual farm components (e.g. soil, crop, livestock, manure), does not necessarily provide enough insight into either the system structure, nor the processes and flows to understand inefficiencies and losses. To tackle these shortcomings, I use in this thesis the Ecological Network Analysis (ENA), which is an interesting tool to quantify nutrient (N) flows into, within, and out of systems and a tool that can provide additional insights into agroecosystem functioning (Groot et al., 2003; Rufino et al., 2009; Alvarez et al., 2014). In addition, ENA offers novelty in understanding efficiency at a systems level, in contrast to other models that calculate single-efficiency ratios at field and/or farm levels. First, it visualizes what happens with N once it enters the farm system, secondly how it is used or recycled, thirdly what the amount of productive output is, and even indicates where N losses might occur. ENA is primarily used to assess indicators of integration and diversity, but it also quantifies the robustness of a system. Robustness 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). Interestingly, it has been hypothesized that sustainable, self-organizing systems with a high degree of robustness, could maintain a balance between order and disorder to be or become productive. Furthermore, it could provide a buffering function and allow a reconfiguration when adaptation to changes or perturbations are required. Although the concept of robustness could be relevant in the analysis of N networks in crop-livestock systems, to date there is no study that operationalize this concept in agroecosystems.

1.5. Understanding local context and design for sustainable integration through farmer participation and perceptions

Farmer participation is considered an important indicator of social sustainability. In fact, farmer involvement has proven to be fundamental to building sustainable agroecosystems (Smith et al., 2017). However, there exists a gap due to a lack of reliable methods to quantify farmer participation within sustainable intensification processes (Pretty, 1997; Smith et al., 2017). Addressing farmer perceptions in a participatory fashion could contribute to understanding the motivation behind the adoption or non-adoption of sustainable agricultural innovations (Yapa and Mayfield, 1978). Besides this necessity to grasp how farmers perceive these innovations, it is equally important to investigate, for example, how they find balance in the trade-offs between farm system intensification for food production or income generation and the sustainability of the environment on which farm systems rely. In other words, farmer perceptions are vital to assess their actual willingness to adopt a proposed transition from current management practices towards more sustainable methods. For instance, it was originally suggested that profit maximization was the main driver of farmer attitudes when it comes to their decisions regarding which farming system to adopt (Gasson, 1973). However, later studies revealed that farmers do not exclusively follow economic principles (Vanclay and Lawerence, 1994; Lockie et al., 1995; Edwards-Jones, 2006; Hyland, 2016). Furthermore, it is important to emphasize that certain perceptions and attitudes are influenced by the agroecological zone and by the level of agricultural development (Paudel et. al., 2019). Farmer attitudes and wishes are influenced by their age, sex, access to or lack of education or information, and by local culture. Therefore, it is important to be aware of possible social and cultural barriers to adopt novel intensification practices (Oakley and Garford, 1985). Recognizing and understanding the intrinsic motivation of farmers in local communities is of vital importance to inform national planners and policy makers, as well as NGOs and developmental agencies (Hyland et al., 2016). In conclusion, there is a need to study the diversity of farmer perceptions to support the design of customized programs regarding agricultural sustainability.

1.6. Problem description and rationale of the thesis

This doctoral thesis has been developed in a collaboration between The Farming Systems Ecology (FSE) Group and the MAIZE Strategic Initiative of the CGIAR, under the umbrella of the Agroecosystem diversity, Trajectories and Trade-offs for Intensification of Cereal-based systems (ATTIC) project.

The objective of the ATTIC project is to understand and design more sustainable agroecosystems by contextualizing and assessing the potential impact of institutional changes and technological innovations through sustainable intensification trajectories. Trade-offs between the multiple objectives pursued by the smallholder households engaged in cereal-based agroecosystems were of particular interest of the project.

Within the scope of this project, Nepal has been selected as the country of interest to investigate sustainable intensification principles for various reasons. First, the mixed nature of agroecosystems dominates the livelihood of the majority of Nepalese people living in rural communities. Nepal has high agrobiodiversity and farmers cultivate several cereals such as rice, maize, and wheat as important staples (FAO, 2019). Second, Nepal has experienced a continuous land fragmentation movement, both in the lowlands and the mid-hills, which emphasizes the importance of a better integration of crop and livestock subsystems to attain agricultural intensification. Third, the increasing demand for livestock products in various regions of Nepal might offer farmers an interesting option to embrace sustainable intensification.

However, the livestock sector contributes notably to serious environmental issues. Besides substantial impacts on land degradation and a higher pressure on (arable) lands for pasture or feed crops, it also results in an increase in shortages of water and water pollution, and loss of biodiversity (Steinfeld et al., 2006). Therefore, natural capital needs to be considered, as it constitutes the base of the agroecosystem sustainability. In addition, Nepalese farmers have a history of slow adoption of technological and agricultural innovations (Floyd et al., 2003; Ransom et al., 2003; Pilbeam et al., 2005; Raut et al., 2010; FAO, 2011). As mentioned before, addressing farmer perceptions in a participatory fashion could contribute to the understanding of the adoption or non-adoption of sustainable agricultural innovations. Due to the complexity in understanding and solving systematic problems, future implementations require the direct involvement of farmers in all stages of the innovation process to guarantee the highest chance at the adoption of novel farming practices (Dogliotti et al., 2013).

This thesis explores sustainable intensification trajectories in Nepal using a multi-disciplinary approach. An initial phase included a diagnosis of three contrasting regions (Figure 1). The district of Nawalparasi in the (sub)tropical Terai, which predominantly cultivates rice and has good market access due to a functioning infrastructure, and two distinct regions of the mid-hills. The Palpa district, in the central mid-hills, is well-connected by infrastructure and displays a higher level of development, in comparison to the Dadeldhura district in the remote Far-Western hill regions. Low agricultural productivity and poorly functioning markets resulted in a rural population that is more vulnerable in Dadeldhura. The diagnosis phase was followed by on-farm experiments, modelling, and farmer perception analyses in both mid-hill regions, Palpa and Dadeldhura.

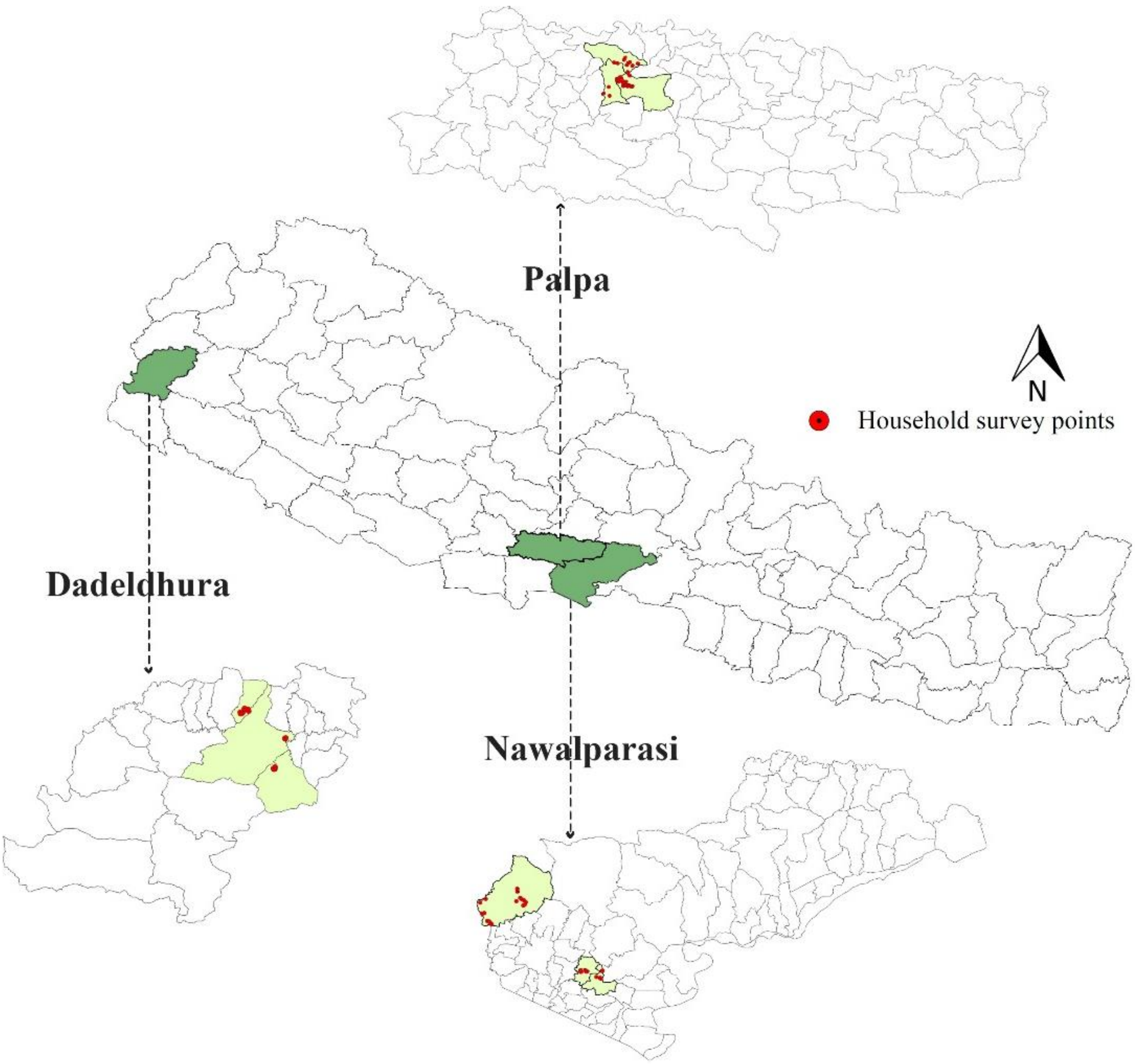


Figure 1. Village Development Committees (VDCs, administrative unit in Nepal, in yellow), with the locations of the households (red dots), where the study took place in the districts of Palpa, Dadeldhura and Nawalparasi (in green). The map of Nepal is displayed in the middle of the detailed maps of the three districts.

1.7. Objectives

This thesis explores and evaluates crop-livestock integration as a pathway to achieve sustainable intensification in cereal-based farming systems in Nepal, integrating farmer's perspectives.

The study uses "support modelling" methodology in which participation with farmers, and modeling are combined. The methodological approach of the thesis is depicted in Figure 2.

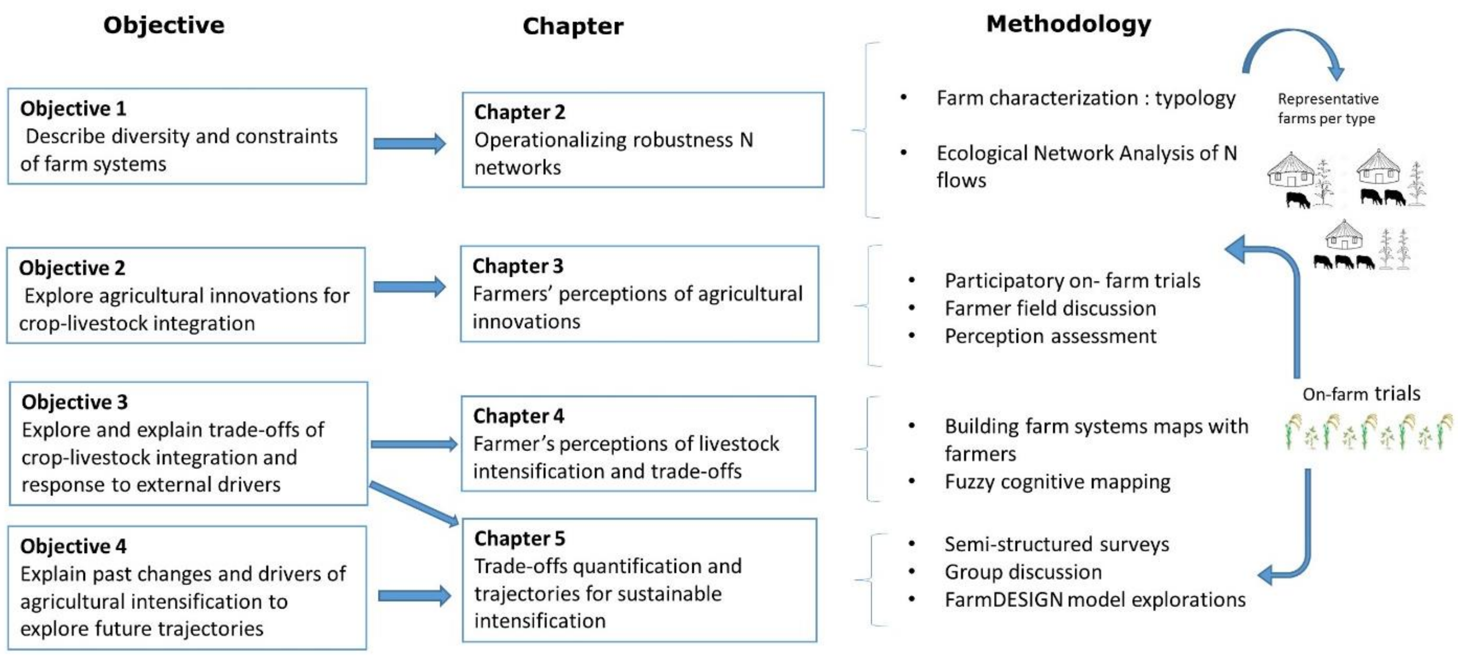


Figure 2. *Methodological approach used to assess the specific objectives of the thesis. The directionality of the arrows indicates the interconnectivity between the different objectives (left), thesis Chapters (middle) and methods (right).*

The specific objectives of this thesis are:

1) To describe the diversity of cereal-based agroecosystems and to identify current bottlenecks constraining crop-livestock systems functioning in terms of N flows (Chapter 2).
2) To explore farmers´ perceptions of agricultural innovations for crop-livestock integration (Chapter 3).
3) To explore and explain trade-offs associated with crop-livestock integration, and potential responses of farm systems components to external drivers (Chapter 4 and 5).
4) To explain the past changes that have occurred in mid-hills farming systems and the drivers accounting for agricultural intensification to explore potential future trajectories (Chapter 5).

1.8. Thesis Outline

In addition to this chapter (1), this thesis is comprised of five additional chapters:

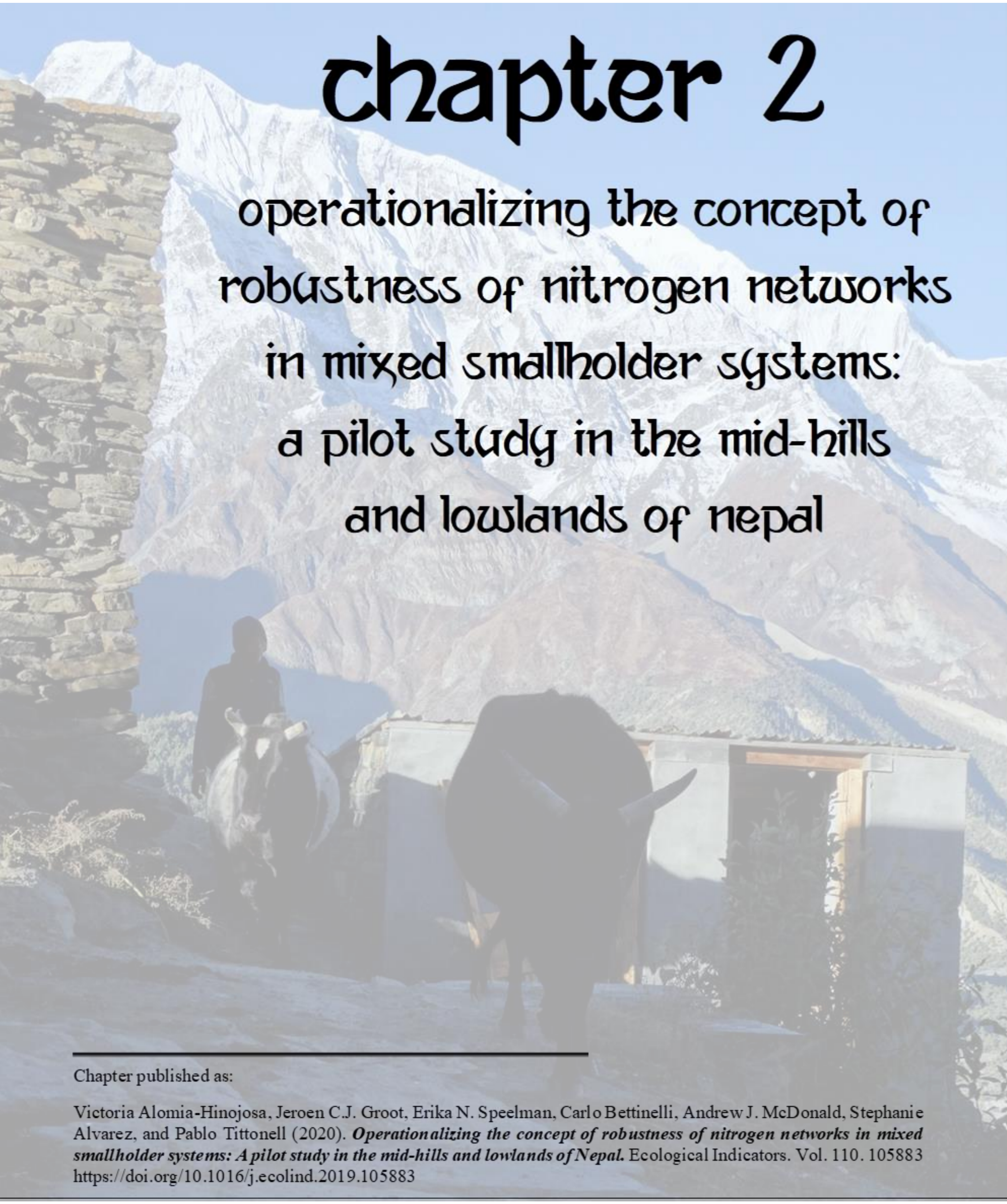
Chapter 2 explores the concept of robustness for nutrient flows in complex mixed smallholder farm systems as a way to i) identify current bottlenecks constraining agroecosystems functioning in terms of N flows, and ii) explore changes in agroecosystems under an intensification scenario.

Chapter 3 assesses the changes in farmer perceptions of the recommended compared to traditional technologies and practices during participatory field experiments. It provides more insights on their perceived constraints to the adoption of agricultural innovations by farmers in the region.

Chapter 4 explores the perception of individual farmers on the presence and importance of trade-offs associated with livestock intensification and compares perceptions about livestock intensification of differently resource-endowed households in two contrasting localities in the mid-hills' region. In addition, it analyses the perceived farm system components/concepts by exploring their potential responses to changes in external drivers.

Chapter 5 identifies the drivers that have shaped mid-hills' farming systems in the last decade and quantifies synergies and trade-offs associated with crop-livestock integration to project future trajectories.

In **Chapter 6** the main findings of this thesis are combined. It provides the main conclusions of the study and recommendations for further research.



chapter 2

operationalizing the concept of robustness of nitrogen networks in mixed smallholder systems: a pilot study in the mid-hills and lowlands of nepal

Chapter published as:

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Abstract

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.

2.1. 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 nutrition 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.

2.2. 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.

2.2.1. 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.

2.2.2. 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.

2.2.3. 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 (Figure 1; Box S1 in 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 (Figure 1) (Ulanowicz et al., 2011).

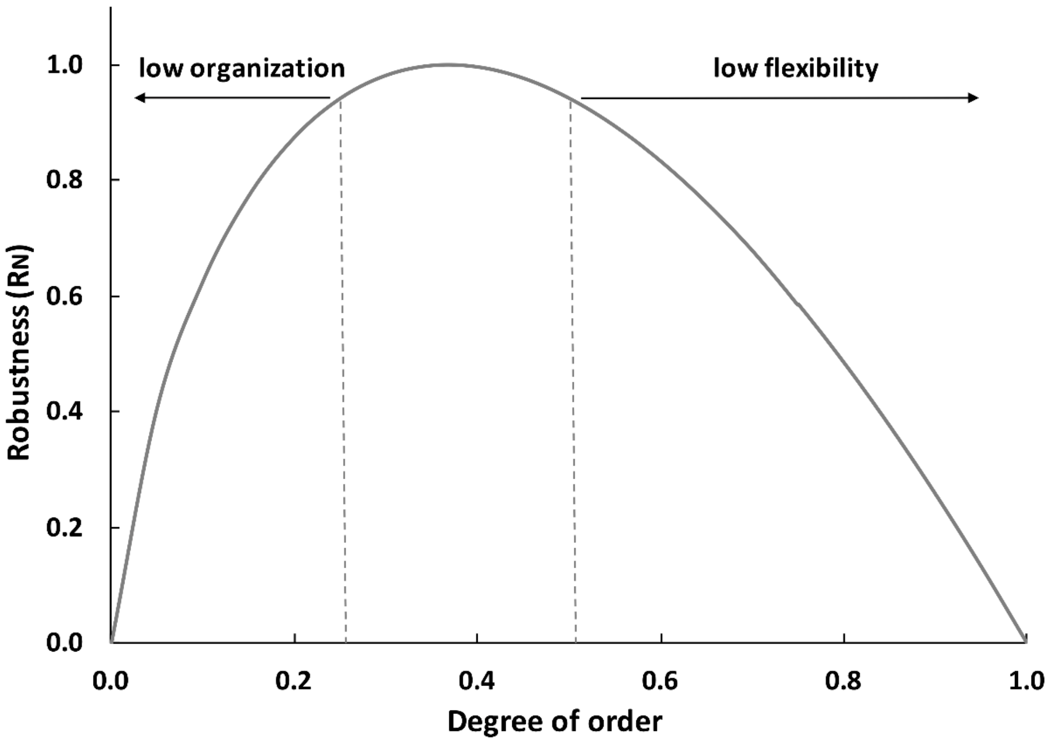

Figure 1: *Fitness curve showing the robustness (R_N) as the balance between system flexibility and organization (Ulanowicz et al., 2009). The degree of system order represents the ratio A/C, with A denoting the ascendency and C indicating the capacity of the system. A simplified example of different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

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 (Figure 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.

2.3. Materials and Methods

2.3.1. Study sites

The research was carried out in three districts in the mid-hills and lowlands (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 lowlands in the Western developmental region (Figure 2).

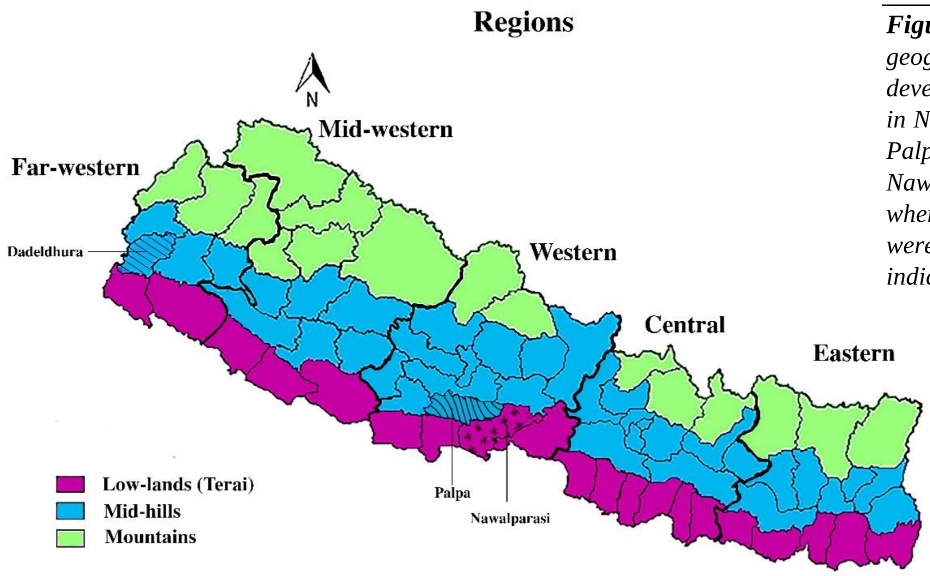

Figure 2. *Map of the geographical and developmental regions in Nepal. Dadeldhura, Palpa and Nawalparasi districts, where the study sites were located, are indicated.*

There are strong ecological differences between lowlands and mid-hills shaped by large differences in climate and topography. Nawalparasi consists of flat land at low altitude (105 meters 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 lowlands 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 lowland 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 lowlands 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.

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

In Nawalparasi, albeit the main cropping season is concentrated in 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.

2.3.2. 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 lowlands. 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.

Table 2. *Main characteristics of farm types with different resource endowment levels (LRE: low, MRE: medium; HRE: high) in Palpa, Dadeldhura (mid-hills) and Nawalparasi (lowlands) 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	10780	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	12420	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 - Lowlands 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 to 5 chickens (0.01-0.05 total TLU)

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 $^{-1}$.

2.3.3. 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 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.

2.3.4. 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.

2.4. Results

2.4.1. 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).

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 Figure 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 lowlands 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 R_N. Farms in Palpa showed the lowest values (Table 3).

A strong correlation between N imports and animal density was identified (Figure 4).

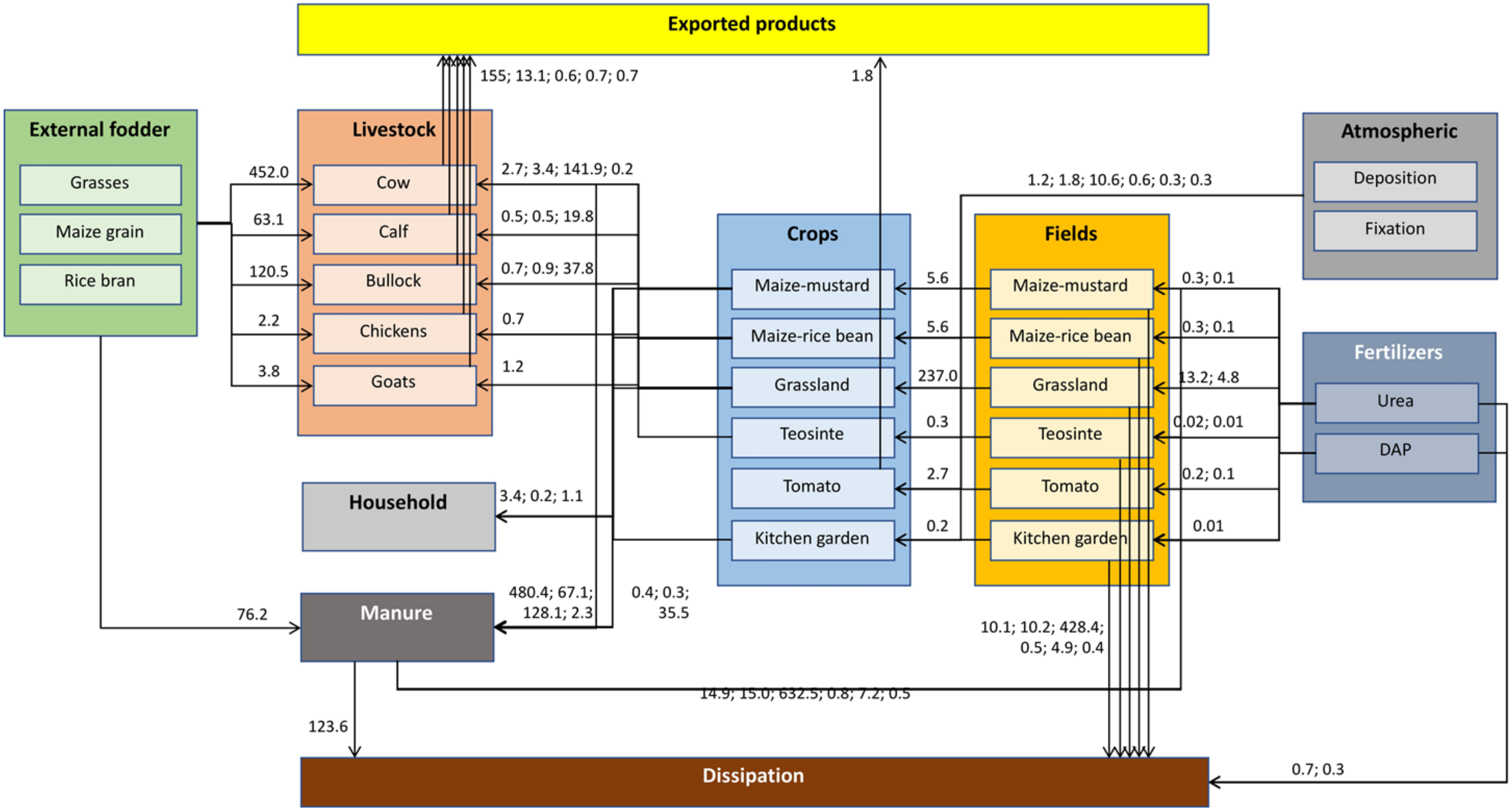

Figure 3. *Nitrogen flows diagram for the HRE farm in Palpa, expressed in kg N ha-1 year-1. The numbers above the arrows represent the quantity (kg N ha-1 year-1) of N that flows between components. The exported products, external fodder, fertilizers, and the N dissipation are outside of the farm system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

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 (Figure 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

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	14176	7635	2749	3209	6787	4967	3945	2510
Φ (kg N ha^{-1} $year^{-1}$)	7059	14187	4752	3139	3793	6824	6008	4149	2227
C (kg N ha^{-1} $year^{-1}$)	15730	28363	12387	5888	7002	13611	10975	8094	4737
Ratio A/C (-)	0.55	0.50	0.62	0.47	0.46	0.50	0.45	0.49	0.53
R_N (-)	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.**

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, Figure 4 and Figure 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 Figure 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 (Figure 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 (Figure 4).

2.4.3. 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 (Figure 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

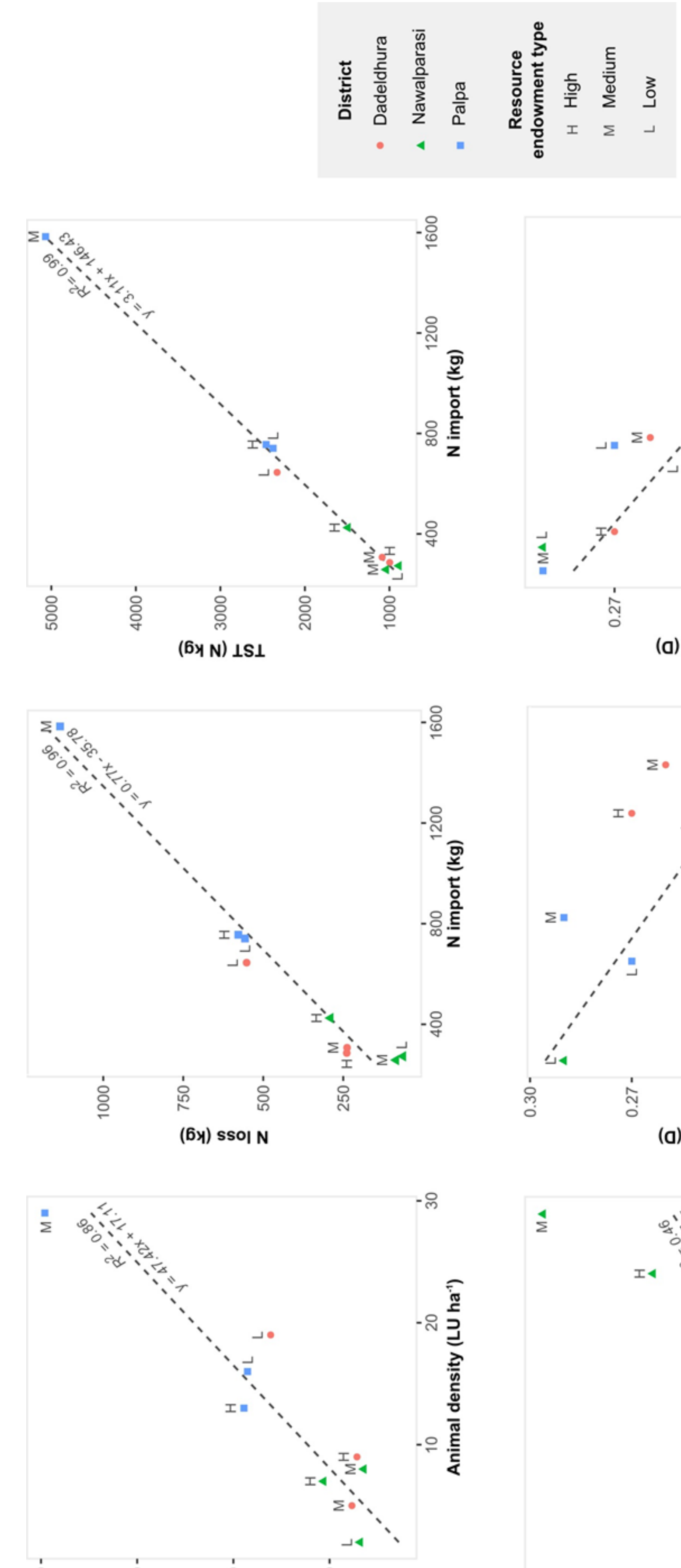

Figure 4. *Relationships between indicators of farming intensity (inputs and animal density), organization, diversity and integration.*

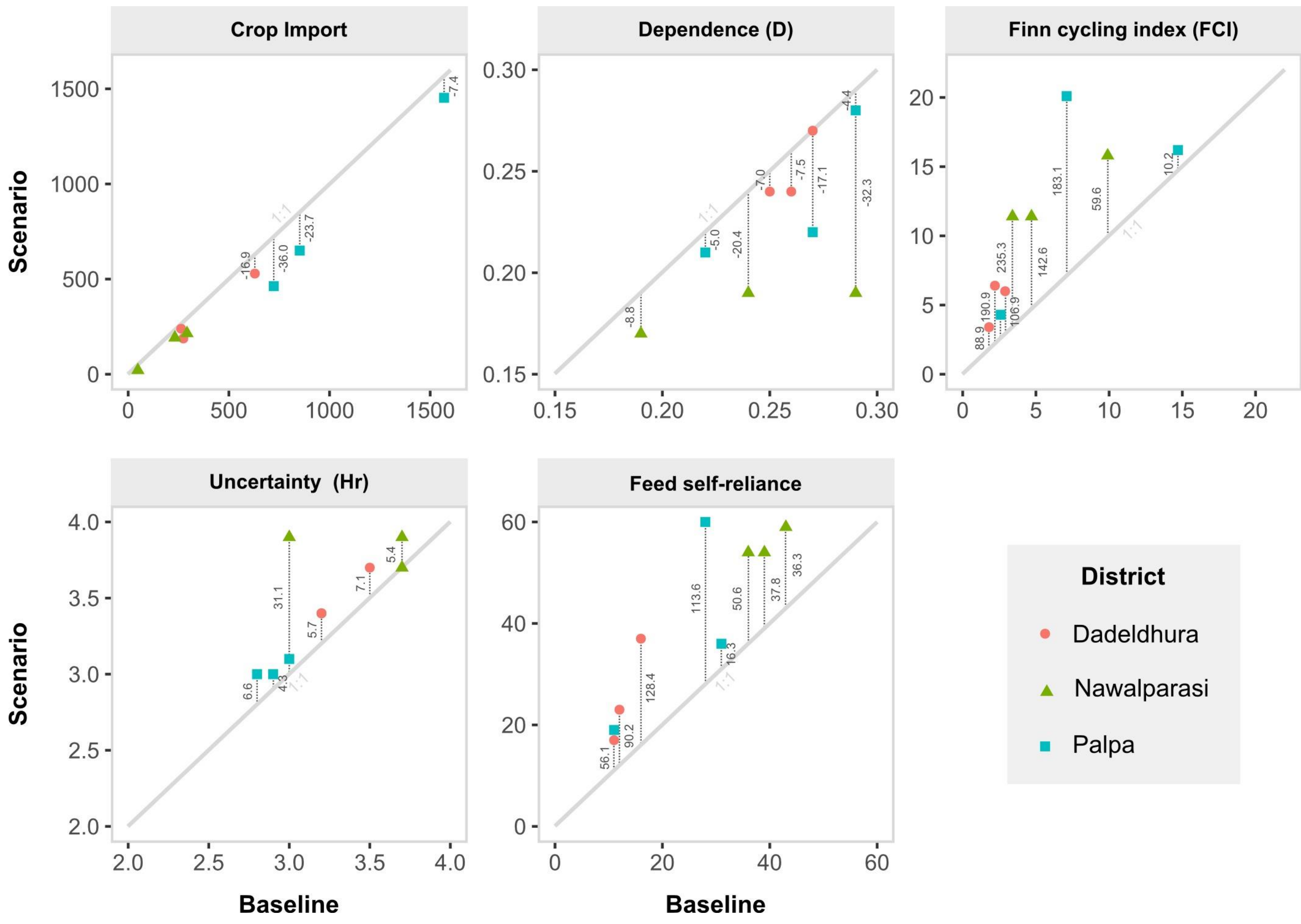

Figure 5. *Comparison between the baseline and the increase crop yield scenario with the percentage of change for the nine mixed farms in Palpa, Dadel-dhura and Nawalparasi districts, Nepal.*

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

Baseline (indicators)															
District	*Type*	NC	TST	TSTc	FCI	AMI	Hr	SR	D	Loss	Balance	FYM	A/C	ϕ	R_N
PLP	H	22	3388	929	14.7	2.11	2.89	30.7	0.22	578	580	20686	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	14187	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	20484	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	15784	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 (-).

of N flows increased as well as the feed self-reliance. The dependence of the farms decreased in the intensification scenario (Table 4, Figure 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; Figure 6).

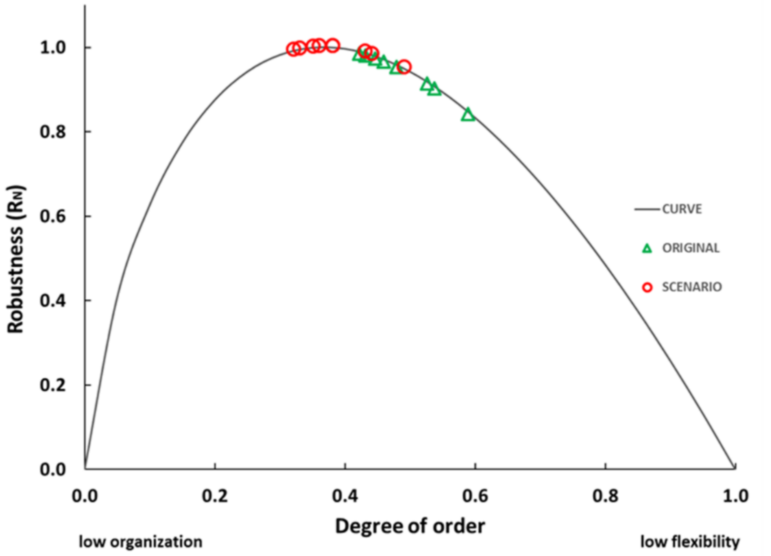

Figure 6. *Relationship between the degree of order and robustness (R_N) of the N flows of nine farms in the baseline (in green) vs the intensification scenario (in red), in Palpa, Dadeldhura and Nawalparasi districts, Nepal.*

2.5. 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, Figure 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 which caused high dependency of N imports in the form of fodder (Figure 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 (Figure 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 (Figure 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 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., 2009; 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, Figure 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 (Figure 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.

2.6. 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.

2.7. Acknowledgements

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2.8. Supplemental material

Box S1. Conceptual example to illustrate effects of farm structure on network metrics.

In Figure B1, we illustrate the application of ecological network analysis to agroecosystems and the response of various indicators to differences in farm configurations using four illustrative simplified examples (from diverse mixed farms) presented.

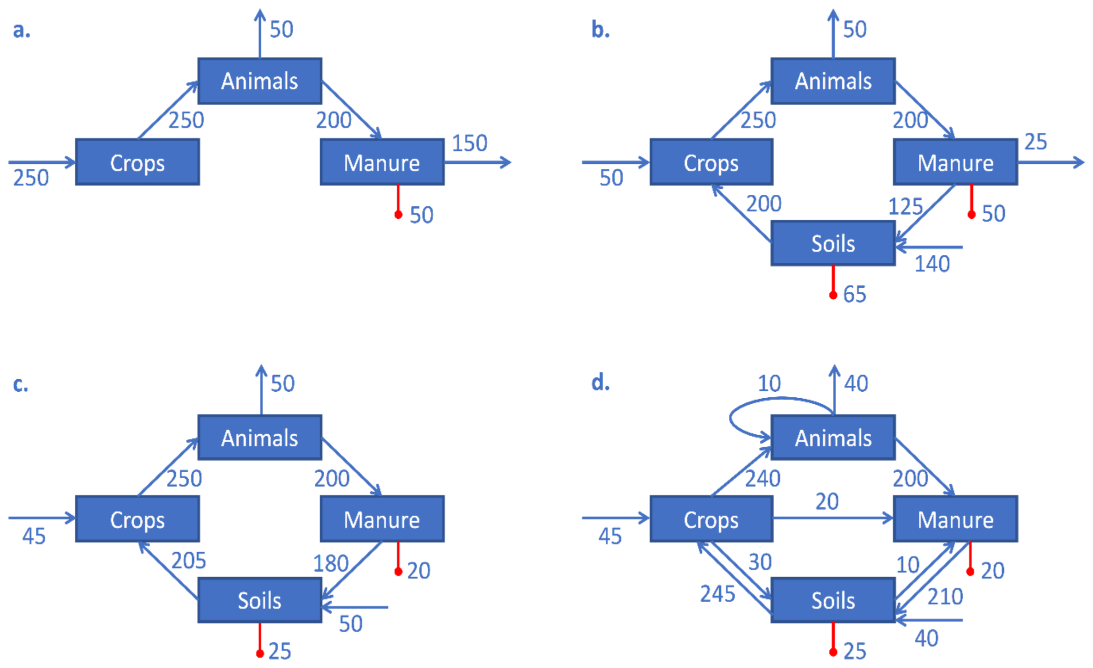


Figure B1. Flows of nitrogen (blue arrows; expressed in kg N ha^{-1} year^{-1}) in conceptual agroecosystems focusing on animal production. Crop, Animal, Manure and Soil (boxes) represent the compartments of these agroecosystems. Red rounded arrows indicate nitrogen losses (dissipation). The values of the flows are illustrative.

These conceptual systems revolve around animal production, e.g. milk and meat by dairy cattle. In all examples, animal intake is 250 kg N ha^{-1} and the conversion efficiency is 20% resulting in production of 50 kg N in animal products ha^{-1}. For farmers in Nepal this would entail a system of 2 cows producing 9 litres of milk per day on a farm with a surface area of 0.74 ha. Crop products fed to animals can be completely imported from outside the system (Figure B1a), or partly grown on-farm with supplementary feed acquisition from outside the system (Figures B1b-B1d). A part of the milk can be used to feed calves (Figure 1d). Losses occur from manure and soil and can be high (Figures 1a and 1b) or reduced with appropriate management practices (Figures B1c and B1d). In systems that produce part of the feed on-farm, the nutrients circulate from soil to crops to animals and back to soil through the produced manure applied as fertilizer (Figures B1b-B1d). Exchanges between compartments can be enhanced when bedding material and feed losses are added to manure, soil is added to manure to reduce losses (Shah et al., 2013) and crop residues are applied to soils as mulch (Figure B1d).

Indicators of activity and integration

The farm system in Figure B1a can be considered as an intensive animal production unit that imports all feed without connection between crop production and animal husbandry. Although the animal production is the same as in the other systems, the manure export results in larger total output. This system has the highest nutrient use efficiency (NUE; Table B1). In this case, losses related to production of feed and disposal of manure are externalised to other systems or the environment. The other farm configurations (Figures B1b to B1d) produce 80-82% of the feed required on the farm, and a nutrient cycle is created because manure is used partly or completely to fertilize the soils on the farm. This leads to a higher nitrogen balance and lower NUE. When losses from manure and soil are reduced and more nutrient flows within the farms are added, the NUE slightly and feed self-reliance increase (Table B1).

Indicators of organization and diversity

In the example agroecosystems (Figure B1), the value of H_R is relatively high for system b., and the AMI is lower for system d. than for the other examples (Table B1). Overall, the AMI/H_R ratio declines with increasing network complexity.

Indicators of systems degree of order

The indicator values for the example networks presented in Figure 1 show that when the number of flows between compartments increases, the activity of the network enhances. The increased exchanges between the compartments lead to lower dependence D and more cycling as indicated by higher values of FCI with increasing network complexity (Table B1).

The example agroecosystems in Figure B1 increase in R_N with increasing connectivity and cycling (Figure 1; Table B1), particularly due to an increase in overhead Φ. All the agroecosystems (Figure B1) show a low system flexibility. Agroecosystem with more exchanges between compartments are closer to the maximum R_N.

Table B1. Network analysis indicators for four illustrative conceptual agroecosystems (a. to d.) presented in Figure B1.

Metric		Agroecosystem			
		a.	b.	c.	d.
Farm nutrient balance, efficiency					
Total inflow	IN	250	190	145	95
Productive output	OUT	200	75	50	40
Nutrient balance	BAL	50	115	95	55
Nutrient use efficiency	NUE	0.800	0.395	0.345	0.421
Feed self-reliance	SR	0.000	0.800	0.820	0.820
Activity and integration					
Link density	LD	2	2.5	2.25	3.25
Total system throughput	T	950	1155	1025	1135
Total system throughflow	TST	700	965	930	1050
Average path length	APL	2.8	5.1	9.8	12.4
Cycled throughflow	TSTc	0	364	597	745
Dependency	D	0.357	0.197	0.156	0.090
Finn cycling index	FCI	0.000	0.315	0.582	0.657
Organisation and diversity					
Average mutual information	AMI	1.82	1.77	1.88	1.58
Statistical uncertainty	H_R	1.99	2.31	2.25	2.23
Ratio AMI/H_R	AMI/H_R	0.914	0.765	0.832	0.708
Degree of order and robustness					
Ascendency	A	1732	2040	1923	1792
Overhead	Φ	505	1439	872	1561
Capacity	C	2237	3479	2794	3352
Ratio A/C	A/C	0.774	0.586	0.688	0.534

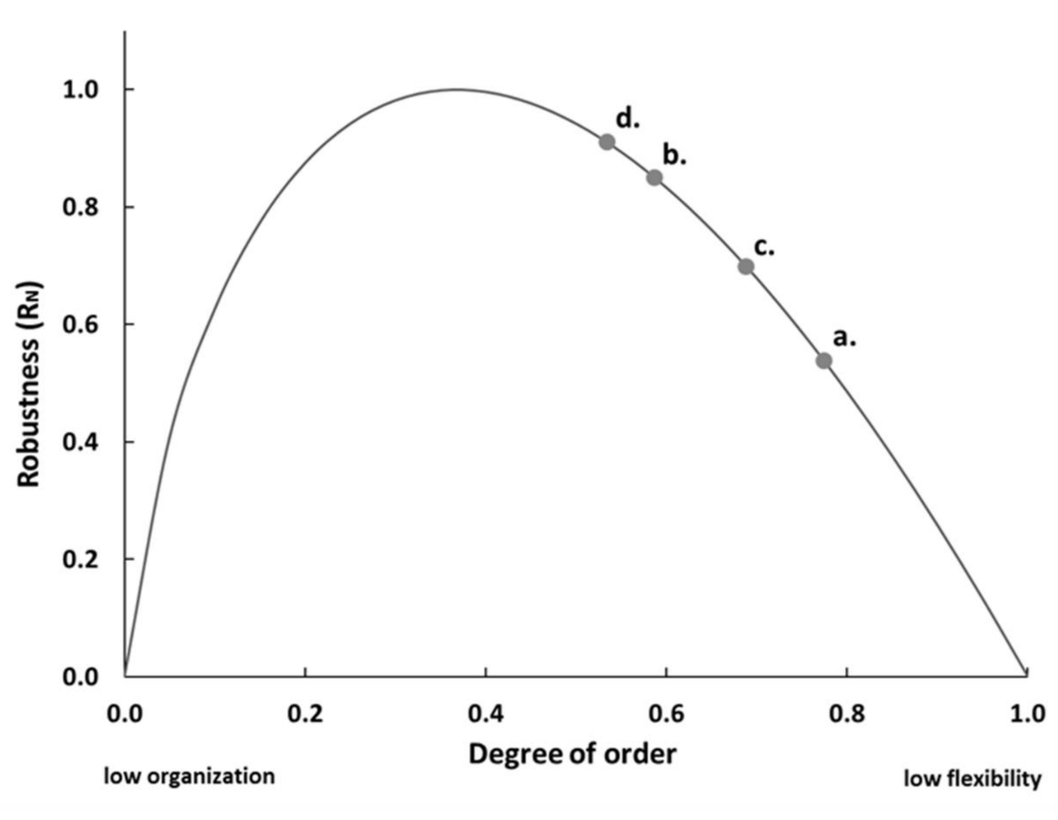


Figure B2. Fitness curve showing the robustness (R_N) as the balance between system flexibility and organization (Ulanowicz et al., 2009), with the position of examples agroecosystems: ***a*** representing low and ***d*** high exchanges among compartments. The degree of system order represents the ratio A/C, with A denoting the ascendency and C indicating the capacity of the system.

Table S1. Equations for indicators.

Indicators	**Calculation**
Imports (IN)	$\mathrm{IN} = \sum_{i=1}^{n} z_{i0}$
Total N outputs	export of crop products, export of animal products, export of animal manure
Nitrogen use efficiency (NUE)	$\mathrm{NUE} = \frac{\text{Total N export}}{\text{Total N import}}$
Total N losses	losses to the air (volatilization) and the soil (leaching and denitrification)
Total system throughput (T)	$\mathrm{T} = \sum_{ij=1}^{n} T_{ij}$
Total system throughflow (TST)	$\mathrm{TST} = \sum_{i=1}^{n} T_i$
Average path length	$\mathrm{APL} = \frac{TST}{\mathrm{TIN}}$
Relative cycling efficiency of the network (TSTc)	$\mathrm{TST_c} = \sum_{i=1}^{n} \mathrm{RE_i T_i}$
Cycling efficiency ($RE_{i)}$)	$\mathrm{RE_i} = \frac{\mathrm{n}ii - 1}{\mathrm{n}ii}$
Dependency (D)	$\mathrm{D} = \frac{IN}{\mathrm{TST}}$
Finn's cycling index (FCI)	$\mathrm{FCI} = \frac{\mathrm{TST_c}}{\mathrm{TST}}$
Average Mutual Information (AMI)	$\mathrm{AMI} = \mathrm{k}\sum_{i=1}^{n+2}\sum_{j=0}^{n}\frac{T_{ij}}{T_{..}}\log_2\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}$
Statistical uncertainty (H_R)	$H_R = -\sum_{j=o}^{n}\frac{T_{.j}}{T_{..}}\log_2\frac{T_{.j}}{T_{..}}$
Ascendency (A)	$A = T_{..}X = \sum_{i,j}\mathrm{Tij}\ \log\frac{T_{ij}T_{..}}{T_iT_j}$
Overhead (Φ)	$\Phi = T_{..}\Psi = -\sum_{i,j}\mathrm{Tij}\ \log\frac{T2_{ij}}{T_iT_j}$
Capacity (C)	$C = T_{..}\Phi = -\sum_{i,j}\mathrm{Tij}\ \log\frac{T_{ij}}{T_{..}}$
Degree of order	A/C
Robustness	R_N= -e(A/C) ln (A/C)
Shannon Index	$\mathrm{H} = \sum_i \mathrm{hi} = -\mathrm{k}\sum_i \mathrm{pi}\log(pi)$

Table S2. Dry matter (DM) and nitrogen (N) content of different crops used for calculations in FarmDESIGN.

Product	DM content (g/100 g FM)	N content (g/100 g DM)
A Lakoocha	43.0	2.03
Annapurna.Wild grass	100.0	1.50
Barley grain	87.1	1.89
Barley straw	91.0	0.67
Berseem	12.5	3.18
Blackgram grain	89.7	3.84
Blackgram stalk	22.9	3.17
Cabbage	9.5	4.05
Fodder grass (Setaria, Cynodon, Eleusine)	39.3	2.75
Fodder trees (Ficus benghalensis)	43.0	2.03
Garlic	33.7	1.48
Good Green grass	39.3	2.75
Lentil seed	88.3	4.30
Lentil straw	92.3	1.30
Litsea monoplotela	33.4	2.45
Maize grain	87.2	1.55
Maize stover	93.4	0.59
Melinis minutiflora	30.5	1.04
Mixed vegetables	100.0	2.40
Mustard cake	89.4	5.58
Mustard grain	91.7	3.74
Mustard stover	94.8	0.64
Napier grass	17.8	1.55
Onion	9.0	2.02
Pigeon pea grain	89.5	3.71
Pigeon pea stover	31.1	2.96
Potato plant	23.0	1.74
Potato tuber	20.2	1.73
Rice bran	90.2	2.03
Rice grain	88.0	1.33
Rice straw	92.8	0.67
Ricebean grain	89.7	3.84
Ricebean stalk	22.9	3.17
Soybean seed	88.8	6.34
Soybean stover	25.6	2.19
Teosinte plant green	26.2	1.36
Tomato fruit	15.0	2.40
Tomato stalk	17.7	1.18
Wheat flour	87.7	2.30
Wheat grain	87.0	2.02
Wheat husk	87.0	2.77
Wheat straw	91.0	0.67

Table S3. *Values of ENA indicators for baseline and crop intensification scenario*

District	*Type*	NC	NL	T	TST	LD	TSTc	FCI	AMI	Hr	SI	SR	D	Loss	Input	Balance	FYM	Crop imp	A	C	A/C	ϕ	R_N
Baseline (indicators)																							
PLP	H	22	94	4105	3388	4.3	929	14.7	2.11	2.89	1.0	30.7	0.22	578	756	580	20686	718	8671	15730	0.55	7059	0.89
PLP	M	13	53	6978	5441	4.1	373	2.6	2.03	2.96	0.8	10.6	0.29	1135	1584	1149	3115	1569	14176	28363	0.50	14187	0.94
PLP	L	12	41	3490	2753	3.4	376	7.1	2.19	2.83	0.7	27.9	0.27	557	741	558	1350	723	7635	12397	0.62	4752	0.81
DDL	H	17	73	1320	1051	4.3	55	1.8	2.08	3.25	1.3	10.7	0.27	239	286	242	5048	263	2749	5888	0.47	3139	0.97
DDL	M	18	73	1460	1172	4.1	85	2.2	2.20	3.47	1.5	16.2	0.26	238	307	239	2564	274	3209	7002	0.46	3793	0.97
DDL	L	17	72	3143	2537	4.2	207	2.9	2.16	3.22	1.2	12.3	0.25	552	645	553	3425	629	6787	13611	0.50	6824	0.94
NWP	H	21	104	2144	1738	5.0	246	4.7	2.32	3.67	1.4	35.8	0.24	290	425	292	4422	292	4967	10975	0.45	6008	0.98
NWP	M	18	79	1603	1356	4.4	317	9.9	2.46	3.70	1.6	43.0	0.19	85	258	86	1556	232	3945	8094	0.49	4149	0.95
NWP	L	10	31	1219	949	3.1	60	3.4	2.06	2.95	0.2	39.2	0.29	63	273	126	125	48	2510	4738	0.53	2227	0.91
Improved yield scenario (indicators)																							
District	*Type*	NC	NL	T	TST	LD	TSTc	FCI	AMI	Hr	SI	SR	D	Loss	Input	Balance	FYM	Crop imp	A	C	A/C	ϕ	R_N
PLP	H	22	102	3935	3278	4.6	1042	16.2	2.13	3.01	1.0	35.7	0.21	518	695	519	20484	650	8398	15956	0.53	7557	0.92
PLP	M	15	65	7076	5571	4.3	241	4.3	2.05	3.08	0.8	18.7	0.28	1075	1550	1086	2784	1453	14511	30295	0.48	15784	0.96
PLP	L	14	50	2682	2196	3.6	863	20.1	2.27	3.02	0.7	59.6	0.22	301	490	302	1062	463	6087	10340	0.59	4253	0.85
DDL	H	20	95	1296	1032	4.8	100	3.4	2.08	3.43	1.3	16.7	0.27	228	281	231	4709	239	2702	6262	0.43	3560	0.99
DDL	M	21	96	1293	1057	4.6	214	6.4	2.23	3.72	1.5	37.0	0.24	164	256	165	2440	188	2885	6833	0.42	3948	0.99
DDL	L	20	95	3142	2576	4.8	155	6.0	2.16	3.40	1.2	23.4	0.24	498	609	499	3164	529	6783	14774	0.46	7990	0.97
NWP	H	21	106	2156	1823	5.1	580	11.4	2.42	3.87	1.4	54.0	0.19	187	355	189	4096	215	5220	11694	0.45	6474	0.98
NWP	M	20	96	1699	1458	4.8	230	15.8	2.46	3.73	1.6	58.6	0.17	38	253	40	1349	192	4175	8721	0.48	4546	0.96
NWP	L	21	106	2156	1823	5.1	580	11.4	2.42	3.87	1.4	54.0	0.19	187	355	189	4096	21	2920	5437	0.54	2518	0.91

Where PLP: Palpa; DDL: Dadeldhura; NWP: Nawalparasi; NC: number of compartments; NL: number of links; T: total system throughput (kg N $year^{-1}$); TST: total system throughflow (kg N $year^{-1}$); LD: link density; TSTc: total cycled system throughflow (kg N $year^{-1}$); FCI: Finn's cycling index (%); AMI: average mutual information (Bits); Hr: statistical uncertainty (Bits); SI: Shannon index; SR: feed self-reliance (%); D: dependency (-); Loss: N losses (kg N $year^{-1}$); Input: N input (kg N $year^{-1}$); Balance: N balance (kg N $year^{-1}$); FYM: farm yard manure (kg DM

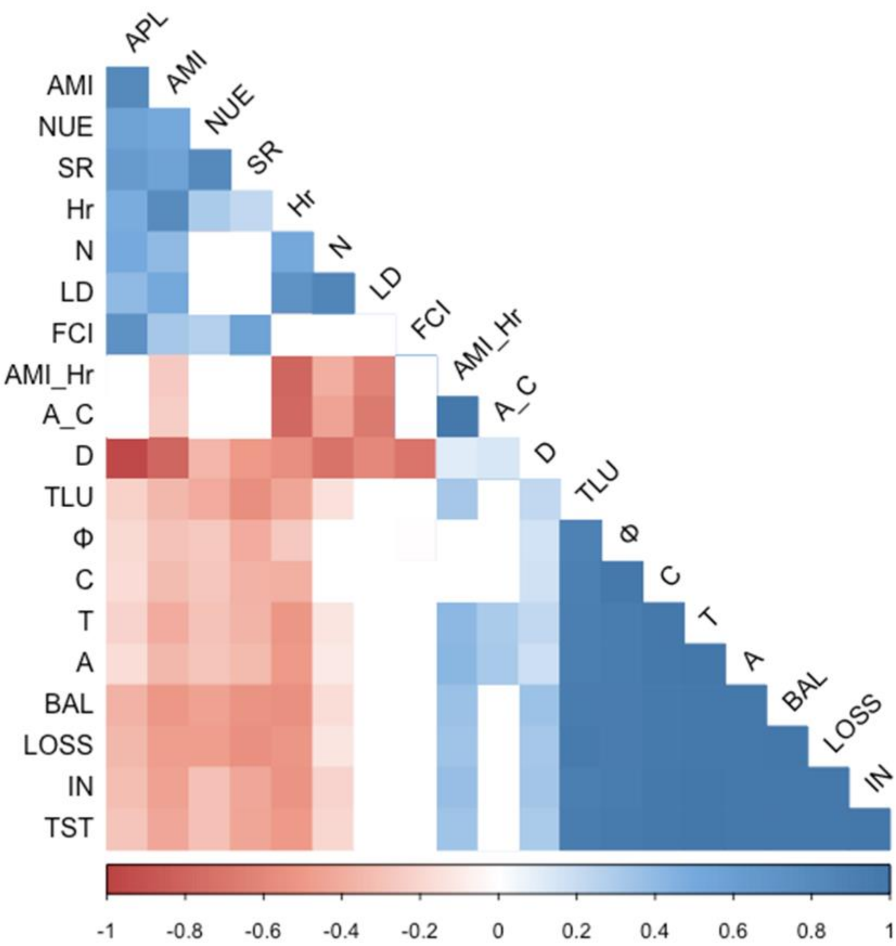
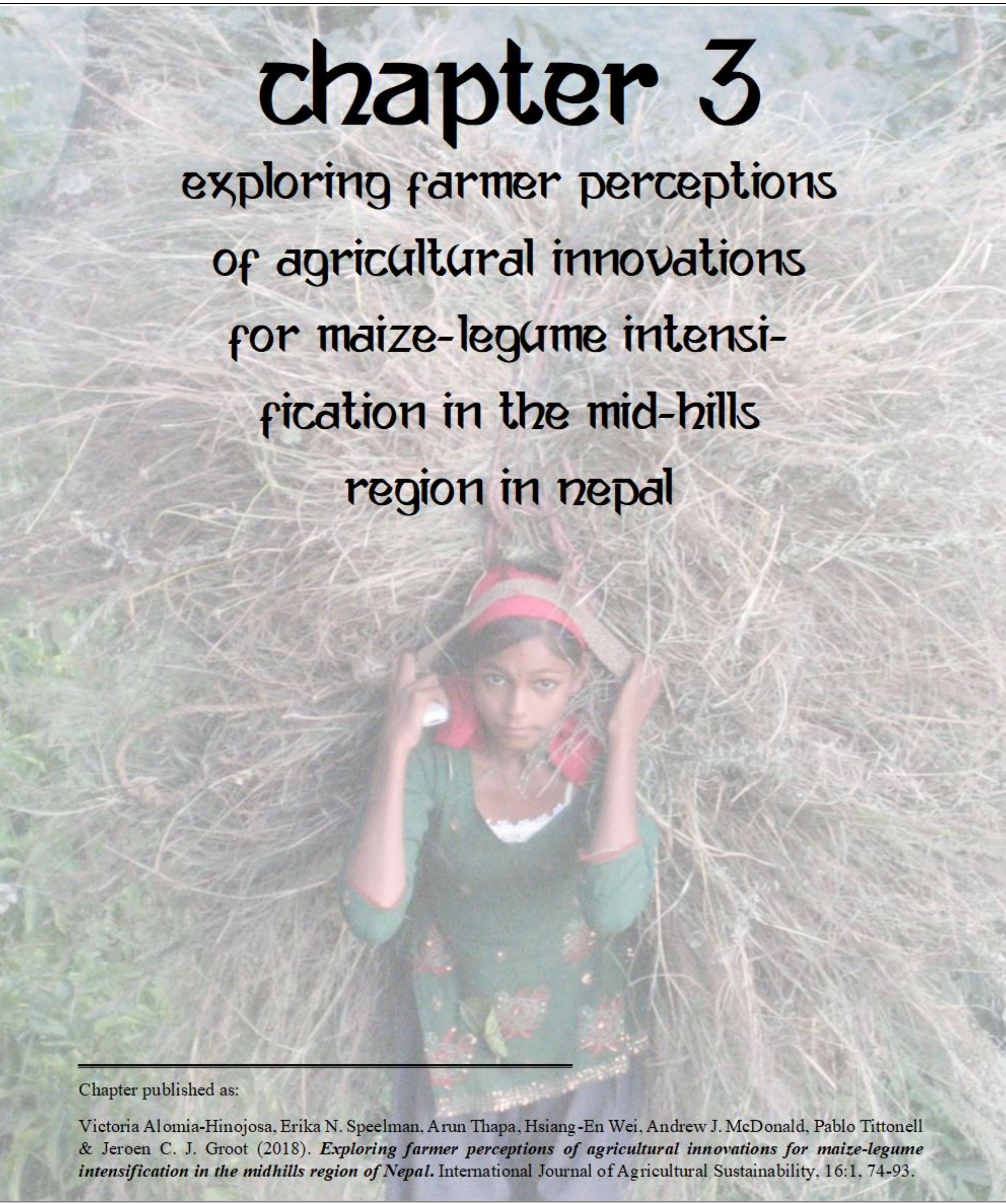


Figure S1. Correlations matrix among indicators of N flow network on nine farms from Palpa, Dadeldhura and Nawalparasi districts, Nepal. The blue gradient (white to dark blue) indicated an increase in the correlation coefficient from 0 to 1 (positive correlation); the red gradient (white to dark red) indicated a decrease in the correlation coefficient from 0 to -1 (negative correlation). Where AMI (Average mutual information); NUE (Nitrogen use efficiency); SR (Feed self-reliance); Hr (Statistical Uncertainty); N(Balance); LD (Link density); FCI (Finn's cycling index); D (Dependency); TLU (Animal density); Φ (Overhead); C (Capacity); T (Total system throughput); A (Ascendency); BAL (Nitrogen balance); LOSS (Nitrogen losses); IN (Total inflow); TST (Total System Throughflow).



chapter 3

exploring farmer perceptions of agricultural innovations for maize-legume intensification in the mid-hills region in nepal

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Abstract

Maize-legume intercropping is a foundational component of the mixed farming systems in the mid-hills of Nepal, but productivity is constrained by several biophysical and social factors, and the limited adoption of proven agricultural innovations. In this study, we explore changes in farmer perceptions of agricultural innovations through participatory processes. The technologies evaluated included: the mini-tiller for land preparation, hybrid maize, mineral fertilizers, and line sowing. These technologies resulted in higher maize yields than those obtained with farmers' current practices. Furthermore, we assessed farmers' perceptions of these practices as well as their reasons for adoption or rejection before and after the two-year participatory trials. We showed that the active involvement of farmers in on-farm trials increased understanding of underlying decision-making factors to adopt or non-adopt agricultural innovations, and that the engagement of farmers positively influenced farmer perceptions towards the adoption of innovations. Nevertheless, farmer decisions to apply the evaluated practices on their own fields were not determined solely by awareness of the positive yield and economic responses observed in the on-farm experiments but by a host of factors including labour scarcity, the availability of inputs, and by cultural preferences in particular to low and medium resource-endowed farmers. This study informs the agricultural development sector about the importance to design context-specific projects and policies with active farmer participation.

3.1. Introduction

The increased acknowledgement of the necessity to feed the growing global population, to adapt to climate change and to reach sustainable development goals (e.g. (Hunter et al., 2017; Rockström et al., 2017) lead to more efforts to enhance productivity of smallholder agriculture in a sustainable manner, i.e. by sustainable intensification (Garnett et al., 2013; Pretty and Bharucha, 2014). In less-favoured areas such as mountainous regions smallholder farms play an important role in food security, but are often based on traditional practices (Dahal et al., 2009). The aims of the farmers and their context-specific access to financial and labour resources should guide decisions about intensification (Raut et al., 2011; Tiwari et al., 2008). Hence, externally proposed technologies and practices that are potential improvements in farming to support the sustainable intensification process should be evaluated by farmers themselves.

Participatory approaches have been emphasized in agriculture in the tropics as an effective method to explore traditional farmers' practices. In addition, it has been applied as a means to diffuse agricultural innovations and improve their adoption (Choudhary and Suri, 2013; Hoffmann et al., 2007), to develop breeding strategies (Almekinders and Elings, 2001), to encourage sustainable intensification practices (Blackstock et al., 2007; Meijer et al., 2015), to empower farmers (Hellin et al., 2008) and to build adaptive capacity towards climate change (Mapfumo et al., 2013). In addition, through participatory approaches, immanent local innovation trajectories could be identified and supported.

Within the participatory approaches there is a vast range of scientist and farmers involvement. The range varies from the independent decision making from the scientist to a coordinated process in an organized communication between scientist and farmers. (Lilja and Ashby, 1999) allowing both stakeholder groups to learn from each other. Among the participatory methods, the Farmer Field School (FFS) approach, developed in Asia in the late 1980's to promote Integrated Pest Management (IPM) practices, has been broadly used to provide farmers with an opportunity 'for learning-by-doing' (Braun et al., 2000). FFS were shown to increase integrated agricultural knowledge and to improve farmers' decision-making skills (Braun et al., 2000; Mancini et al., 2006). Participatory approaches also have been reported to contribute to positive changes in farmer perceptions and willingness to adopt innovations (Kraaijvanger et al., 2016; Misiko, 2009). Even though the positive impact of these approaches on rural development has been demonstrated in numerous studies, participatory technology evaluations have only been applied in some cases in South-Asia (Karki et al., 2015). Actively involving farmers in the selection and exploration of new technologies and system improvements, might also lead to a better understanding of the reasons of farmers for adoption or rejection. For instance, in the western and far-western mid-hills districts of Nepal the use of agricultural technology is incipient. The agricultural practices have remained traditional and inefficient in terms of labour use, and productivity during the last decades. Labour efficiency might be attained by improving crop and livestock management, and by introducing mechanization (i.e. for ploughing) appropriate for the hill zones. The mid-hills represent the largest geographic zone of Nepal, covering approximately 42% of the total land area (MoAD, 2014) Maize is the principal staple food and fodder crop of small-scale farmers in this region covering 73% of the total production in the country (MoAD, 2014). Maize is usually sown together with legumes or cucurbit species, with finger millet often relay-planted into the standing crop (Subedi 1996 in Tiwari 2004). However, over the last two decades the productivity of maize remained at a low level of about 2 to 2.5 Mg ha^{-1} and only in some cases increased marginally (Devkota et al., 2015; Ghimire and Huang, 2015; Paudel and Matsuoka, 2008).

Many interventions have focused in closing yield gaps of maize in the mid-hills of Nepal by promoting improved technologies and the adoption of modern inputs such as new crop varieties (Becerril and Abdulai, 2010; Ghimire and Huang, 2015). By conducting on-farm experiments Devkota et al. (2015) determined that there is a remarkable scope for improving maize productivity by maintaining higher plant densities, cultivating hybrids, and increasing fertilizer use. However, the adoption of the combinations of such technologies is still low in the mid-hill regions. The reasons include, among others, lack of information of technology and motivation of farmers (Ransom et al., 2003; Tiwari et al., 2004),and increased costs and risks for the farmers. Furthermore, there are still gaps between the results obtained in experimental research stations and farmers' fields (Ghimire and Huang, 2015; Karki et al., 2015; Paudel and Matsuoka, 2008) that could be bridged by improving the communication between farmers and extension systems (including the non-governmental community) (Karki et al., 2015; Ransom et al., 2003), and possibly a stronger role of the private sector.

Farmers' subjective preferences for the characteristics of new agricultural technologies (Adesina and Baidu-Forson, 1995) and their knowledge and perceptions when involved in participatory experimentation and exchange, could influence their adoption behaviour. Moreover, it would lead to accumulation of knowledge and adjustment of initial perceptions, which can influence attitudes that can result in the adoption of technologies (Meijer et al., 2015). Farmer knowledge and perceptions are intrinsic factors that influence the decision for adoption of innovations, while the technology, the external environment and the adopter (structural) characteristics are the extrinsic factors that affect farmer decisions (Meijer et al., 2015).

Our objectives were (i) to assess the changes in farmer perceptions of the agricultural innovations compared to traditional technologies and practices during participatory field experiments and (ii) to gain more insights on their perceived constraints to the adoption of agricultural innovations in the region. We addressed these objectives using a two-year participatory approach based on a portfolio of methods including the farmer field school approach, participatory on-farm trials, field discussions, and perception and adoption assessments (Braun et al., 2000; Hoffmann et al., 2007; Mancini et al., 2006; Meijer et al., 2015; Zabala et al., 2013). The trials included different sustainable intensification options that include the following technologies and practices:

1) Crop composition (maize and legume intercrop instead of maize sole cropping)

2) Sowing methods (in line instead of broadcasting)

3) Tillage (mechanized instead of animal traction)

4) Use of fertilizers (instead of farmyard manure)

5) and hybrid seeds (instead local seeds).

These agricultural innovations were selected as best-bet options to increase crop productivity on the basis of previous trials in the region (Devkota et al., 2015).

3.2. Materials and Methods

3.2.1. Description of the study sites

The study took place in Nepal in two villages, governmentally referred to as village development committees (VDCs), in the western region (Palpa district) and two VDCs in the far-western region (Dadeldhura district) (Figure 1).

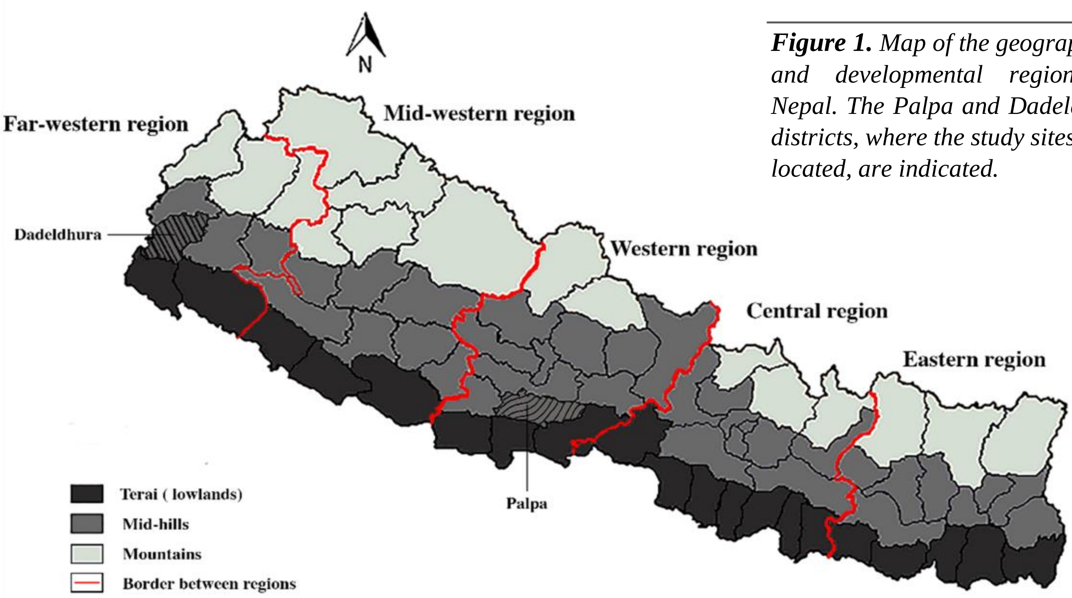

Figure 1. *Map of the geographical and developmental regions in Nepal. The Palpa and Dadeldhura districts, where the study sites were located, are indicated.*

In socio-economic terms, the far-western regions are less developed and less exposed to information and technology than the western region (UNDP 2011) (Table 1). Nepal development gradient ranges from low to high from east to west, and from south to north. The Terai (valley) is the main agricultural production area and the most connected and developed region of Nepal (Fig.1). A large proportion of the male workforce in the mid-hill region temporarily migrates to obtain additional income. In Dadeldhura, migration

Table 1. *Characteristics of farms and agricultural households in the western and in the mid- and far-western mid-hill regions of Nepal (CBS Nepal 2011).*

Characteristics	***Western region***	***Mid- and far-western region***
Agricultural households (%)	93	97
Literacy of agricultural household head (%)	60	47
Average age agricultural household head (years)	48	43
Average farm size (ha)	0.5	0.5

mainly entails seasonal work in India, while in Palpa men migrate for longer periods to the Persian Gulf countries. Due to the high rate of male migration, farming has become a predominantly female activity in both the western and far-western regions.

The topography of the two regions is similar with Dadeldhura situated at a slightly higher altitude (1500 m a.s.l.) than Palpa (1300 m a.s.l.). Overall, the soils in both mid-hills are chromic cambiosols (Dijkshoorn and Huting, 2009) with a silty-loam texture in Dadeldhura, and loam to silty loam in Palpa. The climate in the two areas as described by the Koppen climate classification is subtropical-dry winter with monsoonal influence. The wet summers (June-September) have a similar average precipitation with 990 mm in Dadeldhura and 1052 mm in Palpa, while in the dry winters (December-March) the precipitation is slightly higher in Dadeldhura (349 mm) than Palpa (228 mm) (Department of Hydrology and Meteorology of Nepal, 2015).

Farming in both Dadeldhura and Palpa is rain-fed, and is characterised by small-scale (on average 0.5 ha) mixed farms. The average number of tropical livestock units (TLU) per farm is 2 in Dadeldhura and 3 in Palpa. Both regions commonly have two cropping seasons per calendar year, namely summer (May-September) and winter (October-December). However, in some cases a third season is added during spring (January-April).

In both sites maize is commonly sown with different species of beans, pumpkin and finger millet. The plant population and species varies among the fields. The main crop grown in summer in Palpa is maize (mainly mixed with legumes, cucurbits and finger millet), while in winter mustard mixed with chickpea or lentil 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 or 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.

On average, 14% of the households in Palpa, and 6% in Dadeldhura use improved seeds for cereals and vegetables, while respectively 30% and 19% of the farmers use mineral fertilizers (CBS Nepal 2014). Previously, the International Maize and Wheat Improvement Centre had projects in Palpa (IFAD-supported, 2011- 2013) and in Dadeldhura (USAID-supported, 2013 – 2015). Both projects were based on on-farm experiments with the objective to close maize yield gaps. The experiments were composed of single or layered combinations of five agronomic practices: i.e. use of hybrid cultivars, adjusted plant density and fertilizer rate, weed control and crop establishment practices (Devkota et al., 2015).

3.2.2. Participatory process

Our research targeted agricultural intensification in small-scale mixed farms in the mid-hills of Nepal through the following activities: 1) Participatory on-farm trials, 2) Farmer field discussions (FFD), 3) Perception assessments (PA), and 4) Innovation adoption assessment (IAA) (Fig 2). The project was conducted over two years, 2014 and 2015, in Dadeldhura and for one year (2014) in Palpa, where it was not possible to continue the project for the second year due to the major earthquake of April 2015.

Traditional farmer practices and agricultural innovations were explored. We assessed seeding method (seeding in lines vs. broadcast), tillage method (land preparation with a mini-tiller vs. oxen-ploughing), cropping pattern (sole cropping vs. intercropping), type of fertilizer (mineral vs. farm yard manure) and crop cultivars (hybrids vs. local and/or open pollinated varieties). The proposed practices were demonstrated in the on-farm experimental trials and compared with the traditional farmer practices in their own fields. Farmer perception was assessed by comparing 1) costs, 2) amount seed required, 3) labour requirement, 4) weed pressure and 5) yield potential of the traditional and proposed practices. These five key factors were identified together with diverse farmers/households through a rapid rural appraisal at start of the participatory project, in 2013. The farmers/households were selected randomly in each site using a Y- shaped method described by Tittonell et al. (2010), and characterized through typologies based on their resource endowment. Only the practices which could be compare with the traditional ones were part of this comparative assessment, the inputs such as mineral fertilizers and crop cultivars were excluded since such inputs were part of the key factors to test perceptions of the practices assessed: mini-tiller vs. ploughing with oxen and the line sowing vs. broadcasting practice. In addition, we explored all the practices and input technologies through the IAA and the FFD. All the field activities and evaluations are summarised in Table 2.

In total seventy-one farmers participated voluntarily in the FFD and PA, of whom 39 in Palpa and 32 in Dadeldhura. The on-farm trials took place in fields of 22 representative farmers (11 in Palpa and 11 in Dadeldhura) belonging to different resources endowment categories from existing typology. The 71 farmers were categorized into farm types based on the yearly income, land holding size, number of tropical livestock units (TLU),

Table 2. *Overview of the assessments and the improved and traditional technologies and practices explored.*

	Seeding		**Crop pattern***			**Tillage**		**Fertilizers**		**Variety**	
Assessment	**Line**	**Broadcast**	**Inter-crop**	**Sole-crop**	**Mix-crop**	**Mini-tiller**	**Animal traction**	**Mineral**	**FYM**	**Hybrid**	**Local**
Experimental trials	✓		✓	✓		✓		✓		✓	
Farmers' practices		✓			✓		✓		✓		✓
Perception assessment	✓	✓	✓	✓		✓	✓				
Innovation adoption assessment	✓		✓			✓		✓		✓	
Perceived constraints to adoption	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Farmers field discussion	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓

*** Inter-crop refers to the mix: legumes-maize in optimal plant population (used in the trials), while mixed-cropping refers to the traditional farmers practice of maize mixed mainly with legumes, cucurbits and millet.**

available labour force and food availability during the year. In Palpa the low resource endowment farmers were characterized by low off- and on-farm income (on average 1626 USD per year total income), small productive land holdings (on average 0.20 ha), few TLU (on average one), food self-sufficiency for less than six months per year (on average five months), and limited labour force. The 'high' resource endowment farmers obtained greater income (on average 4752 USD per year), had larger land holdings (on average 0.40 ha) and number of TLU (on average 6), were food self-sufficient for more than six months (on average nine months), and had more labour available. In Dadeldhura, the types followed the same pattern but in general the farms had a considerable lower yearly income than those in Palpa. For instance, the yearly income from the high and low resource endowment farmers in Dadeldhura was approximately half and one third of the average income of the high and low resource endowment farmers in Palpa, respectively.

3.2.2.1. On-farm trials

The experiments were designed in collaboration with farmers and CIMMYT researchers. The objectives were: 1) to improve maize grain yields under farmer management to reach the attainable yield of 6.5 Mg ha^{-1} previously obtained in on-farm trials conducted by CIMMYT (Devkota et al., 2015), and 2) to explore possibilities to attain additional biomass for livestock feeding from legumes through intercropping. We compared productivity of maize mono-crop with maize-cowpea and maize-soybean intercrops. The main characteristics of the cropping systems are presented in Table 3.

Table 3. *Treatments of the on-farm trials in Palpa (2014) and Dadeldhura (2014 and 2015).*

Year	***Cropping system***	***Plant population[a] (ha^{-1})***	***Mineral fertilizer (N-P-K; kg ha^{-1})***	***Crop varieties***	***Tillage***
2014	Sole maize	66666	150-60-60	Rajkumar	Mini-tiller (two wheel tractor)
	Sole soybean	194444	10-40-30	Puja	
	Sole cowpea	194444	10-40-30	Tane bodi	
	Maize + soybean	55555/111111	150-60-60/60-60-40[b]	Rajkumar/Puja	
	Maize + cowpea	55555/111111	150-60-60/60-60-40[b]	Rajkumar/Tane bodi	
	Farmers practice	*35000[d]*	0	Local	Oxen/tractor
2015	Sole maize	66666	150-60-60	Kanchan	Mini-tiller
	Sole soybean	194444	10-40-30	Local	
	Sole cowpea	194444	10-40-30	Mei Wu Jia	
	Maize + soybean	55555/111111	90-60-40	Kanchan/local	
	Maize + cowpea	55555/111111	90-60-40	Kanchan/Mei Wu Jia	
	Farmers practice	*35000[d]*	0	Local	Oxen

[a] The plant population was obtained by a line sowing.
[b] In 2014 different mineral fertilizer application rates were used for maize and legumes.
[c] The farmers practice consisted of maize and different species of legumes and pumpkin intercropping and application of 9 Mg/ha farmyard manure.
[d] The plant population in average was taken for a previous study in the zone (Devkota et al., 2015).

Maize in monoculture was sown in lines (in contrast to broadcasting methods used by farmers) with spacing of 0.60 m between lines and 0.25 m within lines separating plants. The intercrop spacing between maize lines was 0.70 m, and within lines 0.25 m. The legumes were planted in a single line between the maize lines (0.35 m distance) and 0.10 within lines, while distances of 0.50 m between lines and 0.10 within lines were used for the sole legumes. In the second year, we slightly adjusted the trials in discussion with the farmers. The initial hybrid maize cultivar was changed for an early-maturing hybrid. The improved soybean variety used in the first year was changed to a local variety. Cowpea was replaced from a climbing to a bush cultivar. The rate of mineral fertilizer was reduced in the intercrop treatments. We analysed the trials as a randomized complete block design with the farms as blocks individually for each year. To determined significant differences between cropping systems we performed an Analysis of Variance with Tukey HDS test. Additionally to the grain and biomass yield, we calculated the Land Equivalent Ratio (LER) which represents the total land area of sole crops required to achieve the same yields of intercrops (Li et al., 2011).

3.2.2.2. Farmer field discussion

Following the Farmer Field School (Braun et al., 2000; Mancini et al., 2006) approach, we organized farmer field discussions (FFD) twice every year during the growing season, once after sowing and once right before harvest (cf. Figure 2). In each of the FFD, three trials on three different farms were visited. On each of the farms, farmers were asked to

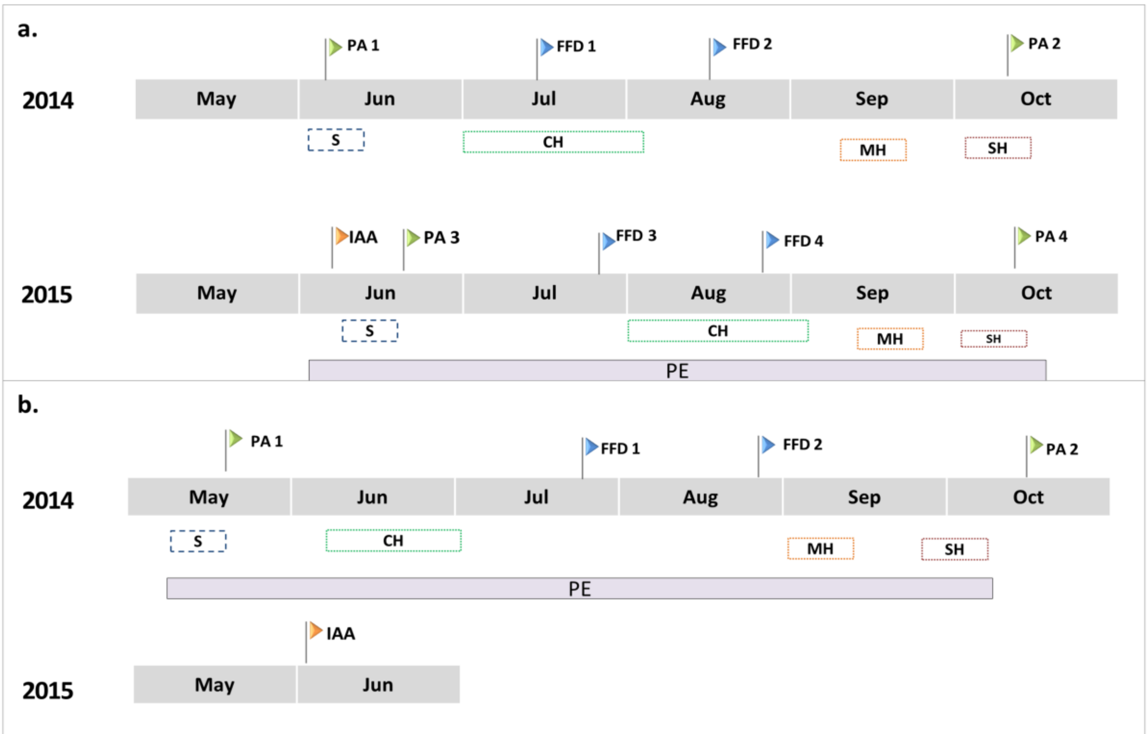

Figure 2. *Time line biophysical and social processes for year 2014 and 2015 in a) Dadeldhura and b) Palpa. PA: perception assessment, FFD: farmer field discussion, PE: participatory on-farm experiment, IAA: innovation adoption assessment S: sowing, CH: cowpea harvest, MH: maize harvest, SH: soybean harvest. CSISA project have had summer and winter trials from 2013 to 2015 in Dadeldhura; and IFAD-CIMMYT project had had summer and winter trials in 2012 and 2013 in Palpa.*

discuss and summarise in keywords their discussion in subgroups of 2 to 3. Thereafter, they were asked to share a summary of their discussion with the whole group. The topics to discuss were introduced one by one and included: 1) the performance of the trials, 2) the proposed practices explored in the trials, 3) the pros and cons of the proposed practices, 4) the feasibility of integrating the proposed practices in current farmer's management strategies. In the last FFD, yields of the trials were also presented and discussed. These discussions were taped with the permission of the participants and notes were taken during the sharing of views.

3.2.2.3. Perception assessments

The impact of actively involving farmers in research was evaluated by assessing changes in farmer perceptions of the agricultural practices explored in the on-farm trials before and after they took place. Through comparing the before and after the trial perceptions each year, we aimed to determine if and how farmers changed their pre-conceived ideas on the innovations. Farmer perceptions were assessed for three choices: 1) Cropping pattern – intercrop or monocrop, 2) Sowing methods – broadcasting or line sowing and, 3) Tillage – minimum tillage through the use of a mini-tiller or conventional ploughing with oxen.

We developed a visual board (Figure 3a) to assess farmer perceptions following Zabala et al. (2013). This perception assessment tool consisted of a board that showed all the management practices proposed to farmers and a set of tokens. Farmers rated their expectations about different characteristics of the practices by assigning between 0 and 10 tokens per characteristic for each of the practices. The number of tokens assigned represented a score. The evaluated characteristics were:

- Input requirements in terms of costs, labour and seeds.
- Severity of incidence of weeds.

- Crop yield.

We considered a change of perception when the number of assigned tokens changed in comparison to previous perception assessments. We defined positive change in perception as a relative decrease of tokens allocated to costs, labour, seeds and weeds and a relative increase in tokens allocated to yield for the tested technologies. Through using this visual method, we aimed to reach the illiterate farmers and strengthen the focus of the discussion.

Figure 3. *Participatory process with farmers in Palpa and Dadeldhura, a) farmers using the perception assessment board, and b) farmers farm discussion and mini-tiller use.*

We assessed the perception (trough the perception assessment) of 32 farmers in Dadeldhura and 40 in Palpa. The results were analysed using a Generalized Linear Model to test for significant differences of the binomial proportions after Logit transformation. To gain more in-depth understanding on changes in farmer perception, we determined to which endowment type the farmers with a positive change in perception belonged.

3.2.2.4. Innovation adoption assessment

Before an innovation is incorporated in the farm management, i.e. the actual adoption, farmers experiment with the innovation to determine if it provides a certain degree of relative advantage. In this study we refer to try-outs, which were described by Misiko (2009) as the decision of farmers to start experimenting with the demonstrated innovations. In order to assess whether farmers who participated in the trials and/or the farmer field discussions started trying any of the proposed practices, we used semi-structured open interviews. Farmers were not given pre-selected options (multiple-choices) for their answers. We performed these interviews to assess the use of technology or practices before the start of our participatory project and after each year to assess if farmers started trying each of the proposed practices and technologies as a result of the participatory project. Furthermore, they were asked to elaborate on the reasons why they were or were not using these innovations before, as well as the constraints associated with their implementation. In Palpa and Dadeldhura, 39 and 32 farmers were part of the assessment, respectively.

3.3. Results

3.3.1. Participatory on-farm trials

3.3.1.1. On-farm trials

The average yield of maize monocrop and intercrop in both districts was about 7.0 Mg ha^{-1} in contrast to 2.5 Mg ha^{-1} in the farmer’s practice plot in both years (Table 4). However, in 2015, when mineral fertilizer was reduced in the intercrop system, the yield of the sole maize was slightly higher than the intercrop 6.9 and 5.9 Mg ha^{-1} respectively. In addition, the legume yield was higher in the sole crop than in the intercrop. In both years, the Land Equivalent Ratio (LER) was higher than one in all the intercrop treatments compared to the monocrop treatments (Table 3).

Table 4. *On-farm trials yield and yield components in Palpa and Dadeldhura in 2014 and 2015.*

Year	Treatment	Crop	DADELDHURA							PALPA						
			Grain yield Mg ha^{-1}	# plants harvested (ha^{-1})	Stover yield Mg ha^{-1}	LER	LAI	HI	Gross margin ($ ha^{-1})	Grain yield Mg ha^{-1}	# plants harvested (ha^{-1})	Stover yield Mg ha^{-1}	LER	LAI	HI	Gross margin ($ ha^{-1})
2014	Farmers plot	maize	2.7	*33160*	4.2			0.4	275	2.5	34141	6.0		0.6		206
	Sole maize	maize	7.5	49026	10.0		2.0	0.4	1056	6.7	62500	10.6		2.7	0.4	830
	Sole soybean	soybean	1.8		4.0		5.3	0.3	592	1.8		9.5				258
	Sole cowpea	cowpea	6.2		1.6			0.8	669	2.5		0.4				-227
	Maize-soybean					1.5	4.8				54043		1.3	2.5	0.4	966
		maize	7.3	49188	9.7	1.0		0.4	1528	6.5		10.3	1.0			
		soybean	1.7		1.7	0.6		0.4		0.7		1.5	0.3			
	Maize-cowpea					1.7			1669				1.6	2.8	0.4	968
		maize	7.7	49675	8.4	1.2		0.5		6.7	52809	10.9	1.0			
		cowpea	1.5		1.4	0.5		0.7		1.3		0.4	0.6			
2015	Farmers plot	maize	2.0	37436	2.3			0.5	204							
	Sole maize	maize	6.9	56204	10.2		2.9	0.5	378							
	Sole soybean	soybean	3.6		2.4		6.0	0.6	732							
	Sole cowpea	cowpea	3.6		2.1		1.0	0.7	-222							
	Maize-soybean			50185		1.4	4.9									
		maize	6.0		7.4	0.9		0.5	861							
		soybean	1.6		1.2	0.5		0.6								
	Maize-cowpea			50000		1.3	2.9									
		maize	5.8		6.7	0.9		0.5	309							
		cowpea	1.5		1.3	0.5		0.5								

3.3.1.2. Farmer field discussions

Although farmers listed many perceived benefits associated with the tested practices (Table 5) and technologies during the FFD's, they indicated many reasons why those interventions were not used in their fields (Table 6). Concerning the on-farm trials, both in 2014 and 2015 farmers exhibited marked preferences for intercropping in both districts. In Dadeldhura the maize-cowpea intercrop was most preferred in 2014, and maize-

Mini-tiller	**Legume intercrop**	**Line sowing**
-Time/labour saving -Cheaper -No bullock husbandry -Easy to use (women might be able to use it) -Uniform ploughing and levelling -Better crop performance -Make soil friable and fine -Improved cutting of the remainders of the previous crop -To avoid deep ploughing that damages soil -All family members could use it	-More food and feed production (two crops) -Legume increases soil fertility and loosens the soil -Legume is a cash crop -Conserves soil moisture/less runoff -Less labour (weeding done at the same time) -Land-use advantage (used as green manure) -Good interaction as maize holds the climbing legume -Legume fixes nitrogen	-Weeding and fertilizer application is easier -Prevents maize lodging -Uniform crop growth -Lower seed quantity (when planted in appropriate density) -Advantage in land-use -Less labour (weeding and fertilizer is easier) -Reduces lodging of maize -Higher yield

Table 5. *Treatments of the on-farm trials in Palpa (2014) and Dadeldhura (2014 and 2015).*

soybean was the first choice in 2015. In Palpa maize-soybean was the first choice in 2014. In both districts sole soybean was the least preferred cropping system.

3.2.2. Impact assessment

3.2.2.1. Farmer perceptions

Within the two years, the standard deviation of perception scores was lower after the experiment than at the start of the season, which could indicate a convergence of opinion about comparisons of both line sowing vs. broadcasting, and mini-tiller vs. animal traction with oxen (Figures 4 and 5).

3.2.2.2. Seeding method

There were clear differences in perceptions of seed required and yields obtained when comparing seeding methods that persisted throughout the two-year project duration (Figures 4a and 5a). Farmers in both Palpa and Dadeldhura clearly perceived that more seeds were required when seeding by broadcasting than with line sowing (Figure 4a and 5a).

Table 6. *Stated reasons why farmers did not try-out the selected agricultural innovations. The percentage of farmers is an average of two observations (before and the trials and after the first year of trials).*

Palpa	%	Dadeldhura	%
Line sowing			
Lack of labour force at planting	55	Lack of labour force at planting	73
Tradition	13	Inappropriate rainfall	8
Lack of capital	12	Tradition	6
Inappropriate rainfall	7	Lack of knowledge	5
		Lack of capital	5
Mini-tiller			
Difficult to take to the sloping plots	25	Not available	43
Not available	16	Lack of capital	12
Availability of tractor	12	Difficult to take to the sloping plots	11
Lack of knowledge	12	Lack of person to operate it	9
Lack of person to operate it	11	Lack of knowledge	2
Hybrid seed			
Insect in storage	19	Preference local variety flavour	25
Prefer to use own seed	11	Not available	18
Tradition(neighbours use local varieties)	10	Expensive	13
Preference local variety flavour	5	Prefer to use own seed	9
Not available	5	Long maturity	8
Long maturity	4	Tradition(neighbours use local varieties)	8
Wild animals/less stover/insects inf.	2		
Mineral fertilizer			
FYM is enough	50	Not enough rainfall (soil becomes hard)	28
Not always available locally	14	FYM is enough	27
Not enough rainfall (soil becomes hard)	13	Lack of capital/expensive	15
Lack of capital/expensive	10	Tradition	13
Reduces soil fertility	2	Reduces soil fertility	11

Similarly, they expected yields to be higher after seeding in lines than by broadcasting. In addition, at the start of the project farmers in Dadeldhura expected that lower costs and labour inputs were needed for seeding by broadcasting, while in Palpa the costs of broadcasting were perceived higher than line sowing. The anticipated costs of line sowing were lower in Palpa after the first year of trials (Figure 5a). Some of the perceptions changed during the project. The perception of labour requirement of line sowing was lower after the two years of trials in Dadeldhura. The perceived differences between line seeding and broadcasting were smaller after the project (Figures 4a and 5a).

The number of farmers that had a positive change of perception towards line sowing increased after the second year of trials. Yield had the highest number of farmers with a positive change of perception, followed by labour required, the amount of seeds used,

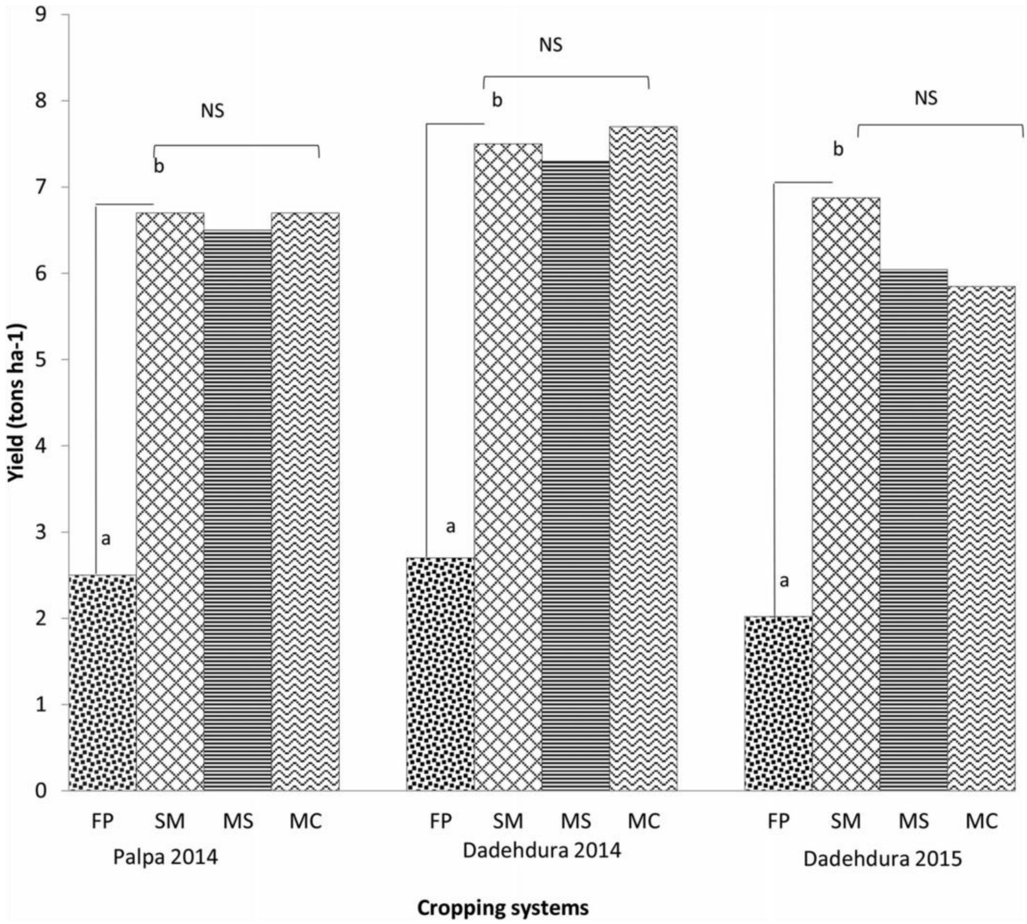

Figure 4. *Maize grain yields for the 4 cropping systems where FP: farmer practice, SM: maize mono-crop, MS: maize and soybean intercrop, MC: maize and cowpea intercrop in Palpa and Dadeldhura. Different characters indicate significant different means (P<0.05). NS: represent No-significant differences.*

expected costs and the incidence of weed. While in Palpa the amount of farmers with positive perception in order of descending significance was: costs, labour, yield obtained, seed required and weeds pressure (Figure 5).

3.2.2.3. Tillage

In Dadeldhura the differences in perceptions of different tillage methods (mechanised tillage with a mini-tiller and animal traction with oxen were less pronounced than for the perceptions of the sowing method. The main difference between the two tillage methods was the lower perceived labour requirement for mechanised tillage with a mini-tiller (Figure 4b). Within both experimental years, the expectation of labour requirements was higher after the experiment than at the start of the season for both tillage methods. The initial farmer perception about the expected lower costs and labour inputs with a mini-tiller changed to a comparable score of ca. 5.5 for both tillage methods. In Palpa, the cost and labour required for the use of animal traction were perceived much higher than when using a mini-tiller (Figure 5b). However, the perception of the amount of labour required for the mini-tiller increased during the two years in Dadeldhura. Similarly, the cost of the mini-tiller was perceived higher at the end of the trials in comparison to the initial perception (Figures 4b and 5b).

In Dadeldhura yield scored the largest number of farmers with a positive change in perception of the mini-tiller, followed by seed requirement and weed incidence. Fewer farmers changed their perception about costs and labour requirements at the end of the second year (labour scored high only after the first year) (Figure 4b). In contrast, in Palpa the majority of farmers had a positive change in perceptions of expected costs, followed by labour needed, yields, weed incidence and amount of seed (Figure 5b).

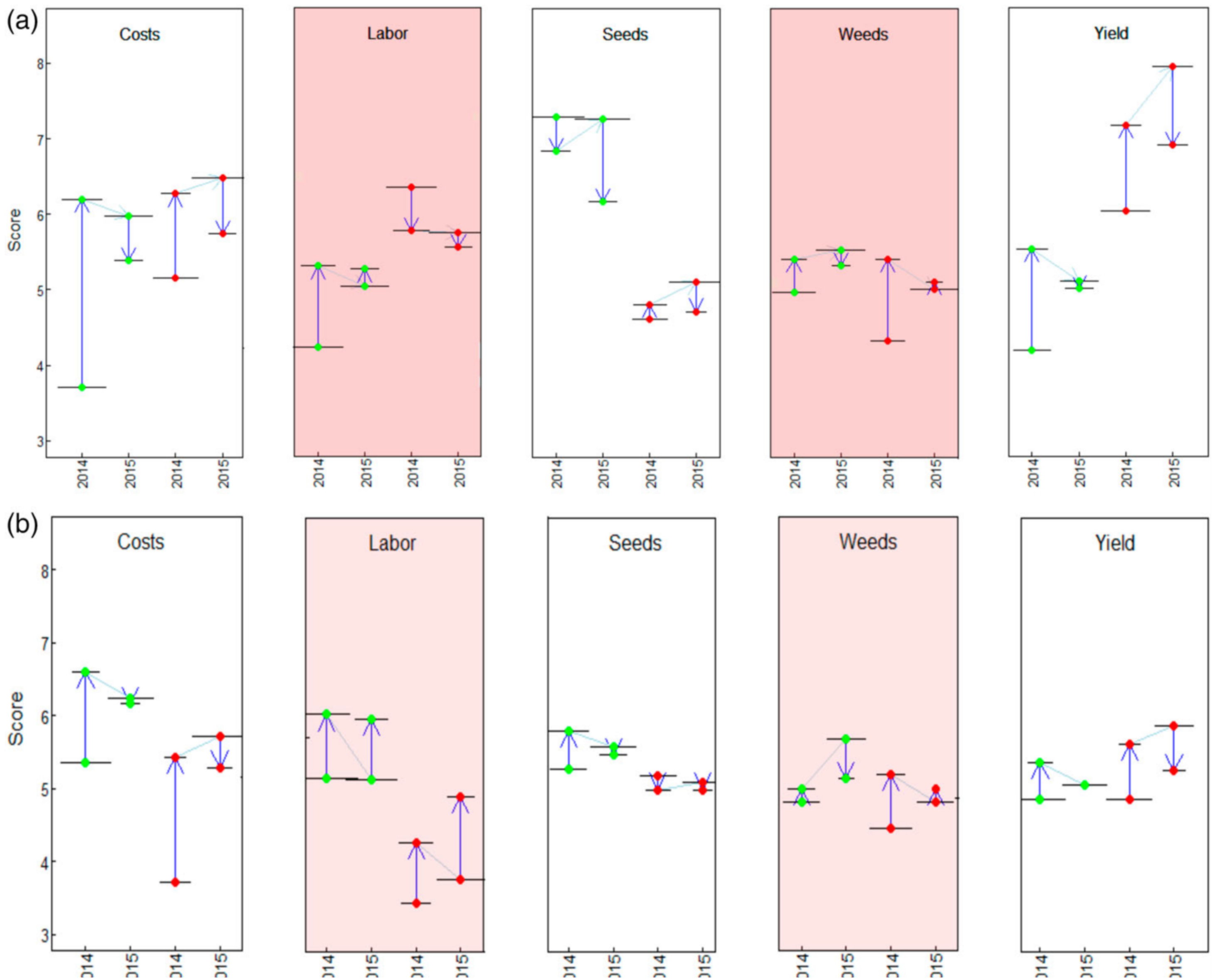

Figure 5. *Scoring of the relative input requirements (costs, labour, seeds) and crop performance (weed pressure, yield) of* ***a)*** *seeding by broadcasting (green) vs in lines (red), and* ***b****) tillage using a mini-tiller (red) vs. animal traction with oxen (green), in Dadeldhura on a scale of 0-10 in 2014 and 2015. The blue arrows represent the change in perceptions before and after experiments within a year, the grey lines connect the last scoring of 2014 with the first of 2015. Error bars indicate the standard deviations.*

3.2.2.4. Perception by different types of farmers

In general, a larger proportion of medium (MRE) to high resource endowment (HRE) farmers changed their perceptions in Palpa, while in Dadeldhura there was not a clear pattern but mostly low (LRE) to medium resource endowment farmers had a positive change of perception. The farmers that had a positive change in perception of labour required for seeding in lines belonged to the low resource endowment type in Dadeldhura, while those that had the positive change of opinion in Palpa belonged to the medium and high resource endowment types.

The farmers that had positive change of perception about the obtained yield and required seed in Dadeldhura belonged to the low resource endowment type. The positive change of perception of cost required for the use of mini-tiller in Palpa was indicated by low to medium resource endowment farmers.

3.3.3. Early adoption of the technologies and practices

3.3.3.1. Farmer's perceived constraints to adoption

The reasons of low adoption of innovations discussed with the farmers previous to the trials in 2014 and after one year of participatory on-farm trials are depicted in Table 6. The main reasons for non-adopting innovations in both sites were stated to mainly relate to the labour constraint, the low availability of the technology and farmer perception and preferences.

3.3.3.2. Try-out of practices and technologies

The try-out of the practices and technologies was based on the farmers that indicated that they started to use the technologies since 2015 (Table 7). All of the farmers experimented only partially and only in plots close to the homestead.

Table 7. *Percentage of technology and practice innovation users in 2015.*

Innovation	**Palpa**		**Dadeldhura**	
	(%)	**(#)[b]**	**(%)**	**(#)**
Line sowing	5	(2)	20	(7)
Mini-tiller	15	(6)	0	
Hybrid seed	5	(2)	17	(6)
Improved OPV [a] seeds	20	(8)	20	(7)
Mineral fertilizers	10	(4)	3	(1)

[a] Open pollinated varieties.
[b] Number of farmers

3.3.3.3. Type of farmers

Most of the farmers that used the practice of sowing in lines and mineral fertilizers in 2015 belonged to the HRE type and to a high social cast level. The only farmers that bought hybrid seeds belonged to the HRE type; additional farmers that used the hybrid seeds obtained the seed from development projects.

In Palpa, only HRE farmers used hybrid seed before the start of our study. However in 2015, MRE and LRE started using hybrid seed. It is important to note that these farmers had our trials in their fields and were active in the development of the experiments. Predominantly MRE farmers used the improved OPV *Manakamana*, line seeding and mineral fertilizer. Only one HRE farmer practiced seeding in lines in all the fields of his farm. Farmers from all endowment types started using a mini-tiller in Palpa.

3.3.3.4. Relation between try-outs and perceptions

Early adopter farmers demonstrated a positive change of perception at least in one of the factors evaluated. The farmers that tried line sowing in Palpa had also a positive change of perception about the required costs and labour. Only one had a positive change in perception about yield (Figure 6(a)). While in Dadeldhura, the farmers that tried out had a positive change of perception for at least one of the variables tested. Thirty three percent of those farmers had a positive change of perception of labour needed, 29% about money required, 24% about yield obtained, 22% about the amount of seed needed and 8% about weed infestation (Figure 6(b)).

Concerning the use of mini-tiller, in Palpa most of the farmers had a positive perception of costs (46%) and labour (33%). Yield and weed population (28%) and only 23% had a positive change of perception about required seed (Figure 6(c)). None of the farmers adopted the use of a mini-tiller in Dadeldhura.

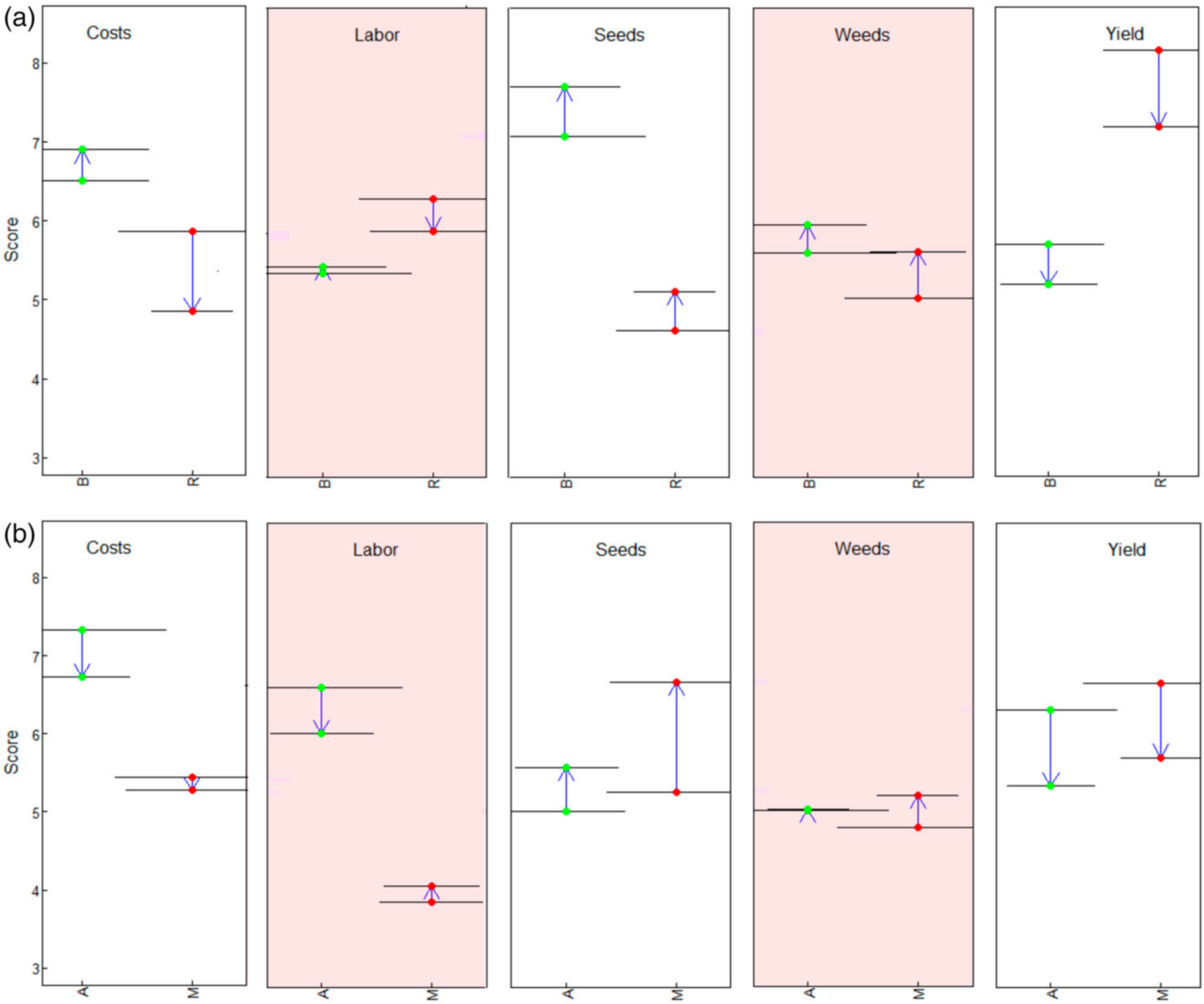

Figure 6. *Scoring of the relative input requirements (costs, labour, seeds) and crop performance (weed pressure, yield) of (a) seeding by broadcasting (B) in green vs. in lines (R) in red, and (b) tillage using animal traction with oxen (A) in green vs. mini-tiller (M) in red in Palpa on a scale of 0–10 in 2014. The blue lines represent the change in perceptions before and after experiments within a year, the grey lines connect the scoring before and after the trials in 2014. Error bars indicate the standard deviations.*

3.4. Discussion

Through the participatory approach in our study, farmers were informed about experimenting with new practices and technologies by providing training and experiential learning on their fields, and had the chance to reflect upon their previous perceptions, while the researchers were able to improve their understanding of the factors that constrain farmers' adoption of innovations. In addition, the project gave insights of how participatory approaches can have an impact on the perceptions of farmers towards innovations and their potential adoption. According to Tiwari et al. (2004) participatory methods provide a way to assess and inform farmer perceptions that cannot be captured in on-station trials. Similarly, Pircher et al. (2013) indicated that social analysis is crucial to understand the effectiveness of participatory technology evaluations. In particular women household members are difficult to reach, while they play an important role in farming in the Mid-hills of Nepal. Through the participatory method it was feasible to involve women, to compile their reasons for adoption or non-adoption and to understand their perceptions. This study contributed to the evidence that considerably higher yields (Devkota et al., 2015) can be obtained in farmer fields in our case study areas, and it enriched the knowledge on the performance of maize-legumes intercrops. Furthermore, with the FFD and the perception assessment we demonstrated that farmers are aware of the advantages that sowing in lines can bring in terms of yield and seed saving, and the use of a mini-tiller in terms of labour and costs. However, farmer decisions to use those practices and technologies were affected by a multitude of biophysical, social (including cultural) and institutional factors.

3.4.1. On-farm participatory learning

The effect of our project and in particular of the experiments was shown by the convergence of opinion that occurred during the two growing seasons, and was observed for the comparisons of both line sowing vs. broadcasting and mini-tiller vs. animal traction with oxen (Figures 3 and 7). Also, Kraaijvanger et al. (2016) showed that attitudes and congruency of opinion of farmers towards agricultural innovations were affected by participatory experimentation.

The scoring procedure applied allowed to assess the changes in farmer perceptions. Farmers partially trying out one of the technologies or practices after the first year of the project had a positive change in perception. At least in one of the factors used in the perception assessment. Hence, not all assessed factors (labour, costs, yield, seeds and weeds) needed to be changed positively to allow an adjustment in behaviour. There were less positive changes in the perceptions of the mini-tiller than about line sowing. Farmers' perceptions of both line sowing in comparison to broadcasting, and mini-tiller as opposed to animal showed that yield is not the only decisive factor affecting adoption of the practices.

Through the reasons given by farmers and the assessment of their change of perceptions we could explore a broad range of farmers' reasons of reluctance to 'innovate' in the mid-hills agro-ecosystems. Many of the stated constraints to try-out new practices and technologies were related to timely labour availability, supply of inputs (by costs or availability), and cultural preferences (including socio factors) Similar factors affecting

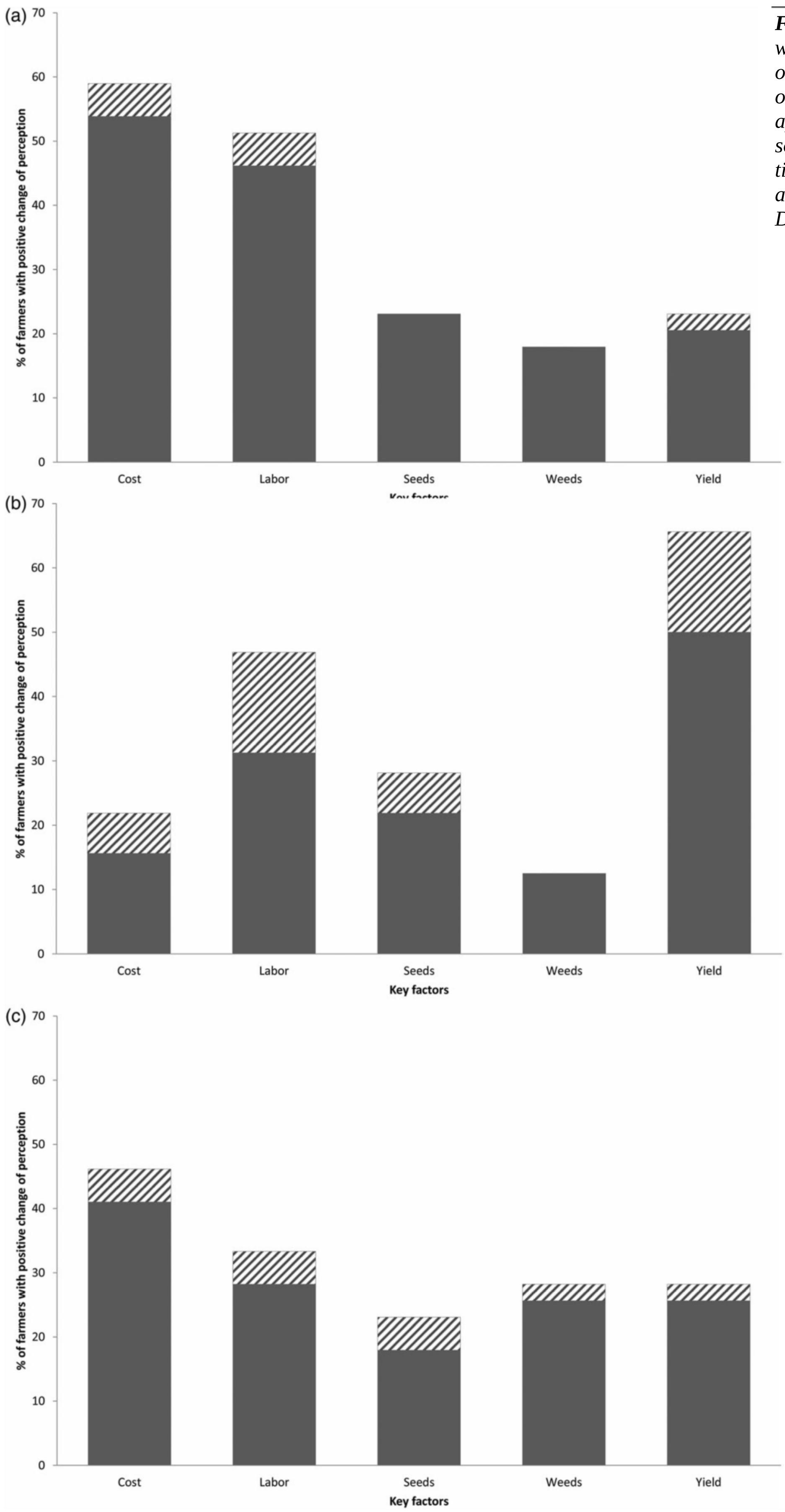

Figure 7. *Percentage of farmers with positive change of perception of the key factor and the percentage of early adopters in dotted font for a) line sowing in Palpa, b) line sowing in Dadeldhura, and c) mini-tiller in Palpa. There were not early adopters of mini-tiller in Dadeldhura.*

adoption have been described previously in small farming systems (Andersson and D'Souza, 2014; Awan et al., 2015; Brown et al., 2017; D'Souza et al., 1993; Kotu et al., 2017; Mbosso et al., 2015; Ransom et al., 2003; Toth et al., 2017).

Aw-Hassan (2008) argued that farmers involvement (through participatory approaches) in the design and implementation, enhance the impact of agricultural research. Yet, these approaches have been also criticized as impractical to scale out technologies, especially because of the high cost involved. We argue that the stage in which farmers are involved is key. The initial phases of the project are the most important to involve farmers. As mentioned by other studies, farmers should be involved in early stage of the design of innovations and the practices and technologies should be built or adjusted on existing local knowledge traditional practices, and livelihood goals (Millar and Connell, 2010; Pretty, 2002). In addition, the farmers sample should represent the heterogeneity in the zone.

3.4.2. Timely labour availability

Labour availability has been mentioned as one of the main causes of low agricultural productivity in the mid-hill regions in Nepal (Tiwari et al., 2004). This was also observed in our study, as a mismatch between the demand for labour to carry out farm activities in a timely manner and the availability of labour was identified as one of the main reasons for not using the proposed practices. For example, in Palpa the main constraint for not practising sowing in lines mentioned by farmers was the narrow time window for sowing after the onset of rains and the limited availability of oxen ploughing or tractor to rent during that period. The farmers in both Palpa and Dadeldhura were constrained by limited availability of labour due to migration of young male household members and low involvement of the youth. Especially in Palpa farmers repeatedly stated that '*young* *people don't want to work in agriculture, it is difficult to find people to hire in this area*'. As a result, there is a large labour constraint at moments with peaks in labour demand, such as sowing time.

The proposed technologies were evaluated for the expected demand of labour. Farmers initially expected benefits of reducing the labour demand by mechanisation of tillage with a mini-tiller, but that perception was adjusted when they experienced the difficulty of taking the mini-tiller to remote plots located on steep slopes with difficult access (Figure 3b). For the proposed practice of sowing in lines farmers initially thought it would require more labour input than the traditional practice of broadcasting the seed (Figure 3a). Although this perceived higher labour demand for line sowing declined during the project, timely availability of labour was still mentioned as the main reason for low try-out of this practice. As a consequence, the try-out of line sowing was low in Palpa (5%) but relatively high in Dadeldhura (20%) where farm activities are mostly performed by family members, in contrast to Palpa were hired labour is more common. Furthermore, line sowing is a relative easy practice to implement, with low input requirement, low risks and high returns. These simple technologies are more likely to have a shorter adoption and are more likely to be scaled out (Millar and Connell, 2010; Rogers, 2003).

3.4.3. Access to inputs (cost and availability)

The lower try-out of mini-tillers, and mineral fertilizers in Dadeldhura than in Palpa was probably related to lower levels of village connectivity, supply of technology information and connections to markets in Dadeldhura. As stated by previous studies in small farming systems(Kotu et al., 2017; Millar and Connell, 2010; Ransom et al., 2003; Reed et al., 2014). Palpa has a better connection to markets to the more developed lowlands of the Terai, which might have influenced access to inputs. This reflects the findings of Andersson and D'Souza (2014) and Reed et al. (2014) that indicated that smallholders with some market access, maybe be primed for adoption of conservation agriculture practices. The adoption of mineral fertilizer in the mid-hills has been conditioned by the timely availability and the quality of the fertilizers in local markets.

In general, the expected costs for use of mini-tillers were lower than for oxen use, but the difference in perceived costs between the two technologies decreased in both case study areas (Figures 3b and 4b). During the project farmers realised that acquiring the mini tiller will imply additional costs due to the cost of fuel, maintenance and skilled labour to operate. On the other hand, farmers in Dadeldhura seemed to underestimate the costs of ploughing with oxen (owned or shared with neighbours), because they do not necessarily consider their own labour as an extra financial cost. In contrast, farmers in Palpa were able to compare these costs with the cost of renting oxen or tractor and perceived lower cost associated with using a mini-tiller. The highest try-out rates of mini-tillers could be anticipated in Palpa, since machinery ownership is positively associated with household assets, credit availability, electrification, and road density (Mottaleb et al., 2016).

The try-out of hybrid and improved OPV varieties after the first year of our project was relatively high considering only one growing season of participatory trials when comparing to the reported average nine years required to adopt hybrid maize as reported by (Rogers, 2003). In both project sites, the improved varieties were sowed in plots close to the homestead as farmers perceived non-local seeds as requiring more inputs and better soils, as also observed in other tropical smallholder farming systems (Andersson and D'Souza, 2014; Tittonell et al., 2010). Furthermore cultivation of improved varieties was preferred in fields close to the homestead to prevent the attack from wild animals in both regions. We found that mainly high resource endowed farmers started experimenting with improved or hybrid varieties. Ransom et al. (2003) had similar findings.

3.4.4. Cultural preferences

The feminization of agriculture may have limited the mini-tiller try-out in both regions. In the villages studied in Dadeldhura, farming is predominantly done by women, due to out-migration of men. Many of the female farmers here, stated not to be confident to operate machinery. Moreover, ploughing is traditionally seen as a male activity in both mid-hill regions. Similarly, in Palpa men operate and provide service of the mini-tiller, none of the women recalled to have ever used mini-tiller or any other machinery. Moreover, taking over these activities from men would increase their already large labour burden further, while they are already responsible for many tasks (Halbrendt et al., 2014). These cultural reasons are often overlooked by development projects, but already provide a valid explanation of why women are not willing to adopt mechanised technologies in the household as they associated it with an increase in labour specially in Dadeldhura that ploughing services are done by family members in contrast to Palpa that it is a purchased service.

Similarly, in Palpa, traditionally preferred grain colours and flavours were a strong reason for not using improved seed varieties before and after the participatory trials. In addition the growth duration until crop maturity of the hybrid cultivars was mentioned as a cause of low adoption. The hybrids used during the first year of participatory trials took 15 days longer to mature than the local variety. This is a reason of farmers’ concern since the delay in maize maturity and harvest could cause planting delays of the subsequent winter crop (Karki et al., 2015). In addition, in general farmers preferred white varieties (local) in participatory varietal selection Tiwari et al. (2009), because these are considered to be compatible with their farming systems. This is specially the case in Dadeldhura where maize use is mostly used for home consumption, while in Palpa it is used mainly for livestock feed.

Moreover, farmers have the perception that low rainfall availability leads to hard soils when using mineral fertilizers. This was mentioned in both sites repeatedly, and goes in line with earlier conducted studies about perceptions in the mid-hills where farmers expressed awareness that the physical properties of 'soil were damaged by the continuous use of only mineral fertilizers, with soils becoming more difficult to plough and clods more difficult to break' (Tiwari et al., 2004). Cultural preferences and priorities also influence farmers' decisions for crops and activities in other ways. For instance, when asking a farmer why she didn't use line-sowing the answer was: '*I wanted to plant all the field in lines, but I had to go to the temple so I just broadcasted the rest*'.

3.4.5. Farmer diversity

In addition, the perceptions and the experimentation varied among the different type of farmers. As stated by Tiwari et al. (2004) it is unlikely that one combination of traits, will suite all conditions of all farmers population. In both mid-hill regions, the main adopters were the high resource endowment farmers. This is in line with Rogers (2003) who stated that first innovators are usually characterized by a higher social status. LRE farmers have often been found to be limited in development and adoption of innovations. They are grid-locked in so-called poverty traps (Tittonell, 2014) and are less willing and able to take risks (Millar and Connell, 2010).

3.4.6. Sustainable intensification and implications

The changes in perception of farmers throughout the two-year project showed that communication with farmers could influence their opinions. These opinions will eventually inform their decision-making regarding experimentation and subsequent adoption of sustainable intensification practices or technologies. However, the sustainability of the use of combination of external inputs to increase yields requires careful consideration in the farming systems of the mid-hills of Nepal. In the regions characterized by high male migration where women are overloaded, practices that require additional labour (such as line sowing) may be unsustainable (Halbrendt et al., 2014). In addition, most of the farmers in the studied communities have low investment capacity which will limit their possibilities to purchase inputs such as hybrid seeds and mineral fertilizers every year, even if these inputs are available on the local market.

The importance of adopting innovations in mid-hill farming systems depends on the household objectives. Although, the main goal for the farms studied is to safeguard food security, farmers desire to intensify is associated with the wish to move to market orientation. However, crop intensification has been criticized as a pathway to reduce poverty in rain-fed small farming systems due to its limited profitability (Harris and Orr, 2014). Three scenarios were suggested by Harris and Orr (2014) under which crop production may function as a direct pathway to move out from poverty: 1) extensification, 2) commercialisation and 3) income diversification. Farming systems in the mid-hills regions of Nepal are highly constrained by their size (less than half hectare) so extensification is hardly a promising option. Commercialization is restricted to farmers that have invested capacity and connection to markets, who usually commercialize vegetables. Income diversification has actually been the strategy that most of the farmers in the Dadeldhura and Palpa are using in order to cope with poverty. Further special attention shall be given to the trajectories of different types of farms in the mid-hills agro-ecosystems in order to identify farmers whose interest and livelihoods strategies align with (sustainable) intensification.

Different alternatives need to be studied to improve livelihoods of the rural population. All the different components of the farming systems should be assessed to find better options for sustainable intensification. As stated by Blackstock et al. (2007) sustainability requires an integrated and holistic systems approach, where biophysical processes have to be considered in the context of their social-economic drivers and responses.

3.4.7. Limitations

We argue that there were relative differences in perception and relative high try-out rate by the studied farmers after two years of participation. However, farmers' change of perception and try-out could be influenced by other factors. For instance, the farmers may have been influenced by the presence of other (humanitarian) projects in the case study areas. Moreover, farmers might align their answers to expectations about our study, as stated in similar studies (Andersson and D'Souza, 2014). In fact, when farmers were asked about what their practices will be in the future, some responded that their decision will be made depending on the projects available in the future e.g. '*Only if a project comes next year I will change my practices, otherwise I will keep on doing the same*'. Projects often provide incentives such as 'free subsidized fertilizers, seeds, and herbicides', which results in questions about the nature of the adoption claimed (Andersson and D'Souza, 2014). Long term adoption – or abandonment – would be only visible sometime after the project has ended.

3.5. Acknowledgements

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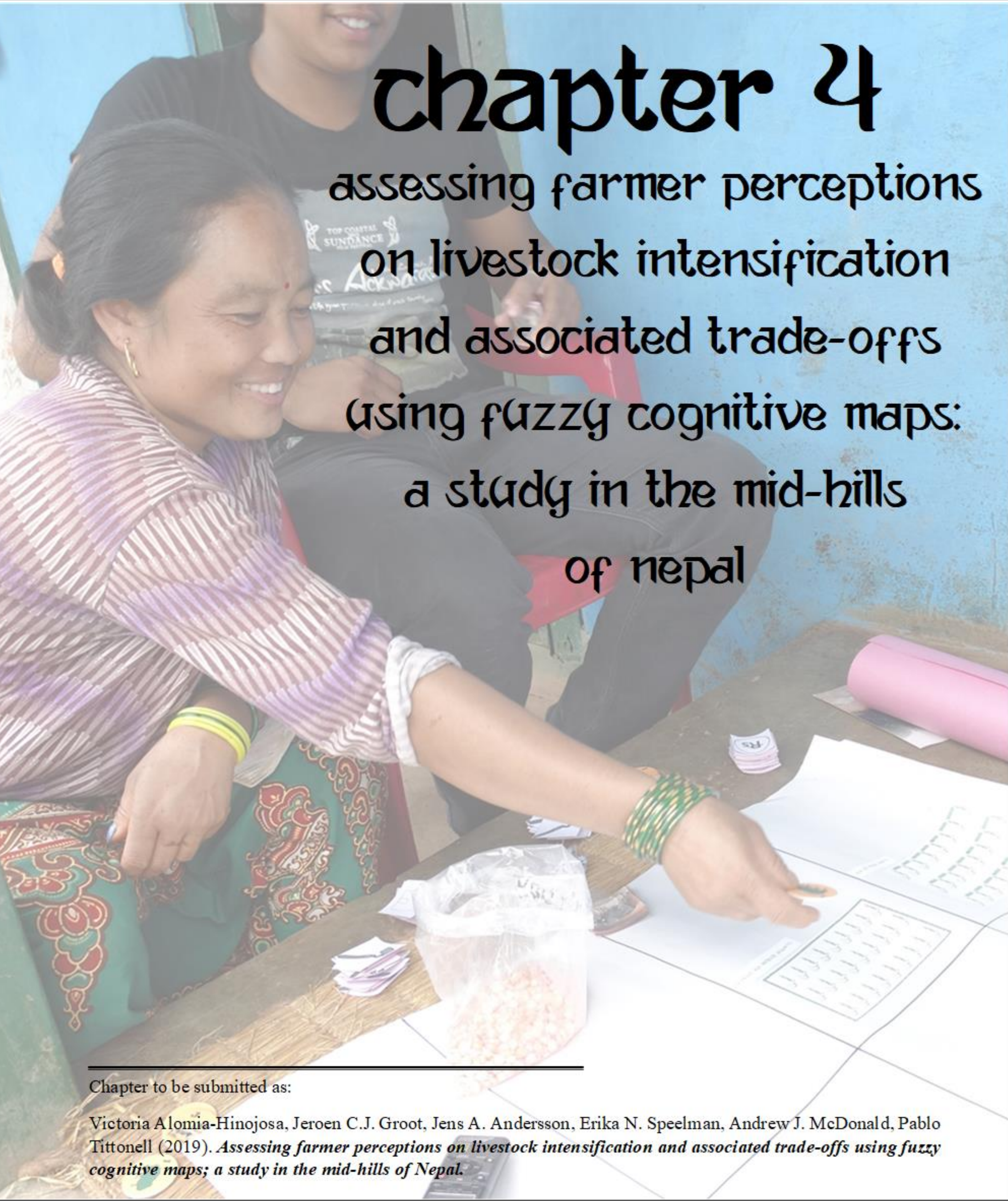

Chapter 4

Assessing farmer perceptions on livestock intensification and associated trade-offs using fuzzy cognitive maps: a study in the mid-hills of Nepal

Chapter to be submitted as:

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Abstract

Intensified livestock production is considered as a promising pathway for smallholder farmers to increase income and to enhance household nutritional security. Nevertheless, this pathway may entail prohibitive investment requirements of labour and capital or trade-offs at farm system level that preclude intensification. We used participatory, ex ante assessment methods to explore farmer perceptions of livestock (dairy-based) intensification in two mid-hill regions of Nepal where maize-based cropping systems predominate. Farm household system representations were constructed together with farmers with different resource endowment levels, using fuzzy cognitive mapping (FCM). FCM was used to assess farmers' perceptions of changes in the farm household system resulting from adding livestock to their farms. We assessed the differences in farmer-perceived external factors that might drive intensification and consequences in terms of interactions among farm components and management and effects on household labour and income. Farmers identified trade-offs between the benefits of increased cash income and farmyard manure (FYM) production from intensified livestock production versus increases in labour requirements for and fodder imports. Farmers were not inclined to make additional investments in on-farm feed production (maize stover and grain), as they perceived these as insufficient to bridge the widening feed gap resulting from additional livestock. The same constraints were mentioned irrespective of farmers' resource endowment levels. Furthermore, a sensitivity analysis performed on the FCMs showed that, given the farmers' perceptions, an increase in milk market demand could have strong positive effects on livestock production and on-farm income. We conclude that FCM is a good tool to rapidly identify trade-offs and analyse perceptions of farmers which revealed that although they consider intensification a promising strategy, the perceived deepening of labour constraints and increasing dependency on fodder import makes a concurrent (sustainable) intensification of these mixed farms' cropping systems unlikely.

4.1. Introduction

The consumption of meat, milk and eggs in low and middle-income countries (LMICs) has more than tripled over the past 30 years (FAO, 2018). In intensive crop-livestock systems in South Asia, livestock numbers are projected to increase significantly: cattle and buffalo from 150 to 200 million animals by 2030 and pigs and poultry by 40% in the same period (Herrero et al., 2010). Poultry meat together with milk are the main animal products projected to increase in consumption in South-Asia. Milk is already high at per capita level, 50% above the average for developing countries. (FAO, 2018).

In the smallholder intensive mixed farming systems that predominate in the mid-hill regions of Nepal, opportunities for expansion of crop production are limited due to their small farm size of less than 0.6 ha on average. Livestock intensification in these systems has the potential to contribute to food security and household income, and it represents a source of manure for increased food and fodder production (Ellis, 2000; Pilbeam et al., 2000; Niehof, 2004; Rufino et al., 2009; Lemaire et al., 2014; Alomia-Hinojosa et al., 2018; Ates et al., 2018; Salmon et al., 2018) . The integration of livestock and crop production can create synergies, such as better regulation of biogeochemical cycles, more diversified landscapes that favour habitats and trophic networks, and greater farm system flexibility to cope with potential socio-economic and climate change hazards (Lemaire et al., 2014). Such synergies could offer opportunities to raise productivity and resource use efficiency both for households and regions (Herrero et al., 2010; Tittonell et al., 2015). In this regard, increased livestock production may be a suitable intensification pathway for smallholder farmers in Nepal.

Increasing livestock production commonly entails a substantial reconfiguration of farming practices related to the use of resources such as land, and nutrients in animal feed and manure. Furthermore, competition of biomass for food and feed and increased labour demands are likely to occur under livestock intensification (Erenstein et al., 2015). This could particularly occur in the mid-hills regions of Nepal where farms have already high livestock densities and are highly dependent on fodder cut from the forested hills (Pilbeam et al., 2000; Alomia-Hinojosa et al., 2018). Such challenges of farm adjustments depend on socio-economic and biophysical specificities and can therefore differ greatly between regions and between farm types. Furthermore, external drivers such as milk market demand have also an effect on livestock production and associated trade-offs. These drivers operating at multiple levels together with systems management influence the agroecosystems dynamics (Valbuena et al., 2015).

Farmer perceptions are key to understand the limitations associated with farm changes and the resulting decision-making of diverse types of farmers, which will affect the extent to which livestock intensification becomes part of livelihood strategies. Understanding such perceptions of different types of farmers on intensification strategies can inform development projects (Alomia-Hinojosa et al., 2018).

Cognitive mapping approaches have been used to identify people's perceptions of complex social and socio-ecological systems (Özesmi and Özesmi, 2004), as well as to analyse their decision making (Vanwindekens et al., 2013). By using Fuzzy Cognitive Mapping (FCM), information on perceptions, behaviour and decision-making in complex situations can be obtained quickly and easily even with small samples (Özesmi and Özesmi, 2004). FCM has been applied in agricultural system analysis (Ditzler et al., 2018) with a multitude of objectives such as: to explore farmers' perceptions about pesticides (Popper et al., 1996); to understand environmental management measures (Ortolani et al., 2010); to describe practices in agroecosystems (Isaac et al., 2009); to understand impact of agricultural systems on the environment (Özesmi and Özesmi, 2004); to evaluate the sustainability of agroecosystems (Rajaram and Das, 2010; Fairweather and Hunt, 2011); to cluster farm types or groups as a function of certain indicator variables (Özesmi and Özesmi, 2004; Ortolani et al., 2010; Mathevet et al., 2011; Vanwindekens et al., 2013); and to explore vulnerabilities of livelihoods to identified hazards (Murungweni et al., 2011). In agriculture, FCM is considered a useful tool to represent farmer's vision on their practices and potentially improve the debate on the sustainability of farming systems (Fairweather and Hunt, 2011).

In this study we use FCM to explore the perception of individual farmers on the presence and importance of trade-offs associated with livestock intensification. We compare perceptions about livestock intensification of differently resource-endowed households in two contrasting localities in the mid-hills region of Nepal. In addition, we analyse the perceived farm system components/concepts by exploring their potential responses to changes in external drivers.

4.2. Materials and Methods

4.2.1. Description of the study sites

The study was conducted in two mid-hill regions of Nepal: the Palpa district is located in the Western region and the Dadeldhura district located Far-Western region. Palpa and Dadeldhura are situated at 1300 and 1500 meters above sea level, respectively. The soils in both districts are chromic cambiosols (Dijkshoorn and Huting, 2009). The soil texture in Palpa is predominantly loam, and loam to silty in Dadeldhura. The climate as described by the Koppen classification in the mid-hills is mostly subtropical to temperate (Department of Hydrology and Meteorology of Nepal, 2015). The two districts have a dry winter and a summer monsoon. The wet summers (June-September) have an average precipitation of 1052 mm in Palpa and 990 mm in Dadeldhura, while in the dry winters (December-March) the precipitation is slightly lower in Palpa (228 mm) than in Dadeldhura (349 mm) (Department of Hydrology and Meteorology of Nepal, 2015).

In both mid-hill districts there are two main cropping seasons. In Palpa the main crop grown in summer is maize (*Zea mays*) usually mixed with legumes such as rice bean -*Vigna umbellata*-, soybean- *Glycine max* and cowpea –*Vigna unguiculata*-; finger millet

(*Eleusine coracana*) and/or cucurbits. In winter prevails mustard (*Brassica nigra*) mixed with chickpea (*Cicer arietinum*) or lentil (*Lens culinaris*). In Dadeldhura, both maize and up-land rice are the main cereals in summer. Maize is mixed with legumes such as soybean, cucurbits and finger millet. In the winter, wheat (*Triticum aestivum*) is the main crop. From January to April-May most of the fields are fallow. In the case of a cropping in a third season (spring), vegetables are cultivated by farmers with access to irrigation. Most of the crops are used for home consumption, while vegetables in both sites and soybean in Dadeldhura are used as cash crops. Cereals, particularly maize are dual purpose used both for feed and food. On average, 90% of maize grain in Palpa and 40% in Dadeldhura is used for feed while the rest is used for household consumption. All the studied farms raised some sort of livestock such as milking cattle, buffaloes, goats, or chicken. In Palpa the average number of TLU is 7, while in Dadeldhura farms own on average 5 TLU. In Palpa milking cows predominate, while in Dadeldhura milk is obtained mainly from buffaloes. One to 3 goats are typical raised per farm.

4.2.2. Farmer diversity

There are significant socio-economic differences between Palpa and Dadeldhura and between farm types (classified on the basis of resource endowment) mainly in yearly income, source of income and number of tropical livestock units (TLU) per farm while the number of household members and the size of productive land are comparable (Table 1). The typologies with lower (LRE), to medium (MRE) and higher (HRE) resources endowment were created per site, and the variables used for their construction were: number of household members, yearly income, productive land holding, labour, number of TLU and months of food self-sufficiency (Alomia-Hinojosa et al., 2019). The LRE and MRE farmers in both sites had smaller productive land size (averages between 0.18 and

Table 1. *Characteristics of farms types with different resource endowment levels, i.e. low (LRE), medium (MRE) and high (HRE), in two districts (Palpa and Dadeldhura) in the mid-hills of Nepal.).*

Farm characteristic	**Palpa**			**Dadeldhura**		
	LRE	**MRE**	**HRE**	**LRE**	**MRE**	**HRE**
Number of household members	4	6	6	7	4	5
Annual income (USD)	1369	2117	6957	703	894	2557
Area of productive land (ha)	0.18	0.29	0.65	0.27	0.33	0.72
Labour force (persons)	2	3	4	3	2	3
Livestock per farm (TLU)	2.27	5.49	12.08	4.11	4.46	4.98
Food self-sufficiency (months)	5	8	11	4	5	10
Income derived from farm (%)	25	33	71	23	24	38

USD = United States Dollar; TLU = tropical livestock units; ha= hectares. The values represent the average of each farm type.

0.33 ha) than the HRE farmers that cultivate on average 0.65 to 0.72 ha. The yearly income varied among the types being the highest for the HRE in Palpa. Interestingly, the percentage of income from the farm activities was also the highest for the HRE and lowest for the LRE. In Palpa the largest proportion of income for HRE and MRE was derived from livestock products, while in Dadeldhura the first source of income were off-farm activities from remittances or jobs outside the farm. The quantity of livestock was on average 9 TLU in the HRE farms and 3 in the LRE. HRE farms in Palpa have the highest number of livestock mainly dairy cows up to 17 TLU. The labour force on average was larger on the HRE farms with up to 4 persons and 2 persons for the LRE farms.

4.2.3. Constructing farm system maps with farmer

We developed cognitive maps of individual farm systems with focus in livestock intensification with 62 farmers (32 farms in Palpa and 30 in Dadeldhura; ca. 10 per resource endowment level: low (LRE), medium (MRE) and high (HRE) in each district). The drawings of these maps were guided by the farm household head using flip chart paper and were used to discuss the perceived consequences of intensified livestock production at farm level. Each farm system map started with the current endowments of the farm in terms of land, labour and livestock resources. Then, the discussion on the consequences of intensification by adding one dairy cow or buffalo to the farm was started (see Figure 1 for an example). Farmers were asked the question: '*What does this mean for your farm?*'. The farmers described the plausible changes that their farming system would undergo in the order of importance as assigned by the farmer. Farmers were asked to develop maps that depicted the relevant components of the farm system as text boxes and the relations among components (positive or negative influences) as arrows. Relative strengths of the relations were not indicated.

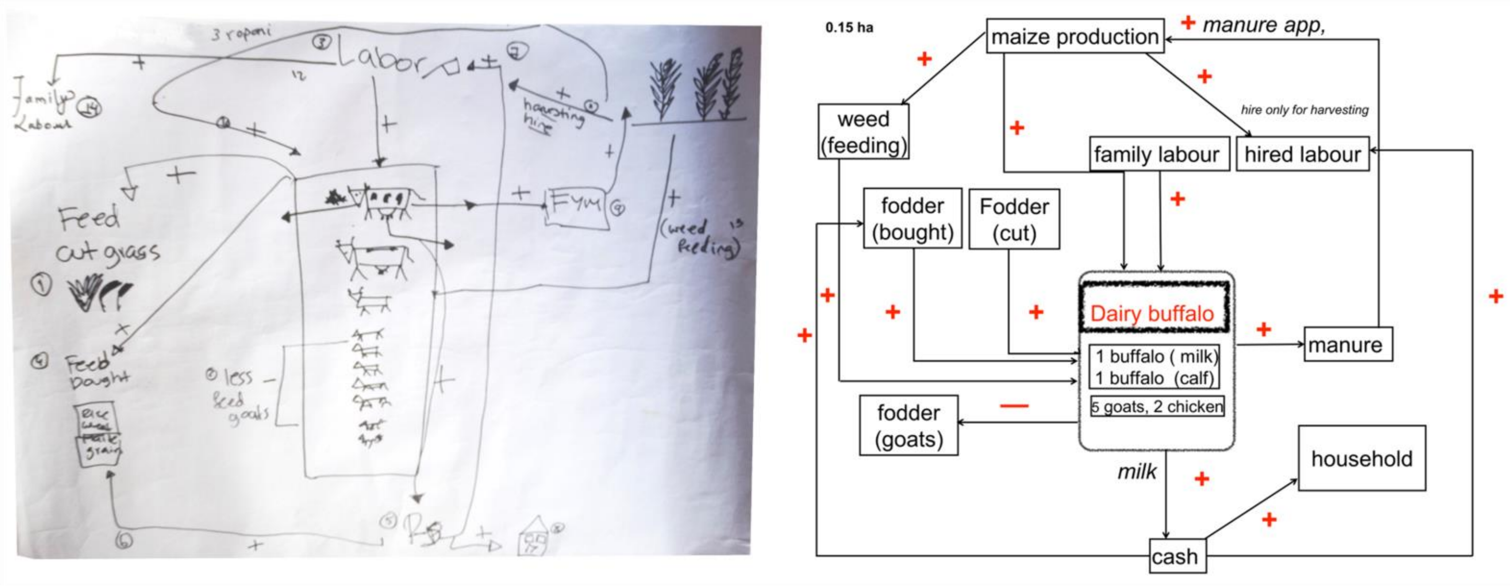


Figure 1. *Example of a farm system map constructed with farmers as drawn in the participatory session (left) and conceptual representation (right). The maps reflect farmer-perceived changes that would occur after adding one livestock unit to the farm.*

4.2.4. Fuzzy Cognitive Mapping

FCM is a semi-quantitative knowledge-driven modelling technique (Fairweather, 2010; Vanwindekens et al., 2014; Ditzler et al., 2018) composed of a number of concepts (represented by boxes) with positive or negative interrelations that are denoted by arrows with weights (Kok, 2009). The FCM is based on key concepts that are defined by one or more constructors and that represent important processes, agents and events within the system that is analysed. The interrelations are perceived causal relationships among these concepts (Özesmi and Özesmi, 2004). These relationships can be either positive or negative and have a weight that ranges commonly between -1 and 1 (Kok, 2009).

4.2.4.1. FCMs of individual farmer perceptions

The system maps of individual farms were translated into FCMs. The entities and processes on the farm relevant to crop and livestock production as listed by the farmers were used as FCM concepts. The original farmer-specified interrelations were used among the concepts, in which the weights were quantified by assigning a value of 1 for a positive effect and -1 for a negative effect. We counted the number of concepts (N_C) and relations (N_R) and calculated the density (D) by dividing N_R by the maximum number of connections possible relations among concepts (Özesmi and Özesmi, 2004). For individual concepts we calculated (Özesmi and Özesmi, 2004):

- Indegree (I_C), which is the sum of absolute weights (-1; +1) of interrelations entering a concept.
- Outdegree (O_C), calculated as the sum of absolute weights of interrelations exiting the concept.
- Centrality (X_C): is the sum of I_C and O_C. It shows how connected the concept is to other concepts and what the cumulative strength of these connections is.

Additionally, we defined the three different types of concepts: transmitter (O_C>0 and I_C=0), receiver (I_C>0 and O_C=0), and ordinary concepts (I_C>0 and O_C>0) (Harary et al., 1965; Bougon et al., 1977; Eden et al., 1992; Özesmi and Özesmi, 2004). Since transmitters have an influence on the system, but are not affected by other concepts in the system we denote these concepts as “external drivers”.

4.2.4.2. Aggregate cognitive maps

With the aim of analyzing similarities and patterns among districts and farm types we developed aggregated cognitive maps using an approach modified from the Cognitive Mapping Approach for Analyzing Actor’s Systems of Practices (CMASOP) (Vanwindekens et al., 2014), which involves building aggregate cognitive maps by combining FCMs that have been constructed by individuals. The FCMs of individual farmers were grouped per district and per resource endowment level. We combined concepts and interrelations mentioned by farmers, and calculated the average weights resulting in aggregate cognitive maps (ACMs) using the +1 and -1 weights. Thus, we assumed that the number of times that a concept was mentioned by farmers reflected the importance of relations. Therefore, the weights in the ACM were calculated as the percentage of maps in which the influence was mentioned. Weights were derived by scaling the percentage-weights to a range of 0.1 to 0.7 for positive influences and -0.7 to -0.1 for negative effects.

4.2.4.3. Matrix multiplications

We performed iterative matrix multiplications on the ACMs to determine the equilibrium state values of the concepts (Kok, 2009). A balanced FCM will lead to equilibrium values for the concept state values. The multiplication function used in this study was independent on the current state of the concept Equation (1) (Stach et al., 2005; Kok, 2009). In Equation (1), t is the iteration number, $A_i(t)$ and $A_i(t+1)$ are the state values of concept *i* at iterations *t* and *t+1*, and w_{ji} is the weight of the relation between concepts *j* and *i*.

$$A_i(t+1) = \left(\sum_{\substack{j \neq j \\ j=1}}^{N} w_{ji} \cdot A_j(t)\right) \quad (1)$$

4.2.4.4. Sensitivity analysis

The results of the matrix calculations on the ACMs were used for a sensitivity analysis of changes caused by three potential drivers that were proposed as external processes that could affect farm activities and configuration as represented in the ACMs (cf. Kok, 2009):

- Livestock intensification (demand): caused by changed diet preferences for more livestock products and better market access for farmers, which would have a positive impact on livestock numbers per farm.
- Losses of manure: due to improper collection, storage and application. This would reduce the availability of manure on the farm.
- Out-migration: part of the labour population could leave farms to urban areas or labour opportunities abroad which would negatively affect the available labour.

Drivers are concepts that influence other concepts but are not influenced by other concepts. The drivers represent external influences in the system. The driver of out-migration corresponded to a common trend occurring in both mid-hills provoking labour shortage in farms in both districts. While the nutrient losses was added due to evidence of nutrient dissipations/losses of N in the studied farms (Alomia-Hinojosa et al 2019).

The target variables for which we determined impact of the external drivers in the sensitivity analysis were “livestock”, “family labour”, “crop production” (maize, cereal or vegetables) and “farm income (cash)”. We used the Winding Stairs algorithm (Jansen et al., 1994; Chan et al., 2000). It allows to quantify the strength of the influence of each driver on target variables (cf. regression coefficient) and the total sensitivity index (TSI)

(Chan et al., 2000), which measures the contribution of an input factor (driver) to the total model output variation (Chan et al., 2000) and is equivalent to the r^2 of a regression.

4.3. Results

4.3.1. Farm systems maps

During the farm system mapping of the impact of adding one dairy cow or buffalo to the farm, the farmers in both Palpa and Dadeldhura mentioned the additional requirements for feed and labour as the most important consequences, rather than the additional benefits of increased income, manure availability and crop production (Table 2). The additional fodder needed to feed the added cow or buffalo would be collected from road-sides and other open or common resources such as forest, or would be purchased. Only ca. 30% of the farmers mentioned the potential positive impact of livestock intensification on income as either a first or second consequence. Extra manure production and higher cereal production were never mentioned as the first consequence, and by less than 25% of the farmers as a second effect (Table 2). The extra manure obtained from the additional TLU would be applied to all the crops, especially cereals: maize in Palpa and maize, rice and wheat in Dadeldhura. As a consequence, extra feed for livestock would be obtained from

Table 2. *The most important consequences of increasing the livestock number with one TLU on farms in mixed systems in the mid-hills of Nepal as perceived by the farmers.*

Perceived consequence	**Palpa**		**Dadeldhura**	
	Mentioned first (%)	**Mentioned second (%)**	**Mentioned first (%)**	**Mentioned second (%)**
Have to collect or buy extra fodder	47	31	45	34
Increased labour requirement	38	31	24	24
Extra income for the household	13	16	24	3
Extra farm yard manure production	-	16	-	24
Increase in cereal production	-	-	-	13
Others	3	6	6	3

Importance is expressed as the percentage of farmers mentioning consequences as first and second in farm systems mapping.

crop residues. But as a trade-off more labour will be needed for crop maintenance, especially for weeding. Few farmers mentioned that if cereal production would increase they would purchase or collect less fodder. During the farm system map construction the majority of farmers expressed an interest to increase livestock on their farms, but in Palpa farmers preferred dairy cows and buffaloes, while in Dadeldhura dairy buffaloes and goats were preferred. Irrespective of the endowment level, farmers were not inclined to make additional investments in (maize) fodder production and associated agronomic activities such as line planting, increasing the plant density, more meticulous weeding, investing in seeds, etc. All resource endowment types implied an increase in labour as the first perceived consequence of adding an extra dairy animal. In Palpa LRE farmers mentioned the increase of hired/family labour; while MRE and LRE mentioned the need to collect fodder (family labour) and the need to purchase extra fodder as a the first consequence. Similarly in Dadeldhura all resource types mentioned the collection or purchase of extra fodder as the first consequence of adding an extra dairy animal on their farms (Table S1).

4.3.2. Fuzzy Cognitive Mapping (FCM)

4.3.2.1. FCMs of individual farmer perceptions

The FCMs derived from the farm system maps contained a larger number of concepts (N_C) and relations (N_R) in Palpa than in Dadeldhura (Table 2). The LRE farmers from both sites mentioned a smaller number of concepts and relations, but D was comparable between resource endowment types and districts (Table 2). The ratio between receiver and transmitter concepts was considerably higher in the farms in Dadeldhura than in Palpa (Table 3).

Table 3. *Metrics of FCMs derived from farm system maps created by farmers with different endowment levels, i.e. low (LRE), medium (MRE) and high (HRE), in two districts (Palpa and Dadeldhura) in the mid-hills of Nepal.*

Metric	Palpa			Dadeldhura		
	LRE	MRE	HRE	LRE	MRE	HRE
Density (D)	0.140	0.131	0.135	0.144	0.137	0.140
Number of concepts (N_C)	9.0	9.5	9.8	7.8	8.6	8.6
Number of relations (N_R)	11.1	11.7	12.5	8.6	9.6	9.8
Receiver/transmitter ratio	0.8	0.8	1.1	2.1	1.4	1.3

The concept with the highest centrality in both sites was “Livestock”, which represented the dairy cows or buffalos on the farm. This concept was the original starting point for the farm systems mapping. In Palpa the second variable with highest centrality was “Cash/income” while lowest centrality was “Household consumption”. In Dadeldhura, the second highest centrality was “Crop production” in all the types and the concepts with lowest centrality were “Family labour” and “Hired labour”.

4.3.2.2. Aggregate cognitive maps (ACMs)

We combined individual FCMs to construct the ACMs for each resource endowment type per district (Figure 2). The weights of the relations among concepts were derived from the percentage of farmers mentioning the relation (see Supplementary Material, Figure S1). In the ACMs the role of purchased feeds and on-farm produced residues were included as important relations to support livestock intensification. The relations between manure production from livestock and its positive effects on productivity of maize (Palpa) and cereals and vegetables (Dadeldhura) were prominent in the ACMs of LRE as well as MRE and HRE farmers (Figure 2). Only a limited contribution of livestock to household nutrition was considered.

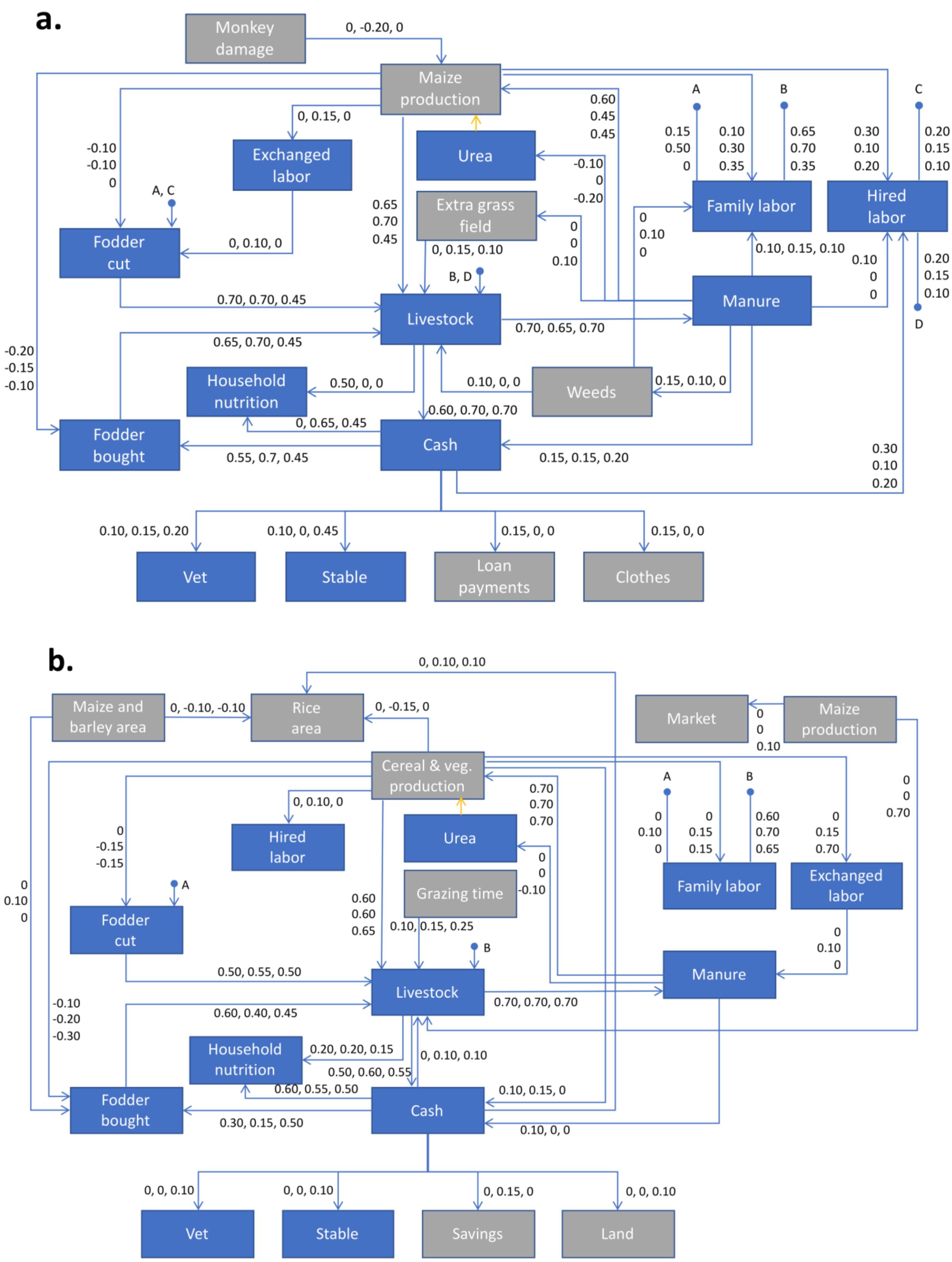


Figure 2. *Aggregate cognitive maps for the perception of livestock intensification on farms of three resource endowment levels in the districts of Palpa (a) and Dadeldhura (b) in Nepal. The three numbers per arrow represent the weights (derived from the percentage of farmers mentioning the relation, see Figure S1) per RE level in the order: LRE, MRE and HRE. The colours of the boxes indicate whether a concept was mentioned by all farmers (blue) or by only a part of the farmers (grey) per district.*

4.3.3. Dynamic Analysis of FCM

The quantification of the dynamics of the state values of the four target concepts for the different types of resource endowment farms in the different districts (6 farms), stabilized after ca. 20 iterations (Figure 3). We analyzed the sensitivity of this value after 100 iterations to the variations.

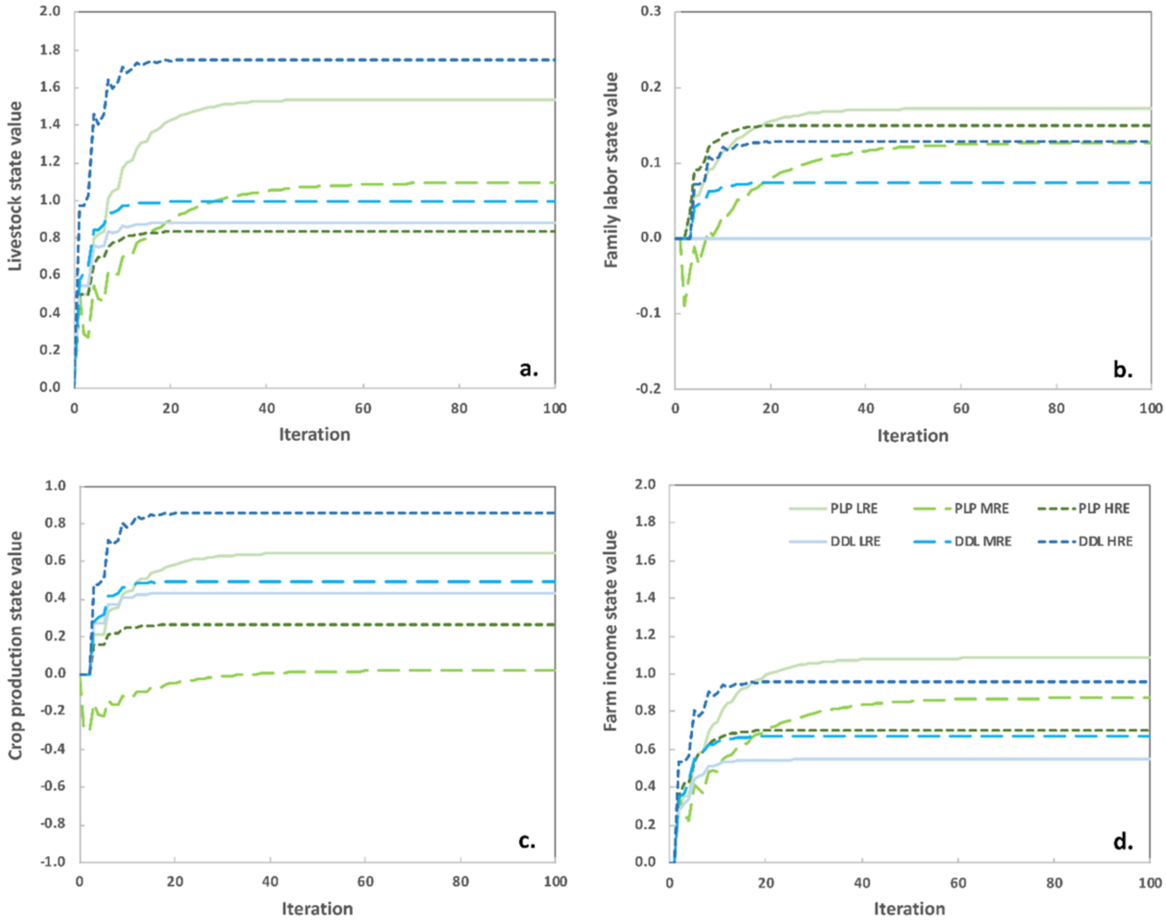


Figure 3. *Dynamics of the state values of the four target concepts for the six farm categories. The dynamics stabilize after 100 iterations.*

4.3.4. Sensitivity Analysis

The sensitivity analysis shows that according to the perception of the farmers there would be strong effects of intensification (demand) on livestock production and farm income (Figure 4a), while out-migration would lead to reduced livestock production and farm income (Figure 4b). Livestock and nutrient losses were positively related (Figure 4c). These trends were strongest for the MRE farm in Palpa. Similarly, the TSI indicated that

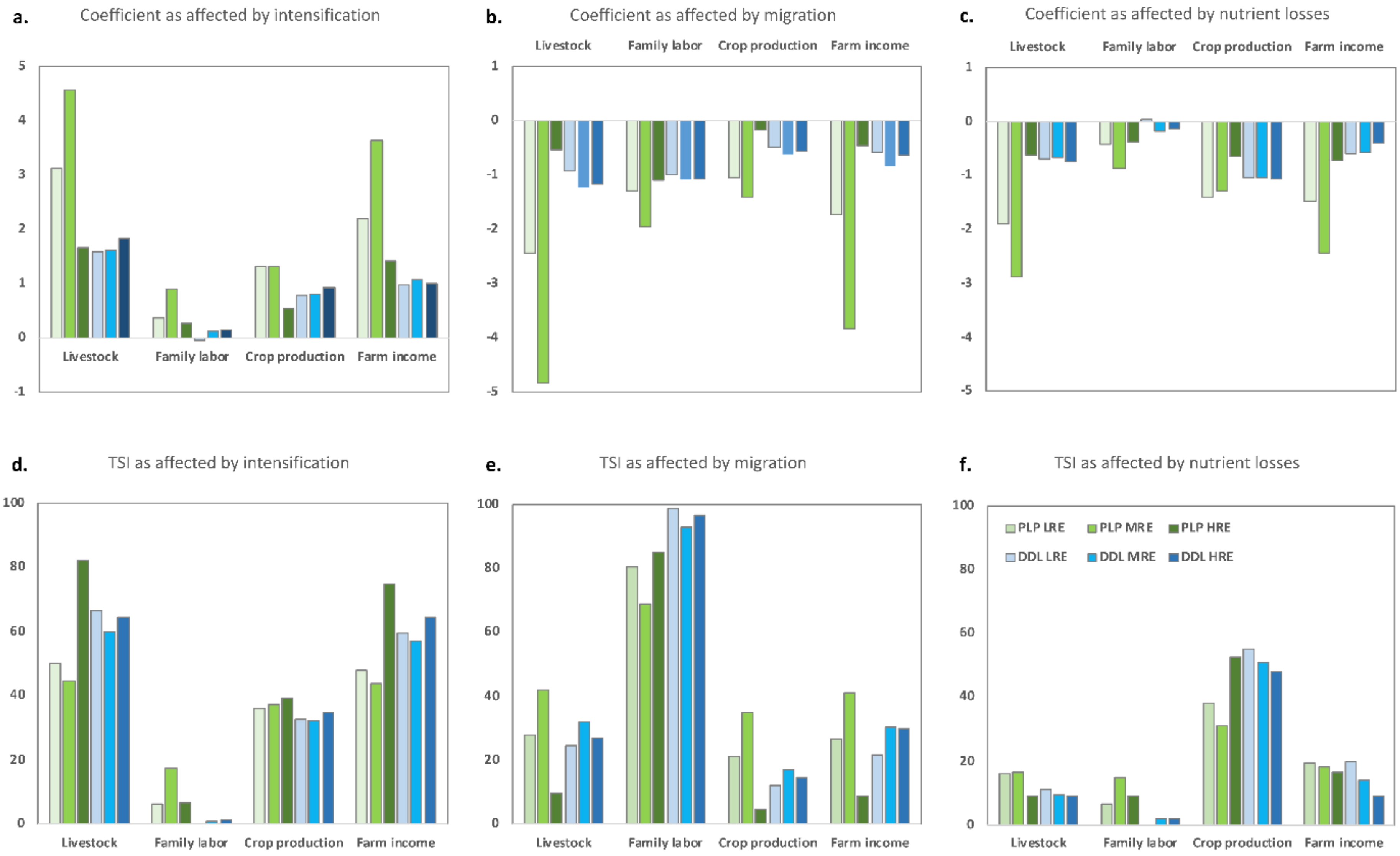


Figure 4. *Result of the sensitivity analysis of drivers on ACMs: impact of variation in drivers' intensification, migration, nutrient losses on variables: livestock, family labour, crop production and farm income expressed as coefficient (a-c) and TSI (d-f). The coefficient indicates the strength of the influence of the driver on the variable, while the TSI*

the family labor is strongly affected by the driver of out-migration in all farm types, while crop production is affected by nutrient losses. Livestock intensification (demand) would lead to responses of livestock, crop production and farm income (Figures 4d to 4f).

4.4. Discussion

Through our participatory research, we were able to rapidly identify trade-offs and perceptions towards intensification together with farmers. It allowed us to understand that differently endowed farmers in terms of resources and capital faced similar trade-offs and therefore were not inclined to make additional investments in on-farm fodder production such as maize, and the associated crop management activities. Farmers perceived on-farm fodder production to be insufficient to bridge the widening fodder gap resulting from keeping additional livestock. In other words, intensification of dairy livestock production would not trigger the intensification of crop production. Most of the farmers did not immediately think in economic terms at the system level, hence they did not fully relate how productivity enhancement of fodder (maize) may lead to more returns at the farm level through increased milk production. The prospects of intensification are restricted to farmers that have the capacity of investment and access to market or to collection centres, such as in some cases in Palpa. The increased labour demand was a factor consistently mentioned by farmers as the main trade-off associated with livestock intensification, rather than the additional benefits of extra income and manure that are normally associated with livestock.

The analysis of the FCM confirmed the differences in complexity of farm systems between districts. Although the density (D) of the networks was comparable in both districts; the number of both concepts and connections depicted in the maps were higher in Palpa than in Dadeldhura indicating that farmers in Palpa might perceive more opportunities available to change things (Özesmi and Özesmi, 2004) and its consequences of livestock intensification. The ratio between receiver and transmitter concepts was considerably higher in the farms in Dadeldhura than the ones in Palpa. This ratio shows (Özesmi and Özesmi, 2004) that farm maps in Dadeldhura are more complex than those in Palpa which means they consider many implications that are result of the system. This could be explained because in Dadeldhura farmers perceived less controlling forcing function affecting the system (Özesmi and Özesmi, 2004). In addition, in Dadeldhura there is more farm diversification due to a larger number of cropping seasons and livestock types, in contrast to the farms in Palpa that were more specialized. It was expected that the highest concept centrality was for livestock as it was the initial concept when drawing the cognitive maps. However, the second highest centrality differed among districts. *Income* was mentioned in Palpa and *crop production* in Dadeldhura, which gives insight on the different priorities in each district. Most of the farms in Dadeldhura are subsistence-oriented while farms in Palpa generated income through trading.

FCM is often used to analyze systems representation of perceptions of multiple stakeholders or stakeholder groups for comparative purposes (Ditzler et al., 2018). The novelty of our research is that maps were drawn directly on the farm with the farmers, the main actors. This approach was useful to model diverse drivers and farmer motivations (Vanwindekens et al., 2014) and to compare farmers from different districts and livelihood objectives. Furthermore, through graphic theory (matrix algebra tools) it was possible to analyze the structure of the system which represents its overall behaviour in contrast to the solely sum of units (Özesmi and Özesmi, 2004). The limitation of the approach could be given by the interviewer effect when guiding the mapping process which can potentially produce errors in the indicators quantification. Nevertheless, we aimed at minimizing errors with the relative high number of interviewees and by conducting additional discussions with farmers inside and outside the population of our study to validate our results. Our study reinforces the evidence that farmers can create maps and represent the character of their farm systems (Fairweather and Hunt, 2011), and how cognitive mapping can contribute to understand farmers systems reasoning and local knowledge which could benefit the management and performance of the farm (Isaac et al., 2009; Fairweather and Hunt, 2011).

Through this research the knowledge on trade-offs around livestock intensification in land constrained hill ecosystems was better comprehended. Including farmers diversity is essential in a trade-off analysis (Tittonell et al., 2015). Although we showed farm structural differences between districts, there was a generalized perceptions of trade-offs around livestock intensification regardless the resource endowment. It explained the low rates of adoption of measures and technologies for livestock intensification in the mid-hills regions of Nepal (Pilbeam, Alomia-Hinojosa, 2018).

Extra livestock production might require higher investments to purchase extra feed which limits livestock intensification for the majority of farmers, particularly the low and medium resource endowed. In addition, the fodder available on or off farm does not cover the already high livestock density in the mid-hills agroecosystems, this goes in line with the perceptions of famers indicating that increasing on-farm fodder production would be possible but not enough to feed an extra animal. Finally, increasing crop/fodder production in the mid-hills is limited by the small size of farms, which explains why farmers did not see clear connections or synergies between on-farm fodder production and livestock. Although demand for animal products would trigger livestock production and farmers consider intensification a promising strategy for income generation, the constraints of intensification makes a concurrent (sustainable) intensification of these mixed farms' cropping systems unlikely. New strategies optimizing crop-livestock integration are needed support these systems.

4.5. Conclusions

This research shows the capacity of using FCM to rapidly identify trade-offs in intensification together with farmers. FCM was proved as a good tool to analyze qualitative data to reveal perceptions of farmers. Moreover, it allowed the exploration of the influence of potential drivers to the perceived farm's concepts.

Farmers in the different regions and different resource endowment, perceived increasing livestock density as a promising pathway for intensification and income generation. Livestock intensification is also enhanced by livestock demand. Yet, all farm types (including different farm complexities) perceived that livestock intensification can deepen the labour constraint and the dependency of external imports hence the realisation of livestock intensification pathway and the adoption of associated practices and technologies could be strongly affected.

Furthermore, livestock intensification does not necessarily have the potential to trigger intensification of crop production in the studied sites as most of the farmers were not inclined to make additional investments in (maize) fodder production as they perceived these as insufficient to bridge the widening feed gap resulting from additional livestock. This can be attributed to perception of higher labour demand to increase on-farm production, which is enhanced by the high out-migration in the region, but also the lack of farmer's perception of how fodder (maize) productivity enhancement may lead to more income through increased milk production. Therefore, additional quantitative farm-level assessments of trade-offs and synergies are needed for smallholder mixed systems in the mid-hills of Nepal.

4.6. Supplementary Material

Table S1. *The most important consequences of increasing the livestock number with one TLU on farms in mixed systems in the mid-hills of Nepal as perceived by different resource endowment farmers' types.*

Perceived consequences	Palpa		Dadeldhura	
	Mentioned first (%)	Mentioned second (%)	Mentioned first (%)	Mentioned second (%)
LRE				
Have to collect or buy extra fodder	43	43	50	50
Increased labour requirement	50	7	13	38
Extra cash for the household	7	7	25	-
Extra farmyard manure production	-	36	-	12
Increase in cereal production	-	-	12	-
Others	-	7	-	-
MRE	46	23	50	25
Have to collect or buy extra fodder				
Increased labour requirement	31	15	25	33
Extra cash for the household	15	54	25	-
Extra farmyard manure production	-	-	-	17
Increase in cereal production	-	-	-	17
Others	8	8	-	8
HRE	60	20	33	33
Have to collect or buy extra fodder				
Increased labour requirement	20	40	33	-
Extra cash for the household	20	40	22	-
Extra farmyard manure production	-	-	-	33
Increase in cereal production	-	-	-	22
Others	-	-	12	12

Where: LRE: low resource endowment; MRE: medium resource endowment; HRE: high resource endowment. Importance is expressed as the percentage of farmers mentioning consequences as first and second in farm systems mapping.

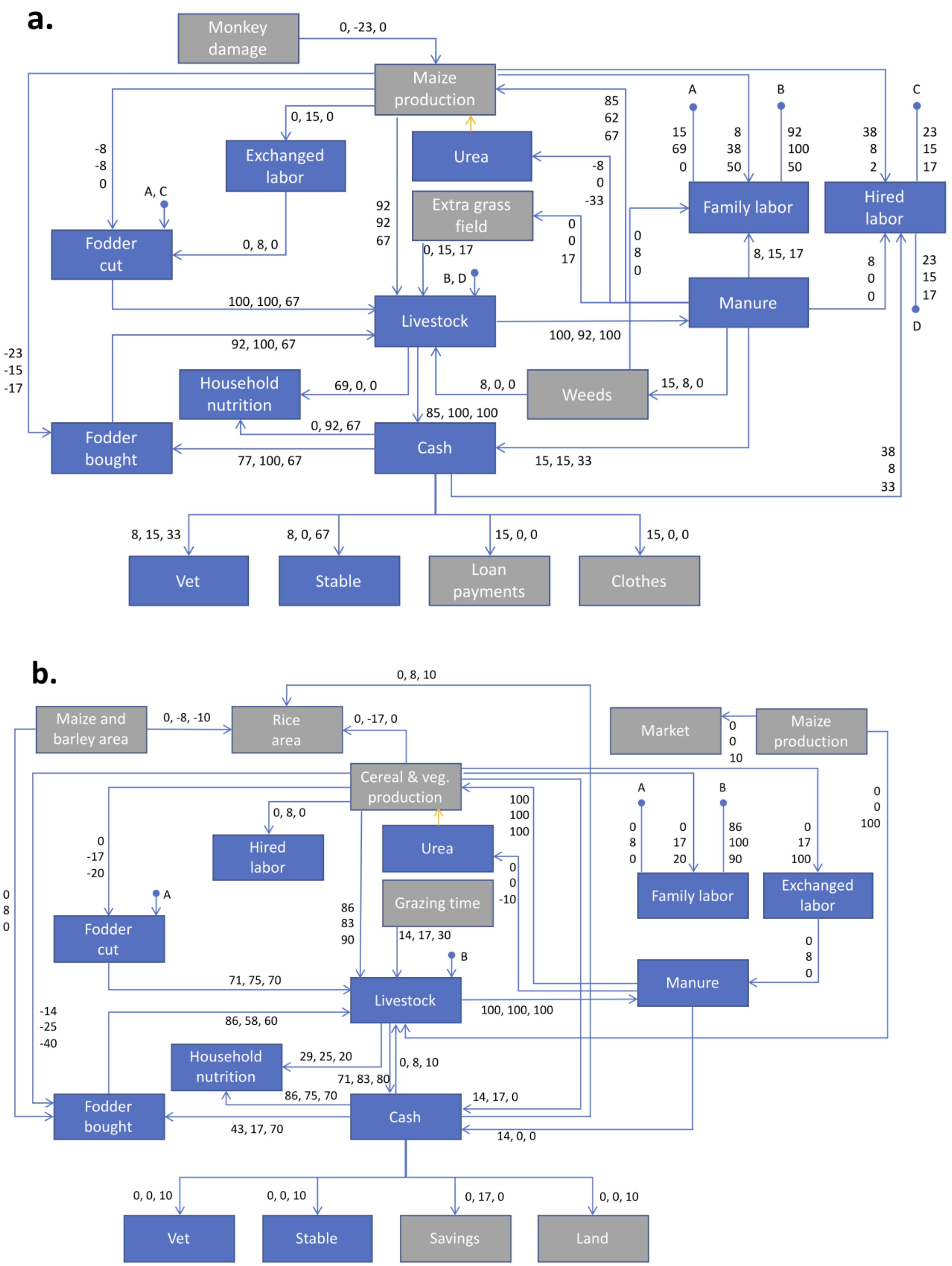
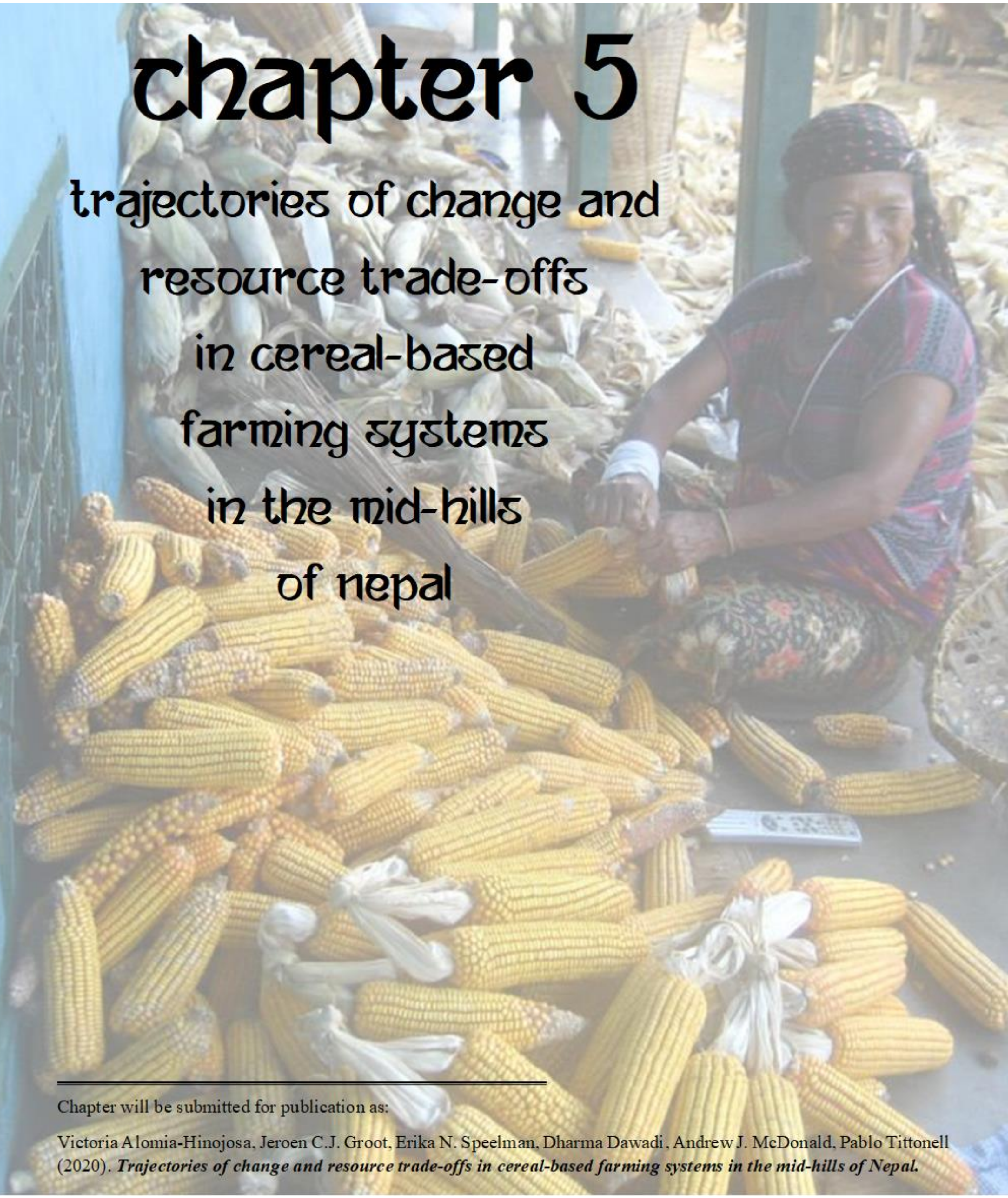


Figure S1. *Aggregate cognitive maps for the perception of livestock intensification on farms of three resource endowment levels in the districts of Palpa (a) and Dadeldhura (b) in Nepal. The three numbers per arrow represent the percentage of farmers mentioning the relation per RE level in the order: LRE, MRE and HRE. The colours of the boxes indicate whether a concept was mentioned by all farmers (blue) or by only a part of the farmers (grey) per district*



chapter 5

trajectories of change and resource trade-offs in cereal-based farming systems in the mid-hills of nepal

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Abstract

The past dynamics and drivers of agroecosystems determine their current configuration and future pathways. This knowledge is particularly relevant for smallholder crop-livestock farm systems to which drivers could influence their capacity to produce sustainably. In this study we identified the changes that have occurred in the farming systems in the mid-hills of Nepal since 1985 and the drivers that have shaped agricultural intensification resulting in the current farm configurations. Furthermore, we analysed two contrasting current farms by quantifying synergies and trade-offs associated with intensification to explore future possible farm configurations. We used semi-structured questionnaires, discussion groups and interviews with key informant farmers to identify the changes and their drivers; and a whole-farm model tool to explore the synergies and trade-offs between farm profitability and services: labour use, N balance and organic matter. The main identified drivers associated with agricultural intensification in the mid-hills regions were based on the access to agricultural inputs such as improved varieties of seeds and livestock. This has been a consequence of improved connectivity and access to markets, which have been stimulated by agricultural policies and developmental projects at national and local level. The trade-off analysis of two contrasting: 1) dairy cattle specialized vs. 2) average mixed farm systems showed that there is more space for improving farm configurations by minimizing trade-offs between livestock intensification (profit) and: N losses and leisure time in the specialized farm. This is associated to the farm larger landholding size. In a scenario of higher crop productivity total costs would increase due to a lower crop gross margin and associated increase of costs of improved technologies. This study contributed 1) to understand smallholder farms' strategies to change under external influences by studying their past trajectories and 2) to provide knowledge of the current status and potential future directions of two contrasting farm systems by analyzing the trade-offs associated with agricultural intensification.

5.1. Introduction

The concept of path dependence proposes that historical events may have a sustainable impact on a system's future evolution (Arthur, 1989). In agriculture, past dynamics and external drivers of agroecosystems determine their current configuration, as well as its resource base (natural infrastructural and economic), performance and potential future pathways. Furthermore, knowing the trajectories of farm systems allows better understanding of how farmers cope and adapt to external drivers (Speelman et al., 2014). This is particularly relevant for smallholder farming systems with livelihoods dependent on agriculture. Several political, social, and environmental drivers influence the capacity of these farming systems to produce sustainably, a prerequisite for food self-sufficiency and decent incomes. However, households and communities differ substantially in their ability to benefit from sustainable agricultural intensification practices (Harris, 2019). Knowledge of past trajectories of smallholder households is essential to contextualise the re-design of more sustainable agroecosystems (Valbuena et al., 2014) and adjust agricultural production practices for the future.

Sustainable intensification of agriculture entails an increase in agricultural production while minimizing or even reversing damage to the environment (Tittonell, 2014; Silva, 2017; Tittonell, 2018; Harris, 2019). Integrated crop-livestock systems may contribute to an efficient design of a sustainable farming systems (Gliessman, 2006, Russelle et al., 2007, Hendrickson et al., 2008a, Erenstein et al., 2015), when they are based on the complementarities between crops, livestock and land (Bonaudo et al., 2014). Integrated crop-livestock systems rely more on efficient nutrient recycling rather than on the nutrient imports from surrounding areas (Nalubwama et al., 2018). The integration of livestock and crop production can create synergies such as better regulations of biogeochemical cycles, more diversified landscapes, and greater farm system flexibility to cope with potential socio-economic and climate change hazards (Lemaire et al., 2014) that offer opportunities to raise productivity and resource use efficiency (Herrero et al., 2010.; Tittonell et al., 2015). Crop-livestock integration is thus a promising pathway for the sustainable intensification of smallholder, cereal based farms in the mid-hills of Nepal which are small, depend on external feeds, and exhibit a mixed configuration (Alomia-Hinojosa et al., 2019).

Most of the farming systems in Nepal are composed of mixed crop-livestock farms. However, the farms in the mid-hills regions, in contrast to farming systems in the lowlands (*Terai*), have poor access to agricultural inputs and arable land. These systems rely on crop and livestock production to attain food security or to generate income. Although some smallholder farms in the mid-hills can achieve intensification through livestock specialization, feeding resources are limited and on-farm feed production plays an important role in their intensification (Alomia-Hinojosa et al., 2018). Trade-offs were identified in the region in terms of resource use, in particular: 1) the use of crop products such maize grain as livestock feed vs. household consumption, 2) the use of residues of maize and other crops either as feed for animals or for soil mulching, 3) allocation of labour since livestock intensification demands more labour for herd management and to collect fodder off-farm (Tiwari et al., 2010). Trade-offs associated with crop-livestock integration include also the risk of nutrient (specially nitrogen) imbalances, as poorly integrated livestock may represent an open gate to nutrient losses (Tittonell et al., 2015). Holistic sustainable intensification should employ trade-off analysis methods (Salmon et al., 2018).

Knowledge on farming systems development trajectories of farms, their resulting current configuration, and the nature and magnitude of associated trade-offs is essential to inform alternative designs and management practices to propend to their sustainable intensification. In this study we identify the drivers that have shaped the configuration of current crop-livestock farming systems in the mid-hills of Nepal over the last decades, and quantify synergies and trade-offs associated with crop-livestock intensification to explore possible future trajectories.

5.2. Materials and Methods

5.2.1. Description of the study sites

The study was conducted in two mid-hill regions of Nepal: the Palpa district is located in the Western region and the Dadeldhura district located Far-Western region. Palpa and Dadeldhura (Figure 1) are situated at 1300 and 1500 meters above sea level, respectively.

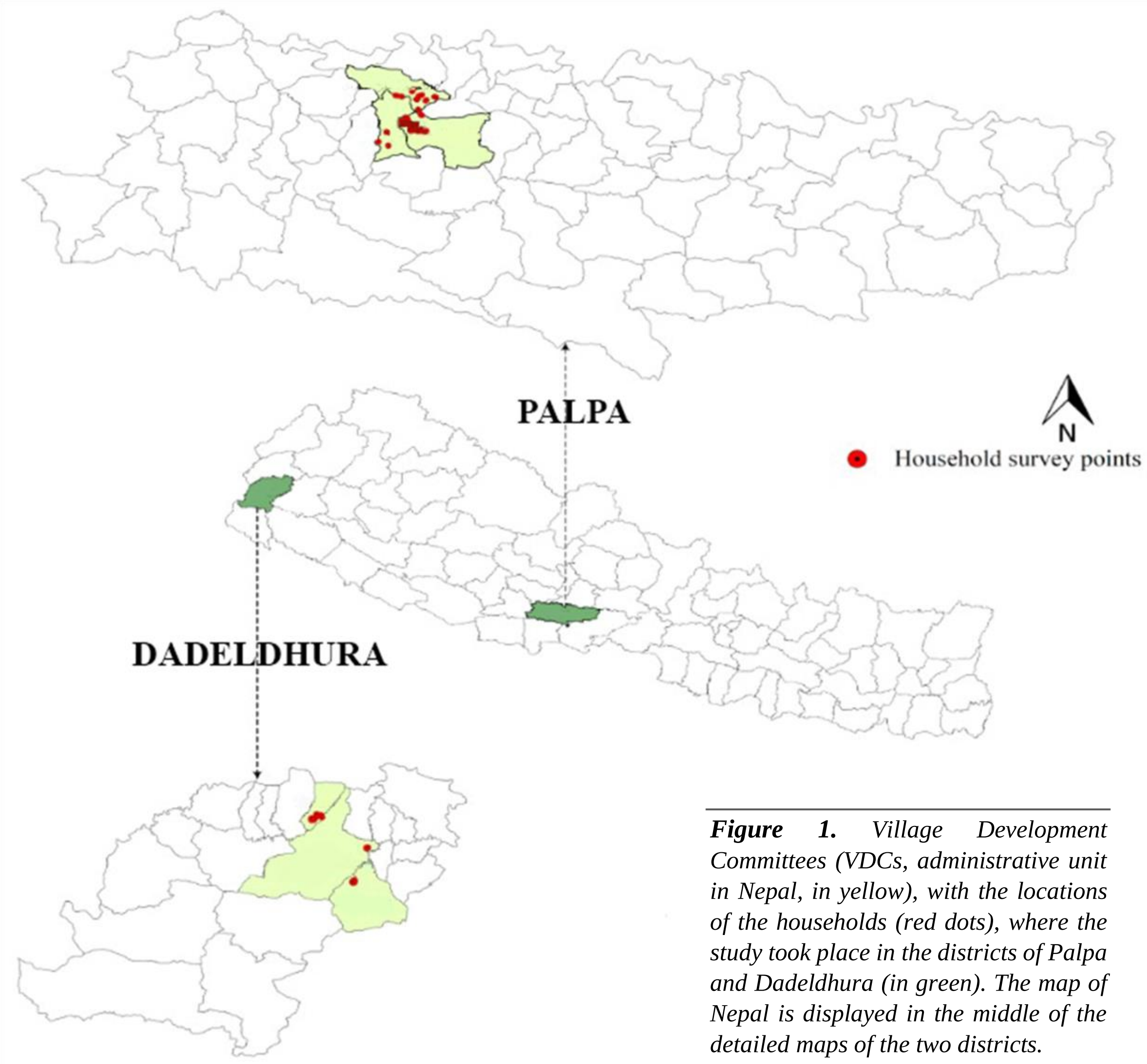


Figure 1. *Village Development Committees (VDCs, administrative unit in Nepal, in yellow), with the locations of the households (red dots), where the study took place in the districts of Palpa and Dadeldhura (in green). The map of Nepal is displayed in the middle of the detailed maps of the two districts.*

Overall, the soils in both mid-hill districts are chromic cambiosols (Dijkshoorn and Huting, 2009). The soil texture in Palpa is predominantly loam, and loam to silty in

Dadeldhura. The climate as described by the Koppen classification in the mid-hills is mostly subtropical to temperate (Department of Hydrology and Meteorology of Nepal, 2015). The two regions have a dry winter and a summer monsoon. The wet summers (June-September) have an average precipitation of 1052 mm in Palpa and 990 mm in Dadeldhura, while in the dry winters (December-March) the precipitation is slightly lower in Palpa (228 mm) than in Dadeldhura (349 mm) (Department of Hydrology and Meteorology of Nepal, 2015). In both mid-hill districts, 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 left fallow. In the case of cropping in a third season (spring), vegetables are the main crop limited to farmers that have access to irrigation. Most of the crops are used for home consumption, while vegetables in both sites and soybean in Dadeldhura are used as cash crops. Cereals, particularly maize are dual purpose used both for feed and food. On average, 90% of the maize in Palpa is used for feed, while in Dadeldhura 40% is used for feed while the rest is used for household consumption. Farms in the mid-hill agroecosystem raise some sort of livestock such as dairy cattle, buffaloes, goats, or chicken. In Palpa the average presence on farms is 6 TLU, while on average 5 TLU are kept in Dadeldhura. In Palpa milking cattle predominates, while in Dadeldhura the consumed milk is mainly from buffaloes.

5.2.2. Past trajectories and drivers of change

The trajectories were assessed by collecting both primary and secondary data. Primary data were collected by using a semi-structured survey with household members and focus group discussion with key farmers. In addition, we performed key informant interviews. Three VDC (Village Development Committees), which are the lowest administrative unit for local administration, were selected in each district (Figure 1). One farm household was randomly selected in each VDC, while the additional households were selected using the snowball sampling method in order to capture different ethnicities in the sites. The snowball sampling method consists of finding one research unit (farmer) and ask the farmer to refer another farmer to the researcher, who in turn provides the name of the third and so on (Vogt et al., 1999). This process continued until 50 households in Palpa and 60 in Dadeldhura were interviewed. The non-responding household were avoided. The snowball sampling method was used due to the diverse and scattered nature of household locations in the hill communities.

We used secondary data to validate the results from the household's interviews. The data was obtained from the Agricultural Development Office (DADO), and The District Livestock Service Organization (DLSO) from each VDC.

5.2.3. Semi-structured surveys and Group Discussions

We used semi-structured surveys with open and closed ended questions to collect primary data. The questions included households' biophysical characteristics such as landholdings size, number of livestock, crops planted in each season and socioeconomic characteristics such as members' migration, labour demand, and months of food self-sufficiency among others. The questions included the present and different time periods in the past from 1985 to 2015, including drivers that lead towards changes. The surveys took place from September to November 2015. In addition, we organized two group discussions mainly with elderly people in each of the VDCs. The participants were influential farmers or community representatives with a good understanding of past and present land holding and territories. VDCs government agricultural development agents and service providers were also participants in the discussion. The discussions were focused on gathering historical changes or crucial periods used as entry points to determine drivers of change in the farm systems.

We employed participatory mapping, sketches and timelines to improve the understanding of farmers past and present perceptions.

5.2.4. Exploration of solution spaces and scenarios for future trajectories

We used the FarmDESIGN model to quantify synergies and trade-offs between specific farm systems objectives. FarmDESIGN is a static model that evaluates the economic, productive and environmental farm performance and can be used as an exploration tool to search improved farm performances. The model uses an evolutionary algorithm to generate alternative farm configurations adjusting farm components, inputs and evaluating consequences through pareto-based multi-objective optimization (Groot et al., 2012). The model requires detailed data about socio-economic aspects such as costs and labour, environment such as climate and erosion and agronomical practices about crops rotations, yield, inputs application, and livestock management (Cortez-Arriola, 2016). The output of the model provides a wide collection of alternative farm configurations. It shows the potential changes that determine the improved configuration and presents correlations between the selected decision variables (farm components allowed to adjust in the farm) and the desired objectives.

We explored solution spaces and evaluated farm re-configurations with the purpose of identifying the trade-offs and synergies that might be present between crop-livestock intensification and ecosystems services with four objectives: maximization of farm profit and of soil organic matter, and minimization of nitrogen balances, and labour demands. The decision variables, which are inputs adjusted in the exploration procedure to allow changes in the optimization, included areas of cultivated crops, destination of crop products, and number of livestock.

We selected two farms in 2015 with different livelihood objectives but yet representative of the diversity of farm configurations and production objectives at both sites. The farm in Dadeldhura produced mainly for household consumption. This farm was close to an average farm in the sample: 4 TLU and 0.8 ha, with a livestock density of 5 TLU/ha. The farm in Palpa produced milk for income generation and had a large number of cattle: 17 TLU and 1.22 ha; livestock density 14 TLU/ha (Figure 2). For both farms we explored opportunities for improvement of farm performance on basis of their current configuration and production activities.

In addition, the explorations were also performed for a scenario in which maize and soybean productivities were higher than the current farm configuration. The increase of productivity of both maize and soybean in an intercrop arrangement in the two farms was demonstrated in a previous on-farm trials done by Alomia-Hinojosa et al. (2018). 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}. The biggest fields dedicated to maize production during the summer in each farm were assumed to produce high yields of maize and soybean. Furthermore, it was assumed that maize and soybean stover was fed to the livestock. The purpose of testing this scenario was to evaluate differences in outcomes for a current configuration and a configuration in which farms are assumed to achieve the highest potential yield for the main crops. In sum, the outcome of the model showed two sets of solution spaces for each farm, which corresponded to 1) the current configuration and to 2) the high productivity scenario.

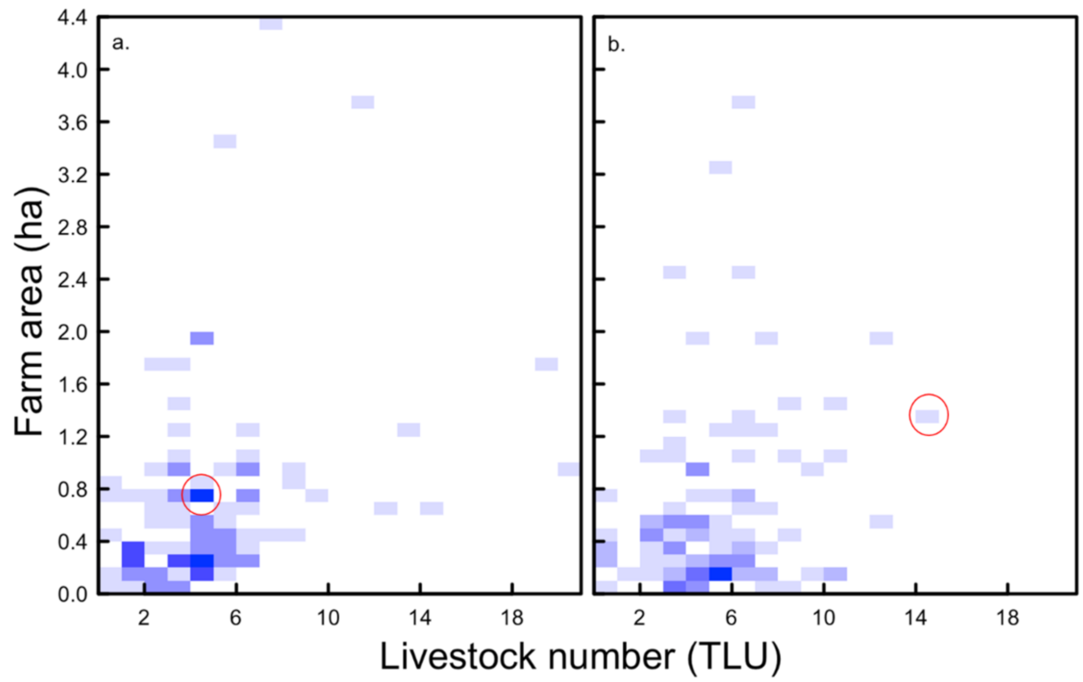


Figure 2. *Livestock density for farms in a) Dadeldhura and b) Palpa. The red circle represents the farm selected for the synergies and trade-offs analysis.*

5.3. Results

5.3.1. Socio-economic and agricultural changes since 1985

5.3.1.1. Household and food self-sufficiency

The number of family members per household has decreased by 6.4% and 20.3% in Dadeldhura and Palpa, respectively, from 1985 to 2015, while the number of migrated members per household increased in both districts in the same period (Table 1). The number of months that households experienced food self-sufficient has increased by 20.3% and 15.6% from 1985 to 2015 in Palpa and Dadeldhura, respectively (Table 1).

Table 1. *Changes of socio-economic and demographic indicators from 1985 to 2015.*

Indicators	Dadeldhura		Palpa	
	1985	2015	1985	2015
No. of HH members	7.9	6.3	7.3	6.9
No. of migrated members per HH	0.0	0.7	0.2	1.1
Food self-sufficiency (months)	5.5	6.4	6.7	8.1

5.3.1.2. Accessibility, information and markets

The access to agricultural extension services increased rapidly from 2000 and reached a level of around 35% of all households in both districts in 2015. In contrast to the access of less than 5% of the household in 1985.

The distance to markets and main roads decreased in both districts from 1985 to 2015, from around 4.5 km to 3 km in Dadeldhura and from 3 km to 2.5 km in Palpa (Figure 3a). There were almost no changes in road access in Palpa and Dadeldhura until 2000. After this period the distance decreased from 0.5 km to 0.25 km in 2015 in Palpa; and from 0.42 km to 0.20 km from 1985 to 2015 in Dadeldhura (Figure 3b).

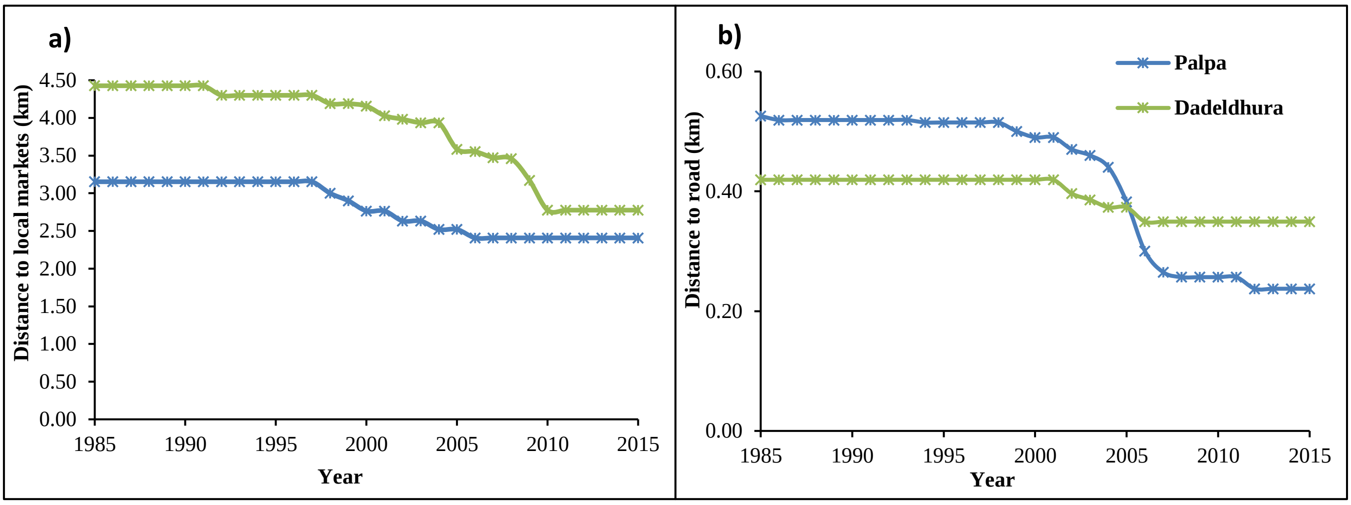


Figure 3. *Changes in distance to a) local markets (km) and b) main roads (km) in Palpa and Dadeldhura from 1985 to 2015.*

5.3.1.3. Crop diversity and crop share

The average land holding per farm in 2015 was 0.61 ha in Dadeldhura and 0.7 ha in Palpa, in contrast to the average size of 1.8 ha in 1985. The diversity of crops per household has increased since 1985 in both districts, from around 6 crops grown annually in 1985 which increased to 10 and 12 in 2015 in Palpa and Dadeldhura, respectively. There were significant changes in the share of different crops since 1985 during spring, summer and winter. During summer, maize-based cropping systems, especially sole maize, maize with rice-bean and mixed crops dominated in Palpa. The share of sole maize cultivation declined considerably since 1985 and instead maize was increasingly mixed with other crops. Furthermore, the percentage of millet decreased from 10% in 1985 to almost 2% in 2015 in Palpa. In Dadedhura, the share of maize mixed with soybean and vegetables increased linearly. However, the rest of cereal crops decreased during the summer season. Maize and soybean as a mixed crop covered more than 30% of the area in Dadeldhura in 2015, while vegetable production increased and reached around 20% of the area in 2015 (Figure 4a).

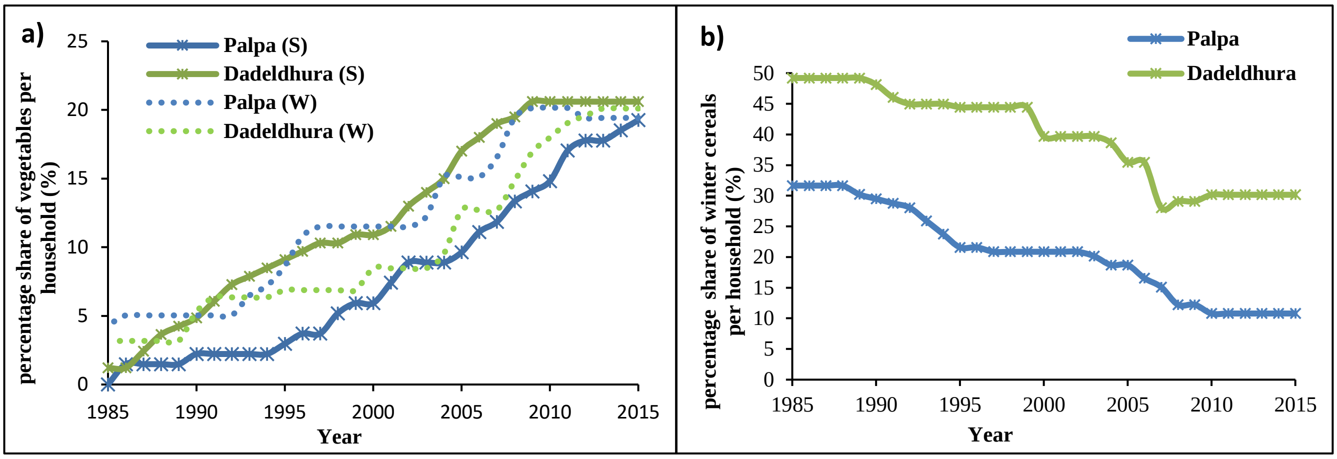


Figure 4. *Percentage of area cultivated per household with a) vegetables (tomato, chlli, cauliflower, cabbage, cucumber) in winter (W) and summer (S), and b) winter cereals, in Dadeldhura and Palpa from 1985 to 2015.*

The share of winter cereals was around 50% in Dadeldhura in 1985 which decreased to 30% in 2015 (Figure 4b). However, winter vegetables production increased since 2005 in both districts. Mustard mixed with lentil, also important winter crops, remained almost constant with only less than 5% changes since 1985. The percentage of sole mustard remained constant in Dadeldhura and slightly increased in Palpa since 1985.

In spring (March to May) more than 50% of land remained fallow in 1985. The higher fallow pattern was observed in Palpa. In 2015, the percentage of fallow land was more than 75% in both districts. Vegetable production increased also in spring since 2000 and reached to around 25% in Palpa and 15% in Dadeldhura in 2015. The change of yearly cropping patterns for both districts from 1985 to 2015 are shown in the supplementary material (Table S1).

The productivity of rice wheat and maize was quite low until 2000 in both districts. However, after the year 2010 there are increasing trends of productivity of cereals in all districts.

5.3.1.4. Adoption of new cultivars and inorganic fertilizers

There was almost no adoption of improved cultivars as well as inorganic fertilizers until 1995 in both districts, and it increased afterwards. Adoption of improved crop cultivars was higher in Palpa after 2012 (50%), whereas in Dadeldhura reached just around 25%. Until 2005, only ca. 10% of the households used urea as an inorganic fertilizer in Palpa which later increased by more than 35%. In Dadeldhura, the percentage of the households using inorganic fertilizer increased slowly from 2003 to less than 5% of households and reached around 20% in 2015.

5.3.1.5. Livestock

The average number of livestock units per farm in 1985 was 8 and 6 TLU in Palpa and Dadeldhura respectively while in 2015 the numbers dropped to 5 TLU in both districts.

The average number of buffalos, goats and poultry per household decreased from 1985 to 2015 in both districts. During the period of 1985 to 1995 there were negative growth rates of both ruminants and poultry. Dairy cattle in Dadeldhura showed an increasing trend after year 2000 and after 2010 there was also an increase in Palpa (Figure 5).

5.3.2. Drivers of change in agricultural intensification

The main drivers of change associated with the intensification of agricultural production in smallholder systems in the mid-hills of Nepal, were grouped as operating at international (I), national (N) and local (L) levels (Figure 6). These drivers were mentioned repeatedly by the interviewed farmers and key informants and were having a large influence on farm configuration during the period studied (1985-2015) in both districts. The main historical international driver mentioned was the India-Nepal border

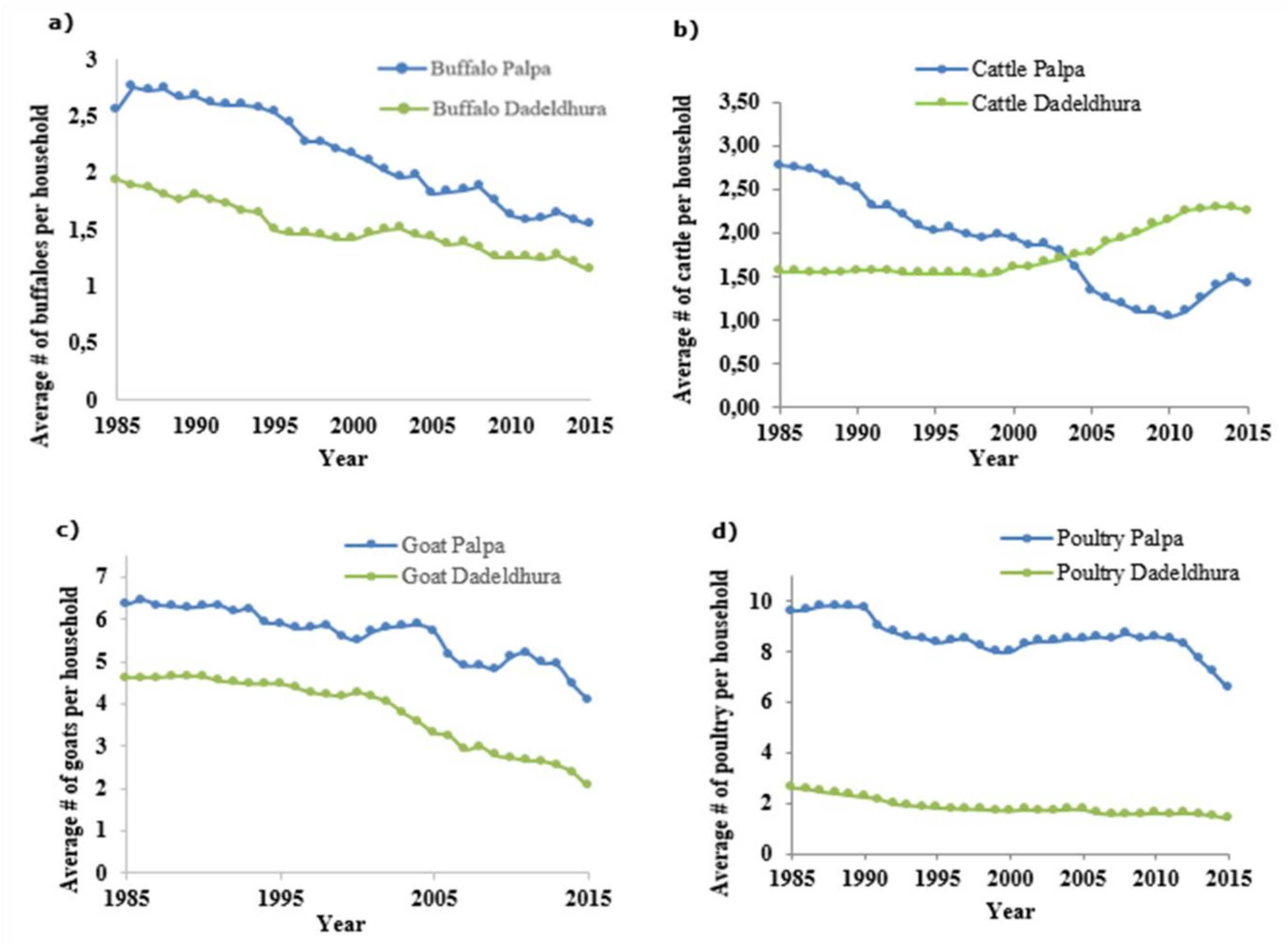


Figure 5. *Change of average number of (a) Buffalos; (b) Cattle; (c) Goats; and (d) Poultry per household in Palpa, and Dadeldhura from 1985 to 2015.*

blockade which had strong negative effects on inputs importations and products commercialization for Nepal particularly in 1989. Among the national drivers, the civil maoist war had also a negative effect on agricultural development, while mostly agricultural policies and developmental projects stimulated agricultural intensification and land-use change (Figure 6). Several local drivers like local developmental projects, local technology transfer and demonstration programs both from private and governmental initiatives influenced both districts. Whereas in Palpa drivers at the three different levels were influencing farming systems throughout the study period, in Dadeldhura most local drivers (L) identified were indicated to start operating only during the last decade.

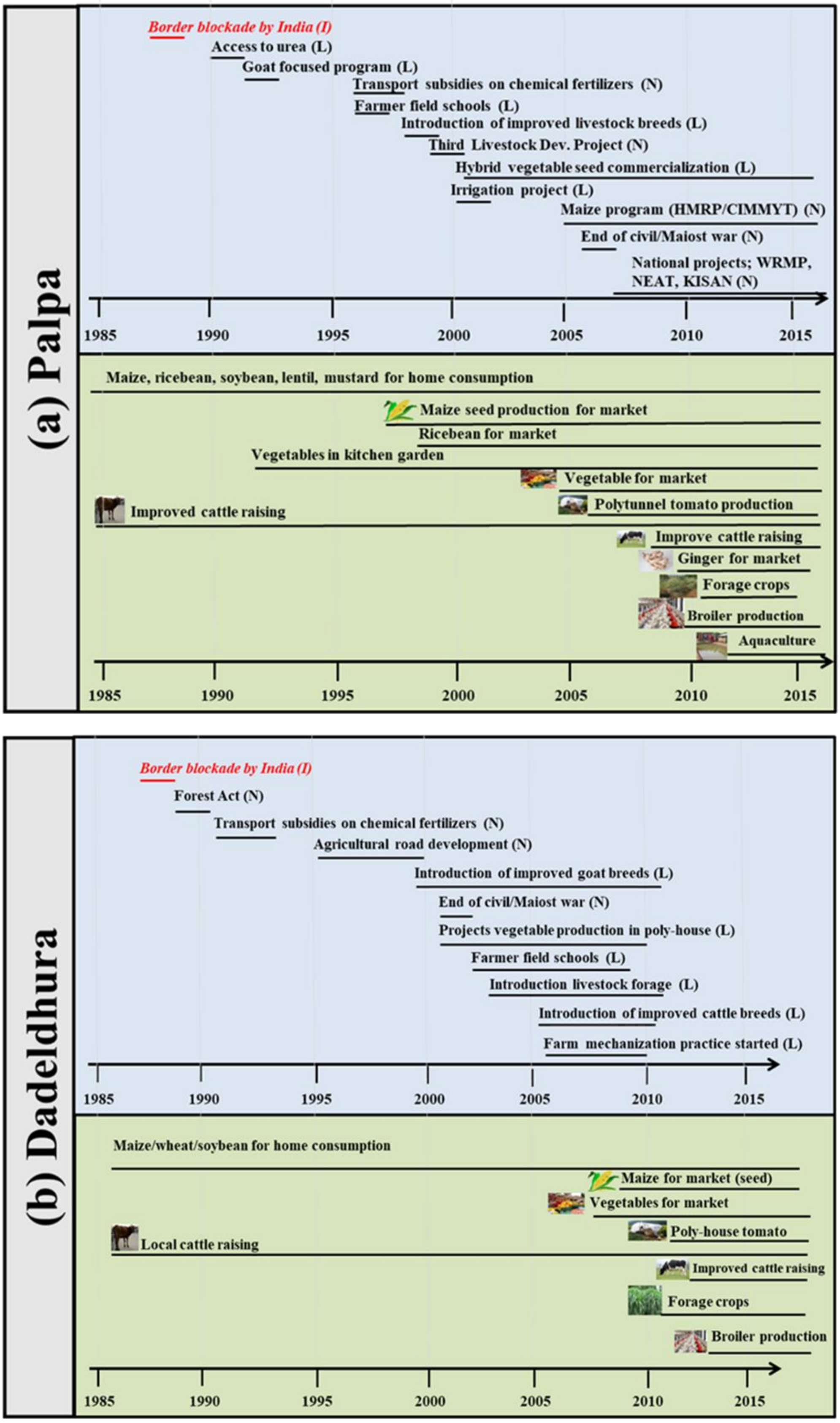


Figure 6. *Drivers of intensification of agriculture (blue compartment) and qualitative land-use change (green compartment) in a) Palpa and b) Dadeldhura from 1985 to 2015. Drivers at local (L), national (N) and international (I) levels are indicated. The* ***bold red cursive letters*** *represent a negative effect.*

5.3.3. Trade-offs and synergies associated with current and alternative farm configurations

In Dadeldhura the farm size was 0.81 ha. There were 4 TLU (Figure 2) that included 2 bullocks, 1 cow, 1 (cow) calf; and 3 goats. Furthermore, the biggest field was covered with the rotation: rice-wheat (0.33 ha), followed by rice/soybean-wheat/mustard (0.27 ha). Maize-wheat/mustard (0.17 ha), and two small areas with soybean-lentil (0.05 ha) and vegetables for home consumption (0.006 ha). While the farm in Palpa had an extension of 1.22 ha and 17 TLU, from which 10 were dairy cows, 4 (cows) calves, 2 bullocks, 2 goat and 6 chicken. The field with mixed fodder species was the largest (0.87 ha), followed by the rotation maize-ricebean (0.15 ha) and maize-mustard (0.10 ha). The area of the Teosinte, used for fodder, was 0.05 ha. Finally, both the fields for kitchen garden and tomato (cultivated in greenhouse) had the same size (0.02 ha) each

In general, the simulations showed more spread/scattered solution spaces for the specialized farm in Palpa than for the average farm in Dadeldhura (Figure 7).

In Palpa, trade-offs were shown between the operating profit or gross farm income and the other objectives: organic matter, N losses and leisure time. The trend was similar for Dadeldhura, except the synergy observed between operating profit and organic matter (Figure 7).

In Palpa, the livestock intensive farm showed that the number of dairy cows was positively correlated with operating profit, organic matter and, N losses; but negatively correlated with leisure time. As expected, the imported fodder such as: good green grass, *Litsea monoplotela*, rice bran and *A. lakoocha* followed the same pattern. Good green grass applied to the soil as mulch had also a positive correlation with organic matter. Among the crop rotations the maize-ricebean field showed a negative correlation with operating profit and N losses and a positive relationship with leisure time. While, for tomato (in greenhouse) the correlations were the opposite to the maize-ricebean field. Tomato showed a positive correlation with operating profit, and N losses and negative with leisure time (Table 2). On the other hand, in the *high productivity* scenario the main outcome was the reduction of fodder imports. In this scenario, the correlations were similar to the original farm configuration except the number of cows showed a lower correlation with organic matter. Furthermore, good green grass (imported fodder) did not show correlation with any objective. The same was true for all the crop-rotations as none of them showed significant correlation with the objectives. The imported fodder: *Melinis minutiflora* and good green grass applied to soil as mulch showed positive correlation with OM and negative correlation with operating profit.

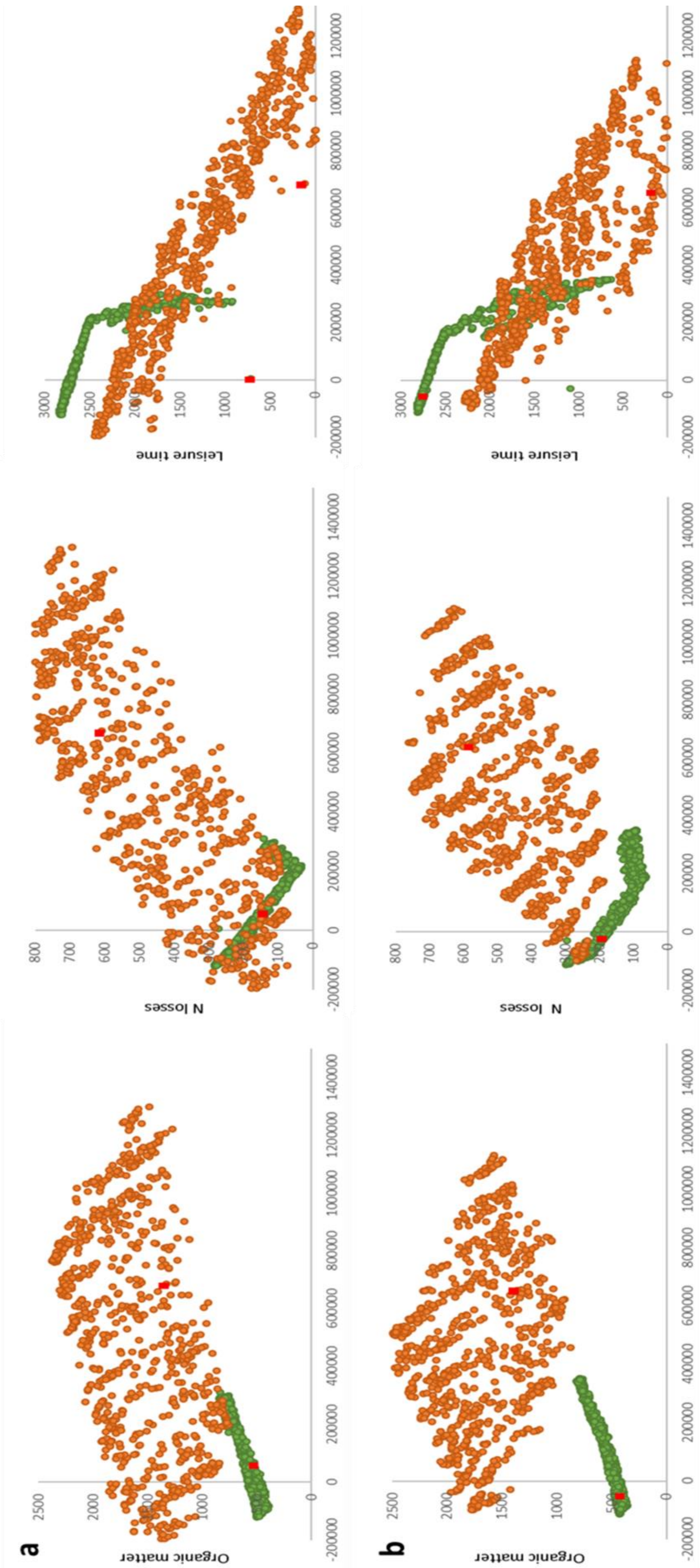


Figure 7. *Solution space for farms in Palpa (orange) and Dadeldhura (green) between the objectives profit (x) and OM, N losses and leisure time (y). a) Original farms b) farms using alternative technologies for maize-soybean intercropping (high productivity scenario).*

In Dadeldhura, the farm that produced for household self-consumption, showed that the number of goats had negative correlation with operating profit and positive correlation with N losses and leisure time. The imported fodder grass had a negative correlation with operating profit. The same was true for imported fodder from trees. Fodder trees showed a positive correlation with N losses and leisure time. Mixed kitchen-garden were negative correlated with operating profit and OM, while they were positive correlated with N

Table 2. Correlations between objectives and decision variables for the solution spaces in the farm of Palpa.

PALPA	Baseline				Improved technology			
Livestock	OP	OM	N loss	Leisure	OP	OM	N loss	Leisure
Bullocks	0.05	0.23	0.18	-0.08	0.02	-0.02	0.01	0.00
Cows	0.95	0.61	0.93	-0.97	0.92	0.20	0.79	-0.89
Goats	0.28	-0.03	0.13	-0.39	0.15	0.17	0.21	-0.57
Fodder								
A. Lakoocha	0.39	0.71	0.68	-0.49	0.22	0.59	0.68	-0.37
Annapurna grass	0.06	0.00	0.03	-0.08	0.09	-0.12	-0.09	0.00
Good Green grass	0.90	0.66	0.93	-0.93	-0.06	0.14	0.10	0.02
Imported maize grain	0.15	0.25	0.23	-0.19	0.39	0.27	0.49	-0.46
Litsea monoplotela	0.56	0.77	0.81	-0.65	0.57	0.62	0.93	-0.72
Rice bran	0.75	0.81	0.94	-0.86	0.67	0.50	0.88	-0.82
Fields								
Grassland	0.11	0.26	0.22	-0.18	-0.17	0.42	0.09	-0.12
Maize + Ricebean	-0.59	-0.26	-0.49	0.55	0.12	-0.38	-0.08	0.14
Tomato (greenhouse)	0.72	0.37	0.63	-0.68	N.A.	N.A.	N.A.	N.A.
Teosinte	0.09	0.08	0.11	-0.09	0.02	-0.04	-0.02	-0.03
Kitchen garden	-0.01	0.07	0.04	-0.01	0.06	-0.20	-0.12	0.02
Maize-Mustard-Radish	-0.15	-0.25	-0.24	0.18	0.26	-0.23	-0.07	-0.17
Maize-Soybean	N.A.	N.A.	N.A.	N.A.	0.13	-0.20	-0.10	-0.04
Soil								
Melinis minutiflora	-0.16	0.10	0.35	-0.03	-0.63	0.66	0.13	0.29
Good Green grass	-0.40	0.52	0.11	0.23	-0.70	0.64	0.08	0.41
Maize stover	0.04	0.11	0.09	-0.08	0.16	0.05	0.16	-0.14
Ricebean stalk	-0.07	-0.02	-0.06	0.03	-0.02	0.08	0.08	0.02
Lentil straw	0.01	-0.04	-0.02	0.04	-0.14	0.18	0.07	0.09
Maize stover	-0.07	0.04	-0.01	0.03	-0.06	0.00	-0.03	0.11
Mustard stover	-0.01	0.16	0.10	-0.02	0.06	0.09	0.11	0.00
Teosinte plant	-0.06	0.01	-0.03	0.07	-0.13	0.06	-0.04	0.05

***The highlighted cells represent a high correlation. N.A. Not applicable, as this crop rotation was not present**

losses and leisure time. The same pattern is followed by the maize-soybean-wheat rotation. But the rotation for soybean-blackgram showed the opposite. This rotation had positive correlations with operating profit and OM and was negative correlated with N losses and leisure time (Table 3). On the other hand, in the high productivity scenario the fodder grass showed higher negative correlations with operating profit and OM. Furthermore, it also showed higher positive correlations with N losses and leisure time. The rotation maize-soybean-wheat and mustard showed a negative correlation with operating profit and OM, and a positive correlation with N losses and leisure time (Table 3).

Table 3. Correlations between objectives and decision variables for the solution spaces in the farm of Dadeldhura.

DADELDHURA	Baseline				Improved technology			
Livestock	OP	OM	N loss	leisure	OP	OM	N loss	leisure
Bullocks	0.21	0.07	-0.13	-0.14	0.18	0.22	-0.23	-0.22
Cows	-0.01	0.02	-0.01	-0.03	-0.06	-0.07	0.10	0.10
Goats	-0.90	-0.25	0.66	0.69	-0.86	-0.41	0.79	0.84
Fodder								
Fodder grass	-0.52	0.07	0.25	0.17	0.01	0.16	-0.03	0.00
Fodder trees	-0.50	-0.43	0.57	0.73	-0.83	-0.51	0.81	0.88
Imported rice straw	0.01	-0.10	0.03	0.03	0.22	0.29	-0.20	-0.17
Fields								
Mixed kitchen garden	-0.67	-0.96	0.97	0.93	-0.83	-0.93	0.97	0.93
Rice (khet)	-0.10	0.33	-0.12	0.01	-0.44	-0.34	0.46	0.48
Soy-blackgram	0.93	0.66	-0.88	-0.92	0.94	0.81	-0.88	-0.85
Maize-soy-wheat	-0.81	-0.32	0.59	0.68	-0.60	-0.32	0.52	0.56
Rice-soy-wheat-mustard	-0.65	-0.16	0.34	0.36	-0.12	-0.11	0.12	0.12
Maize-soy-wheat-mustard	N.A.	N.A.	N.A.	N.A.	-0.84	-0.59	0.63	0.59
Soil								
Maize stover	-0.14	-0.03	0.10	0.15	0.00	-0.05	0.00	-0.04
Mustard stover	-0.03	0.05	-0.03	-0.04	-0.11	-0.17	0.13	0.12
Soybean stover	-0.02	0.10	-0.05	-0.04	0.03	0.06	0.00	0.03
Wheat straw	0.00	-0.18	0.14	0.13	-0.03	0.00	0.04	0.06
Mustard stover	-0.18	-0.20	0.23	0.26	-0.02	0.07	-0.02	-0.01
Rice straw	0.05	-0.05	0.01	0.02	-0.03	-0.02	-0.01	-0.01
Soybean stover	-0.11	0.06	0.02	0.05	-0.07	-0.04	0.05	0.06
Wheat straw	-0.27	-0.15	0.22	0.25	-0.11	-0.23	0.14	0.09

***The highlighted cells represent a high correlation. N.A. Not applicable, crop rotation was not present**

In the scenario where technologies were applied to increase the yield of maize and soybean, the main differences were a reduced profit and OM balance in both districts due to a lower crop gross margin. And leisure time increased in Dadeldhura due to the reduction of labour in fodder collection (Figure 7).

5.4. Discussion

We identified that the main drivers associated with agricultural intensification in the mid-hill regions in the past 30 years were based on the access to agricultural inputs (improved and variety of seeds, improved breeds, fertilizers). This was a consequence of a better connectivity and access to markets. The better connectivity was realised by improvements in infrastructure, while agricultural policies and developmental projects (at national and local level) stimulated agricultural intensification and land use change by supplying agricultural inputs. The connectivity and access to markets improved first in Palpa and only later in Dadeldhura, which caused a higher presence of specialized farms in in the sites studied in Palpa. The analysis of trade-offs and synergies associated with intensification (productivity increase) of two current contrasting farms: one dairy specialized farm in Palpa and one average mixed crop-livestock farm in Dadeldhura showed that there was more space for improved farm configurations by minimizing trade-offs in the specialized farm. This was associated to the larger landholding size of the specialized farm. We showed that trade-offs between farm profit and OM, N losses and leisure time were present in the specialized farm in Palpa. In contrast, in the farm in Dadeldhura there were trade-offs between profitability with N losses and leisure time while profit and OM showed a synergy. On the other hand, in the high productivity scenario, the operating profit of the farm would decrease in both districts due to a lower crop gross margin and associated increase of costs of improved technologies (to increase yields). However, the leisure time would increase particularly in Dadeldhura, helping to solve the on-going issue with labour constraints.

5.4.1. Drivers of agricultural intensification and current farm systems in the mid hills

The drivers and past trajectories explain the current farm situation and contribute to a better understanding of the possible future directions of farm systems (Valbuena et al., 2015b; Salmon et al., 2018). Farm systems in the mid-hills are still conditioned by insufficient connectivity when compared to the farms in the low-lands (*Terai*) (Dahal et al., 2007; Tiwari et al., 2010; Alomia-Hinojosa et al., 2018). However, this study has showed that connectivity has been improving in mid-hills farm systems, hence access to improved inputs might shape the future of these agroecosystems, provided that farmers have the economic potential to invest in agricultural intensification. Farms in these agroecosystems are dynamic which implies that farmers are constantly adapting and looking for income generating products such as vegetables e.g. eggplant, tomato, chilies. The same is true for animal products such as milk from improved breeds of cows or buffaloes as seen in similar studies in Western Kenya (Valbuena et al., 2015a). Cereals are still the staple food in the mid-hills, particularly maize in both districts. However, in the period between 1985 and 2015 the area of maize monocrop has decreased while maize mixed with other species i.e. legumes have increased. This could be explained as in 2015, farmers had on average smaller fields compared to 1985. Therefore, there was not enough space for monocrops. This transition could have been a result of the continuous land fragmentation in the mid-hills (Lowder et al., 2016). Moreover, this change might have been influenced by the competition with newly introduced crops which are mostly planted in the summer (monsoon) season. Finally, the lack of labour force available in the both mid-hill regions (Tiwari et al., 2010) might have contributed to the increase of mixed cultivation, since in farmers' perceptions, mixed cultivation requires less labour than monocrops. Intercropping maize with legumes has seen to be highly productive only if plant density and improved inputs such as seed and fertilizers are used (Alomia-Hinojosa et al., 2019). Furthermore, the decreasing labour force availability is a recurrent problem encountered in the two districts. Temporary (seasonal off-farm jobs) and permanent migration has reduced on-farm labor availability, while offering an alternative to diversify income sources (Dahal et al., 2007; Blake, 2012; Nepal Central Bureau of Statistics, 2012). This can be seen by the number of household members that have decreased progressively since 1985 (Table 1) and by the high percentage (75%) of increased fallow land in both districts in the last 30 years. By the simulations done in this study we showed that increasing maize and soybean yields would reduce labour constraints particularly in the average mixed farm in Dadeldhura, which was not the case for the specialized farm.

Finally, we showed that farmers' perceptions of drivers for agricultural intensification had a strong influence of different developmental projects in the zones. Developmental projects might (temporarily) change the dynamics of crop and livestock production in the mid-hills as farmers would focus on certain innovations during the project duration and change focus after its finalization (Alomia-Hinojosa et al., 2018).

5.4.2. Trade-offs and synergies and implications for future trajectories

Several studies have quantified resource trade-offs in crop-livestock systems associated mainly with crop residue and biomass use (Erenstein et al., 2015; Tittonell et al., 2015; Valbuena et al., 2015b). It has been shown that alternatives such as on-farm fodder production could minimize the trade-off associated with labour demands for livestock production (Kiff et al., 2000; Pilbeam et al., 2005; Dahal et al., 2007; Tiwari et al., 2008; Tiwari et al., 2010). In this study we made a step forward and quantified trade-offs of relations with and among performance indicators.

In the specialized farm in Palpa, as expected, the number of livestock had a great influence on the profit, N losses and OM, as well as in the labour demand. Livestock is known to be a source of household income but increases labour demands considerably (Herrero et al., 2010). Trade-offs between labour and profit were also shown for other profit generating products such as tomato. In contrast, maize production showed low labour demand but also low profitability, which explains why the area of this crop has been decreasing in farms in the mid-hills. The specialized farm in Palpa showed a relatively larger landholding among the farms in both districts; Therefore, adjustments in the crop rotations such as increasing low labour demanding crops and on-farm fodder varieties could be an option to minimize the trade-offs. In contrast, in the farm in Dadeldhura although goats did not produce profit, they required also fodder imports which required also high labour demands. In addition, soybean and blackgram are the only income generating crops but also exhibited a higher labour demand in comparison to the other crops. In sum, livestock and crops are highly labour intensive in Dadeldhura despite their profitability as they are used mainly for household consumption.

Finally, although in this study we showed only two representative farms from different resource endowment; the findings are consistent with the knowledge that high resource endowed households have more opportunities to step up/out improving their wellbeing; while the LRE remain in a poverty trap (Tittonell et al., 2010; Valbuena et al., 2015a).

5.5. Conclusions

The main identified drivers associated with agricultural intensification in the mid-hills regions in the last 30 years were based on the access to agricultural inputs such as improved varieties of seeds and livestock and fertilizers. This has been a consequence of improved connectivity and access to markets, which have been stimulated by agricultural policies and developmental projects at national and local level. The agricultural intensification triggered higher presence of specialized vegetables and dairy cattle farms particularly in the sites in Palpa. While the share of cash crops per farm increased, cereals share as monocrops and in the winter rotations decreased.

The trade-off analysis of two contrasting farms, a specialized dairy cattle farm vs an average mixed crop-livestock farm, showed there was more space for improving farm configuration in the specialized dairy cattle farm. These space for improvement was achieved by minimizing trade-offs between livestock intensification (profit) with N losses and leisure time. This was associated to the larger landholding size of the farm. In a scenario of higher crop productivity, total costs would increase due to a lower crop gross margin and associated increase of costs of improved technologies.

This study contributes to the understanding of the dynamics of small crop-livestock farm systems and their strategies to change under external influences by studying past trajectories. Moreover, it provides knowledge of the current status and potential future directions of two contrasting resource endowed farms by analyzing the trade-offs associated with agricultural intensification.

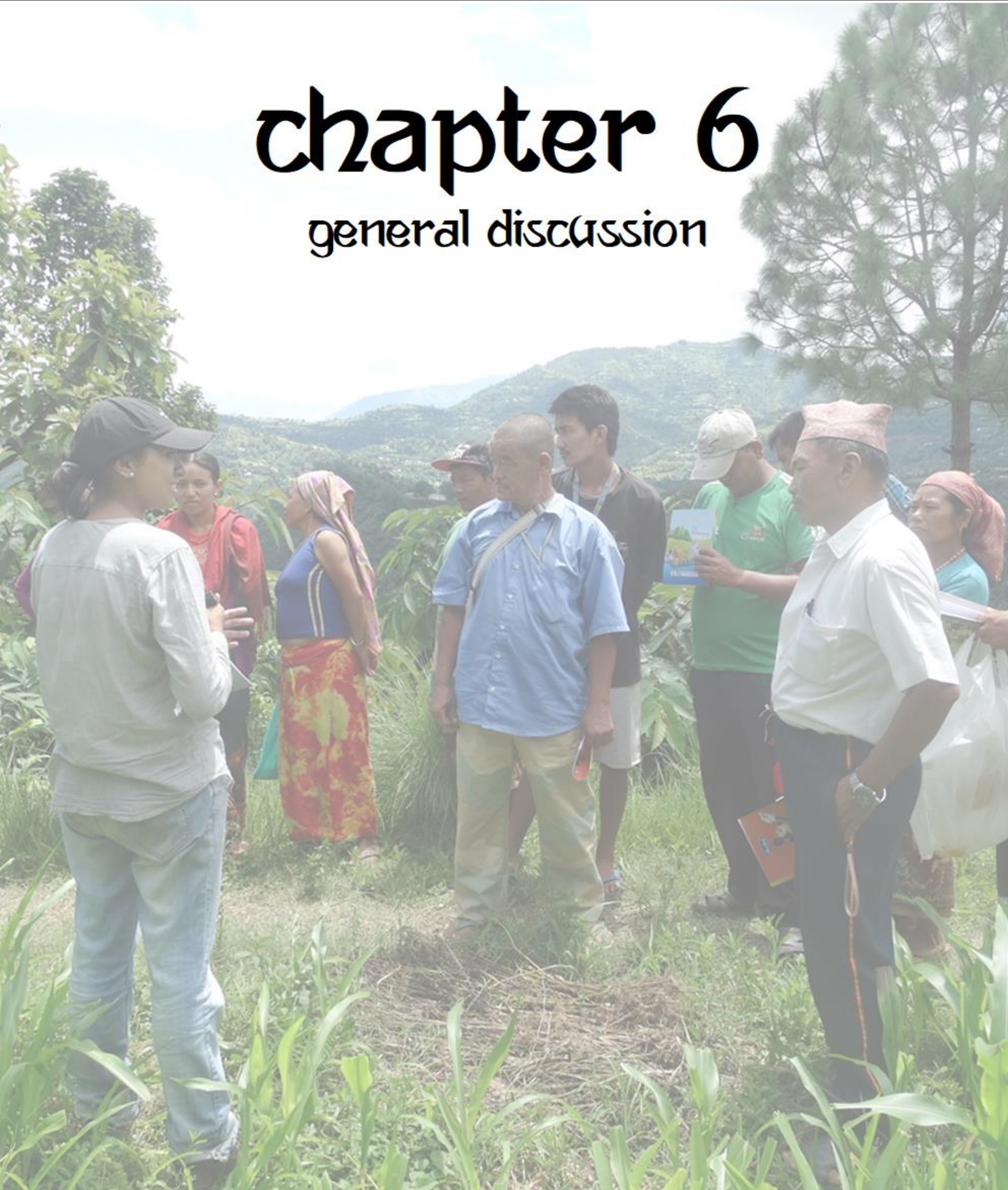
5.6. Supplementary Material

Table S1. *Major cropping pattern from 1985 to 2015 in Palpa and Dadeldhura.nNote: Symbol – represents seasonal difference, ,+ represents the mixed systems and / represents and or.*

	1985 to 1995 (Summer-Winter-Spring)	1995 to 2005 (Summer-Winter-Spring)	2005 to 2015 (Summer-Winter-Spring)
Palpa	Rice-Wheat-Maize	Rice-Wheat/Barley/Buckwheat-Fallow	Rice-Wheat/Barley/Buckwheat-Maize/Fallow
	Rice-Wheat-Fallow	Rice-Winter maize/Vegetables-Fallow	Rice-Winter maize/Vegetables-Spring rice
	Rice-Mustard+Lentil-Fallow	Vegetables-Winter maize-Fallow	Vegetables-Wheat/Winter maize-Spring rice
	Rice-Mustard+Lentil+Pea-Fallow	Rice-Vegetables-Fallow	Rice-Vegetables-Vegetables
		Vegetables-Lentil+Mustard-Fallow	Rice-Wheat/Barley/Buckwheat-Maize
		Rice-Mustard+Lentil+Pea-Fallow	Vegetables-Vegetables-Vegetables
		Rice-Wheat/Barley/Buckwheat-Maize	
		Rice-Mustard+Lentil-Vegetables	
Dadeldhura	Rice-Wheat-Fallow	Maize+Soybean-Wheat/Barley/Buckwheat-Fallow	Maize+Soybean-Wheat/Barley/Buckwheat-Fallow
	Maize+Soybean-Wheat/Barley/Buckwheat-Fallow	Maize-Mustard+Lentil-Fallow	Maize-Mustard+Lentil-Fallow
	Maize-Mustard+Lentil-Fallow	Millet+Blackgram-Mustard+Lentil+Pea-Fallow	Millet+Blackgram-Mustard+Lentil+Pea-Fallow
	Millet+Blackgram-Mustard+Lentil+Pea-Fallow	Rice-Wheat-Fallow	Rice-Wheat-Fallow
		Vegetables-Mustard+Lentil-Fallow	Vegetables-Mustard+Lentil-Fallow
		Maize+Soybean-Vegetables-Fallow	Maize+Soybean-Vegetables-Vegetables
			Maize+Teosinte-Wheat+Mustard-Vegetables
			Vegetables-Potato-Vegetables

chapter 6

general discussion



6.1. Introduction

Prior work has documented that 84% of farms worldwide are categorized as small-scale farming systems (FAO, 2017). Even though these small-scale farms operate 12% of the world's agricultural lands, smallholder farmers play an important role in feeding rural communities in low and low-middle income countries, through the contribution of staple commodities (Lowder et al., 2016; Fanzo, 2017). Small-scale farming systems are often classified as mixed agroecosystems, where the production of food crops is combined with raising livestock. However, smallholder farmers display low to medium levels of productivity, struggling to achieve self-reliance in the production of basic food commodities.

For Nepal, prior work has documented that several factors have been shown to limit agricultural productivity in smallholder farms such as low levels of soil fertility, limited access to external inputs, a lack of functioning irrigation systems, ongoing land fragmentation, and increasing soil erosion (Basnyat, 1995b; Kiff et al., 1995; Pilbeam et al., 2005; Dahal et al., 2007; Tiwari et al., 2010; Das and Bauer, 2012). For instance, the productivity of cereals, an important staple in Nepal, is significantly lower than the productivity of cereals in surrounding South Asian countries (The World Bank, 2018).

Previous studies in Nepal have mainly focused on a specific factor or have implemented purely agronomical aspects. However, this thesis took a multi-disciplinary and integrated approach, combining a diversity of methods from *hard* and *soft* sciences. First, this thesis used intercrop field experiments, Ecological Network Analysis, and biophysical-socioeconomic modelling. Then, it includes semi-quantitative methods such as Fuzzy Cognitive Mapping, interview sessions, on farm-discussion groups with farmers, and analysis of farmer perceptions.

The main objective of this thesis was to explore whether crop-livestock integration is a pathway to achieve sustainable intensification in small farm systems in Nepal. The four main objectives were outlined in Chapter 1, followed by Chapters 2 through 5 which were dedicated to the development of these four specific objectives. In contrast to the study areas in Chapter 2, which included both mid-hills and lowland agroecosystems, Chapter 3, 4 and 5 exclusively focused on the agroecosystems of the mid-hills. The reason for selecting smallholder farms specifically in these regions was the identification of the higher relevance for crop-livestock integration in the livelihood of these families (Chapter 1). It was found that these farm systems have a low cereal (maize) productivity, often sustain high livestock densities, and are dependent on external N mainly in the form of imported fodder. In this final synthesis chapter (Chapter 6), the conclusions of the previous chapters and the main findings regarding the thesis objectives are discussed. Finally, recommendations for further research are presented.

6.2. Societal impact

This thesis has two main contributions of importance to present-day society: First, it informs policy makers and the development sector about the latest knowledge on the diversity and functioning of crop-livestock integrated systems in mid-hills agroecosystems. It emphasizes the importance of farmers' perceptions regarding the adoption and success of innovative agricultural practices. Second, it highlights the importance of the use of multidisciplinary approaches to conduct research in the framework of sustainable agriculture. Therefore, the specific knowledge generated in this study contributes to the approximately two decades of research of context-specific approaches to achieve sustainable intensification of agricultural production systems.

6.2.1. Crop-livestock integration in farm systems sustainability at a global level

Prior studies in the mid-hills and the lowlands of Nepal have focused on closing existing yield gaps by increasing productivity. They suggested to increase this productivity by using inputs such as mineral fertilizers and improved seeds (Devkota et al., 2015; 2016; 2019). Furthermore, these studies claimed that the efficient use of inputs is an entry point to achieve sustainable intensification. Similarly, it has been discussed that in the "developing South", where yield gaps are large and resource use efficiency is low, intensification of input use is required (Silva et al., 2017). Although this approach could lead to increased productivity, this thesis argues that the low adoption and low economic capacity of smallholder farmers in the developing South also requires additional context-specific solutions to achieve sustainable intensification (Chapter 3).

In this context, the integration of crop cultivation and raising livestock in mixed farming systems provides an opportunity to intensify farm production in a sustainable manner in "low-input, low-output" farm systems (Bonaudo et al., 2014), as those studied in this thesis. Integrated crop-livestock systems could even support the re-design of specialized and industrial farm systems by showing how to deal with both complexity and diversity (Bonaudo et al., 2014). Furthermore, several studies emphasize the benefits of crop-livestock integration in farming systems, which are mainly livelihood improvement, and sustainable food production (Thorne and Tanner, 2002; Herrero et al., 2010; Ryschawy et al., 2012; Stark et al., 2017). Crop-livestock integration has also been proposed as an appropriate strategy to optimize resource-use efficiencies (Ruffino et al., 2009) (Chapter 2). Bonaudo and co-authors (2014) affirmed that four agroecological concepts characterise mixed farming systems: resilience, productivity, efficiency and dependency. There are several interpretations and a choice of indicators to measure these concepts.

However, the results presented in this thesis demonstrate that crop-livestock integration can comply with the four agroecological concepts that support well-integrated farming systems. It was shown that through crop-livestock integration, on-farm biomass productivity can be increased (Chapters 2 and 3), resulting in a decrease of dependency on external inputs (Chapter 2). In addition, the study of N flows between the various farm compartments showed that an increase of N network robustness could be associated to the overall N networks resilience. Finally, this thesis presented evidence that a higher level of farm systems efficiency could realize both closing yield gaps and decreasing losses (Chapters 2 and 3).

6.2.2. The importance and role of integrated, multidisciplinary approaches to study agroecosystems innovations

The traditional linear model of technology development and dissemination has supported the growing industrialization of global agriculture. In this model, the knowledge is exclusively produced in research institutions and disseminated to farmers through public or private technical institutions or extension service providers. However, this model has been criticized for alleged negative social and environmental impacts (Vanloqueren and Baret, 2009; Brunori et al., 2013). For instance, the linear model has failed to educate and involve farmers in development and ecological issues (De Snoo et al., 2013; Berthet et al., 2018). In addition, it has not mentioned the prominent position of agricultural design and innovation as part of broader transitions, thereby excluding a focus on diversifying future food systems (Berthet et al., 2018; Pigford et al., 2018). As a result, recent efforts to renew this linear model advocate for more open, decentralized, contextualized and participatory approaches, thereby including innovation as an integral part of current agricultural practices (Berthet et al., 2018).

One of the ways to renew traditional agriculture has been the use of a broad spectrum of diverse disciplines and a variety of methods to promote the re-design and co-innovation of agricultural systems. In line with these attempts, this thesis employs an interesting mix of methods used in natural and social sciences. It illustrates how the combination of both science fields complement the outcome of studies of smallholder farms in seek of transition to a more integrated systems approach. There is sufficient evidence that supports the idea that a transdisciplinary research approach promotes the creation of disciplinary paradigms. Furthermore, the use of participatory methods promotes the inclusion of farmers alongside professionals so that the generation of knowledge becomes a continuous process among all actors involved (Kumba, 2003; Darnhofer et al., 2016). Data generated and assessed in Chapter 3 have included farmers perspectives and needs via these participatory strategies, which also provided data for the Ecological Network Analysis and the analysis of trade-offs that smallholder farmers face, as presented in Chapters 2 and 5, respectively.

Interestingly, the participatory setting as mentioned earlier has rather similar characteristics to *innovation platforms*, which link different stakeholders to achieve a joint objective (Nederlof et al., 2011). Both settings serve as spaces to exchange information. Hence, working alongside each other created stronger linkages, and enhanced a better exchange of information between farmers and researchers. The participatory trials, as introduced in Chapter 3, served to identify the reasons behind the observed yield gaps and to investigate the drivers that play a role in the adoption of practices to increase productivity. The multidisciplinary methodology that was used in this thesis might position itself on the frontline of much more research to come, which might make use of integrated, multidisciplinary approaches to study agroecosystems innovations. Results of the participatory trials as shown in Chapter 3, provide compelling evidence that farmer´s perspectives and participation should be considered a vital part of the eventual success of the adoption process. Thinking one step further, I would suggest a co-innovation process as proposed by Dogliotti et al. (2014), which not only involves systemic diagnosis and re-design of contemporary farm systems, but also includes constructive social learning, dynamic monitoring, and (self) evaluation elements. In conclusion, it would be desirable to opt for a system that combines mutual interaction and adaptation between technological, social, and institutional fields (Kilelu et al., 2013).

6.3. Farmers' perceptions and decision making to design sustainable trajectories

Understanding farmers´ perceptions of agricultural systems and the level of alignment with scientific agendas is crucial to explain (behavioural) patterns that do not conform to the expectations (Cortner et al., 2019). The perceptions of farmers studied in this thesis were first assessed by the use of participatory experimentation methods (Chapter 3) and secondly by using *ex ante* methods accompanying farmers while they generated a scheme that visualized the idea they have of their farm system (Chapter 4). Moreover, the data obtained for the ecological network analysis as well as for trade-offs and trajectories analysis (Chapter 2 and 5) continuously involved farmers' participation via formal and informal discussion groups. Prior to this thesis, related studies focusing on integrated crop-livestock systems, usually adopted the agronomic or economic perspectives from a researcher's point of view (Cortner et al., 2019). The same is true for Nepal, where the study of farmer perceptions has mainly been focused on understanding farm dynamics such as land-use changes (Paudel et al., 2019). Hence, fewer studies have investigated farmer's perceptions in the context of sustainable intensification with the aim to understand the drivers and perceptions that influence crop-livestock integration systems.

Participatory methods exploring farmers' perspectives have been widely used when proposing the adoption of sustainable intensification practices (Pretty et al, 1995; Blackstock et al., 2007; Chaudhary et al., 2013; Meijer et al., 2015). By including the farmers´ perspective throughout this project, the priorities of farmers about efforts to improve crop-livestock integration in small mixed farm systems are better understood. In addition, this thesis presented two essential contributions to sustainable intensification efforts: first, active participation in on-farm experiments could positively influence farmers' adoption behaviour (Chapter 3) and secondly, giving farmers a voice and an inclusive, safe environment to discuss, lightens facts that could have been easily overseen in a conventional research fashion (Chapters 3 and 4). Thus, the results as shown in this thesis emphasize that farmers´ perceptions and intrinsic motivations are essential to understand the decision-making factors influencing the outcome of whether or not to adopt or non-adopt improved agricultural practices.

Finally, most of the data collection as presented here, were supported by a cultural anthropology approach. My close and continuous involvement in the participatory experimentation, being a *real farmer* in the local communities in the mid-hills of Nepal, and performing all of the local and cultural activities such as sowing, applying fertilizers, weeding, harvesting, threshing, collecting fodder, and being part of these rural communities for months in a row, gave me the opportunity to gain and earn the *respect* and trust, as earlier mentioned by Speelman (2014). Although this observation is subjective, reading the gestures of both male and female farmers at the end of the field period, gave me confidence and validity and quality of the collected data as presented in this thesis.

6.4. Network analysis vs. simple changes to improve nitrogen management

As a starting point to identify current bottlenecks in agroecosystems functioning, the Ecological Network Analysis (ENA) was used to assess N as an essential element in crop and livestock interactions (Chapter 2). To date, only a few studies have effectively used ENA, mainly to evaluate *tropical* agroecosystems (Rufino et al., 2009; Alvarez et al., 2014). Although these studies assessed similar indicators such as organization and diversity to evaluate diverse farm system functioning, this thesis added a relevant indicator to measure the balance of the system's degree of order between organization (order) and adaptive flexibility (resilience), regarding N flows between the various farm compartments. To my knowledge, this is the first analysis of robustness ever performed in agroecosystems studies. Conceptualizing the robustness of nutrient networks in agroecosystems is a step forward when it comes to exploring methods aimed at calculating efficiency and resilience of agroecosystems networks. However, this robustness concept must be treated carefully, as it can easily be mistaken for a general measurement of system sustainability (Patzek, 2008). In agroecosystems in which *people* play an important role, this concept should not neglect other aspects of sustainability, i.e. social and economic aspects.

Results of the analysis of ENA as presented in Chapter 2 together with field observations, suggested two main processes that could lead to the loss of N: first, during the storage of out-of-farm collected fodder, and second when manure was stored, regardless whether it was stored traditionally in heaps on the fields or inside of the farm's stable. Simple ways to improve the storage management of both silage and manure were tested by performing micro-experiments in a participatory fashion similar to the methodology used in Chapter 3. These trials took place in the Dadeldhura district and results indicated that simple, hands-on changes in storage management of either can make a difference. On the one hand, manure that has been covered in plastic had a significantly higher N content at the end of the experiment (1.49% N), compared to manure that has been left in open heaps (1.13% N). Moreover, most of the farmers showed a positive perception towards the use of this practice. As local farmers did not have silage practices in place, different combinations of silage were tested on-farm to determine which was the most effective at preserving the high quality of fodder. Compared to the traditional fodder storage, all combinations, including fresh maize leaves mixed with either fresh grasses, Napier grass or a combination of the three stored in a bin, delivered fodder with a higher percentage of crude protein at the end of the experiment (Figure 1).

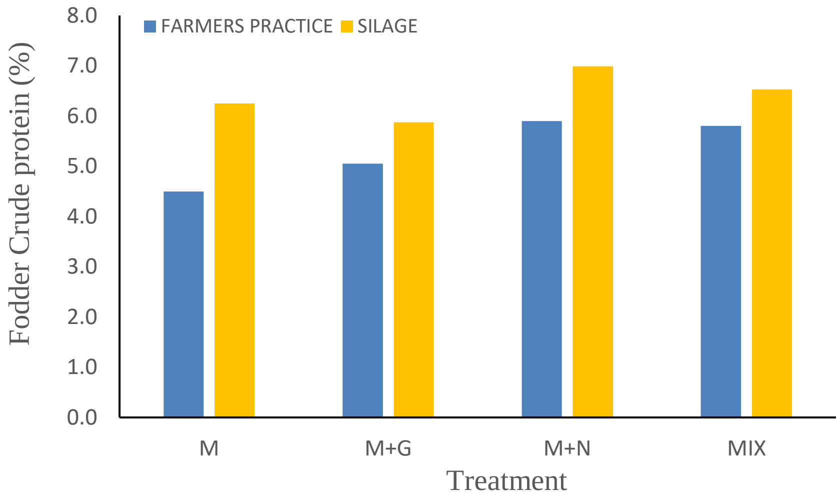


Figure 1. *Percentage of crude protein in silage treatments where M: maize; M+G; maize and collected grass (fodder); M+N: maize and Napier grass; and MIX: mix of maize, collected grass and Napier grass.*

Although the complex process to produce silage involved extra labour and material, farmers positively changed their perceptions while performing the experiments and after seeing the results of the process. These data were not presented in the current thesis, because these experiments were not replicated at all the sites. Nevertheless, as these trials indicate promising methods to reduce N losses in crop-livestock systems in the mid-hills of Nepal, it is suggested to perform repetition experiments. Moreover, these methods were validated in a participatory context with farmers in their own farms.

6.5. Trajectories of dynamic, intensified maize farm systems

Exploring the diversity of farm systems can contribute to visualize heterogeneity, to understand specific dynamics, to target innovations and to contextualize the co-design of more sustainable agroecosystems (Tittonell et al., 2010; Giller et al., 2011; Valbuena et al., 2014). For two sites in different mid-hills districts and in the Terai, farmers were independently categorized according to three resource endowment types: LRE (low resource endowment), MRE (medium resource endowment) and HRE (high resource endowment) (Chapter 2). This original characterization was used throughout the thesis, to explore changes considering farmers heterogeneity. Although N flow indicators varied more between resource endowment types than districts (results of Chapter 2), farmers' perceptions regarding agricultural constraints, innovations adoption, changes of perception in a participatory context, and trade-offs of livestock intensifications (results of Chapters 3, 4 and 5), only slightly differed between resource endowment types. Farmers' perspectives were only assessed in the two mid-hills agroecosystems and results indicated that these farms have similar constraints for sustainable agricultural production: remoteness, irregular and small farm sizes, and a low access to markets (Alomia-Hinojosa et al., 2018; Subedi et al., 2019). However, there were outlier cases of farmers who successfully specialized in the mid-hills agroecosystems. Interestingly, most of these successful farmers chose to specialize in dairy production. Managing high livestock densities, these farmers on average had larger farm sizes and consequently more options to minimize trade-offs between farm profit and organic matter (OM), N losses and leisure time (Chapter 5). Moreover, three specialized farmers in the Palpa district agreed upon changing their farming practices when milk started being a cash product. Responding to the higher fodder demand to feed their large livestock numbers, they reduced their maize cultivation area, while increasing the areas to cultivate forage species such as Napier grass

(*Pennisetum perupureum*) and Teosinte (*Zea mays* subsp. mexicana) (Table 1). Even though maize in the mid-hills and the lowlands of Nepal have a double purpose (food and feed), in the mid-hills maize is mainly seen as livestock feed (Chapter 2 to 5). The transition from traditional to specialized farms gave insights on the potential limitation of maize to exclusively fulfil the feed demands once livestock numbers increase. Although maize is an important traditional crop in the mid-hills (Pilbeam et al. 2010, Tiwari et al., 2014), when farms specialize in livestock production other fodder species might be better options for a sustainable crop-livestock integration.

Table 1. *Main changes in farm components of three dairy specialized farms*

	Farmer 1		**Farmer 2**		**Farmer 3**	
	1.2 ha		1.8 ha		1 ha	
	2010	2015	2010	2015	2010	2015
Dairy cattle	3	16	2	10	2	12
Livelihood objective	self-subs	income	income	income	self-subs	income
Fodder species %	30	70	10	60	0	100
Maize area (summer)%	70	30	50	20	100	0
Vegetables (for market)	yes	no	no	no	yes	no
Household income	low	higher	low	high	low	high
Labour		same		higher		same

Self-subs = self-subsistence
Maize and vegetable area represent the % of area planted

Furthermore, the farm size is an important factor to assure successful farming in the future (Chapter 5). HRE farmers have more options to continue farming in the future. Considering the growing number of rural household migration (FAO, 2018), together with the constraints faced by mid-hill farm systems, MRE and LRE farms might be more prone to depend on off-farm income (Chapter 2 and 5).

6.6. Research for development: the role of research on smallholder farms in the context of poverty alleviation.

How to effectively reduce global poverty remains one of humankind's most pressing questions. In this year (2019), researchers who focused on mechanisms to reduce poverty won the Nobel prize in Economic Sciences. This research performed by Banerjee, Duflo and Kremmer over the last decades, disentangled the knowledge of heterogeneities of low- and middle-income economies affirming that some individuals in developing countries use the latest technology, while others in the same country and sector use outdated production methods. However, in high income countries, these within-sector differences in productivity are much smaller. They proposed that bringing incentives such as access to knowledge and technology closer to direct applicability, is an effective way to reduce poverty (The Royal Swedish Academy of Sciences, 2019). Although this thesis did not follow a solely economic approach, like this year's Nobel Prize winners, it does encourage policy makers to focus on effective solutions for smallholder farmers, which generally reside in the most vulnerable segments of society in the developing South. Context specific policies such as access to and subsidies for well-integrated seeds, information about important fodder species, and providing knowledge of management of communal grasslands could have big impacts on the livelihood and sustainability of smallholder farms in the mid-hills of Nepal.

6.7. Study limitations and recommendations for follow-up studies

As with every scientific study, some limitations are worth noting: The high-magnitude earthquake that struck Nepal in 2015, one of the most devastating in the nation's history, not only impacted all levels of Nepali society, but it created a bottleneck for this thesis. The aftermath of the earthquake delayed the progress of this thesis and complicated the logistics for the continuous data collection. In addition, it undoubtedly complicated the supplies of high-quality inputs in the form of seeds and fertilizers for the field experiments. Moreover, the earthquake and the stress it caused, might have had an influence on the decisions of farmers in 2015, and potentially also in subsequent years. Cross-checking with field trials in the mid-hills confirmed our measurements and the use of models that required detailed information of farm systems components helped in producing additional data.

Another limitation worth mentioning is that using different disciplines could be a challenge in a scientific context. Effectively, most of today´s education systems aim to deliver researchers who are more specialists instead of generalists. The use of both *soft* and *hard* science requires a deeper understanding of multiple disciplines at the same time, and therefore is challenging to the scientist. For example, besides natural and social sciences, the approach for this thesis also included a modelling approach to support the analysis of data collected from both disciplines.

This thesis combined a variety of approaches that contributes to understanding the issues that limit a sound crop-livestock integration in Nepal, thereby creating a multi-dimensional context. It showed scope to improve integration of crop and livestock in small farm systems particularly in the Nepalese mid-hill regions. However, some aspects influencing crop-livestock integration still deserve further investigation. It is recommended that future research includes a landscape level approach, as results in this study demonstrated that smallholder farms are highly dependent on external fodder. Therefore, studies regarding interactions between the forest, roadside grass and communal grasslands with livestock might give more insight on how to improve the farm integration.

Moreover, interactions that promote communal exchanges are pivotal to small farms. Based on experiences of the farmers that cooperated in this study, farms continue to decrease in size due to traditional cultural reasons. Furthermore, in this thesis it was assumed that maize was used mainly as fodder. However, it is recommended to further study other, local species that can complement food crops, which might also function as fodder species.

Finally, this study had a clear focus towards the participation of farmers. However, more actors should be involved in this process to better integrate crop and livestock components. Both agricultural extension services, and representatives from the non-profit and governmental development sectors should be encouraged to work together to strengthen the efforts to integrate crop and livestock components with the objective to achieve sustainable intensification in these agroecosystems.

6.8. Final remarks and conclusions

This thesis explored diverse angles to understand the viability of sustainable crop-livestock integration in smallholder farm systems in Nepal. The main conclusions of this thesis are:

- Increasing farm fodder (maize) productivity through improved management practices contributes to a better crop-livestock integration in the Nepalese mid-hills farm systems by 1) reducing fodder imports, 2) preventing N losses, and 3) increasing the robustness of N flow networks. However, improving on-farm fodder productivity is hampered by the farmers' perceptions of higher labour demand and costs associated with agricultural inputs. Moreover, farmers are not inclined to make additional investments in on-farm feed production (maize) as they perceived these as insufficient to bridge the widening feed gap that corresponds to additional livestock.

- Emerging specialized (high resource endowment) farm systems in the mid-hills have more potential to minimize the trade-offs associated with livestock intensification due to larger landholdings.
- Participatory experimentation has proven to actively engage farmers in adopting sustainable intensification innovations.
- Increasing the productivity of on-farm fodder can not only result in improving livestock productivity, but it can also improve the integration of crop and livestock components. Hence, it generates positive effects regarding food security and well-being of mixed farm systems in Nepal. However, further quantification practices that can be achieved at the farm level such as improving farmyard manure quality and improving management of farm components, should be considered when shaping more sustainable integrated systems.

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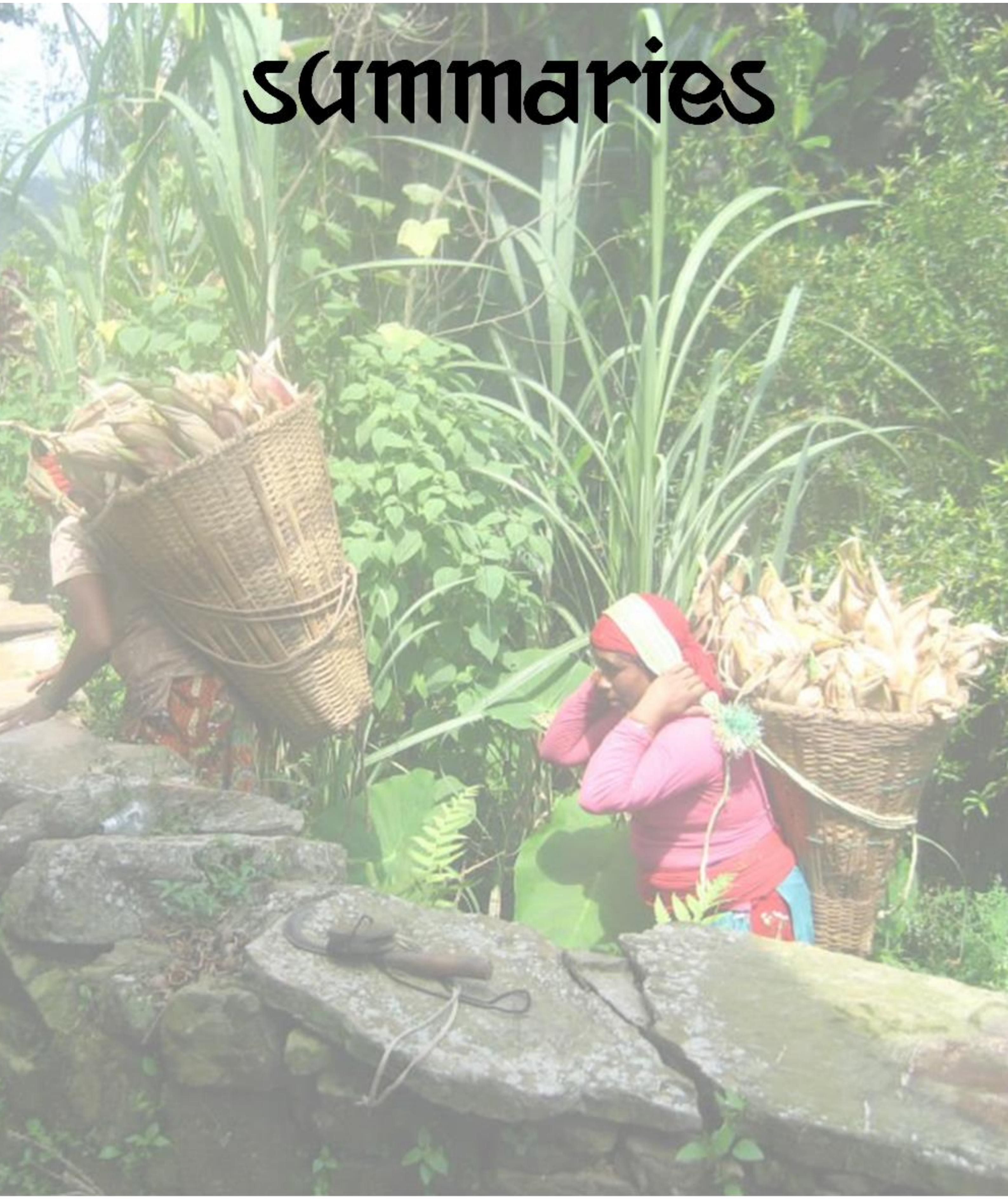
summaries



Summary

Small-scale farms play an important role in feeding rural communities in low and low middle-income countries through the contribution of staple commodities. The contribution of small-scale farmer to communities in e.g. South Asia is estimated as high as 30%. Small-scale farms are often classified as mixed agroecosystems; however, the production of crop and livestock are commonly at low to medium level of intensity. As a result, these farm systems are often affected by food-insecurity. Moreover, the demand for animal protein is estimated to grow rapidly as a result of a fast population growth. Therefore, there is a need to increase food productivity. However, productivity should be achieved in a sustainable manner with less external inputs and more in balance with nature. Hence, this thesis investigates options to achieve sustainable intensification in smallholder farm systems in Nepal.

In Nepal, most of the farm systems are characterized as small-scale. These farm systems are mixed, as they are based on a combination of cereal production (maize, wheat and rice) and livestock. Both cereals and livestock are a source of income and buffer against food shortages. Moreover, livestock provide both manure to fertilize crops and draught power to cultivate crop fields. Nevertheless, Nepalese crop-livestock systems are low productive. In addition, farms are continuously decreasing in size due to land fragmentation due to cultural reasons. Thus, the importance of better integrating crop and livestock subsystems to attain agricultural intensification could be promising in the context of agroecosystems in Nepal. Integrated crop-livestock systems may contribute to an efficient design of a sustainable farm system, as they aim at achieving synergism between soil, plant, animal and atmosphere.

This thesis explores and evaluates crop-livestock integration as a pathway to achieve sustainable intensification in cereal-based farming systems in Nepal from a farmer's perspective. The objectives of the thesis (Chapter 1) are: 1) to describe the diversity of cereal-based agroecosystems and to identify current bottlenecks constraining crop-livestock systems functioning in terms of N flows (Chapter 2); 2) to explore farmers perceptions of agricultural innovations for crop-livestock integration (Chapter 3); 3) to explore and explain trade-offs associated with crop-livestock integration, and potential responses of farm systems components to external drivers (Chapter 4 and 5); and to explain the past changes that have occurred in mid-hills farming systems and the drivers accounted for agricultural intensification to explore potential future trajectories (Chapter 5).

This thesis employs a diversity of methods from *hard* and *soft* sciences with quantitative methods: intercrop field experiments, Ecological Network Analysis, biophysical-socioeconomic modelling; and semi-quantitative methods: Fuzzy Cognitive Mapping, interviews, and on farm-discussion groups with farmers.

Chapter 2 explores the concept of robustness for nutrient flows. The main results show that the farms in the different agroecosystems recycle only a small portion of the total N inputs (<15%) and have therefore high rates of N losses (63-1135 kg N per ha per year). Moreover, they display a high dependency on N imports in the form of fodder (feed self-reliance 11-43%). Furthermore, farm N networks are organised (high productivity) but inflexible (poorly resilient) and consequently unbalanced (low robustness). However, scenarios of improved management demonstrate that crop production can be improved, leading to reduced fodder imports and less N losses. Consequently, the N networks increase the flexibility, which results in higher level of robustness of the N flow network in the investigated farm systems.

In Chapter 3, through a two-year farmer-oriented participatory research project, results show that: 1) substantial productivity improvements can be achieved through intensification methods, 2) the active involvement of farmers in on-farm trials increases understanding of underlying decision-making factors to adopt or non-adopt improved practices, and 3) engaging farmers positively influence farmer perceptions towards the adoption of innovative practices. Even though it is shown that productivity increases significantly by the explored improved methods, social and cultural factors still limit its fast adoption.

Chapter 4 shows how farmers identify trade-offs between the benefits of increased cash income and farmyard manure production from intensified livestock production versus increases in labour requirements for fodder imports. It is shown that farmers are not willing to make additional investments in on-farm feed production, as they perceive these as insufficient to bridge the widening feed gap resulting from additional livestock. The same constraints are mentioned irrespective of farmers' resource endowment levels. Furthermore, a sensitivity analysis shows that, given the farmers' perceptions, an increase in milk market demand could have enhanced positive effects on livestock production and on-farm income.

Chapter 5 identifies the main drivers associated with agricultural intensification that occurred in the farming systems in the mid-hills since 1985. These drivers are based on the access to agricultural inputs such as improved varieties of seeds and livestock. This has been a consequence of improved connectivity and access to markets, which have been stimulated by agricultural policies and developmental projects. Furthermore, the trade-off analysis of two contrasting scenarios: 1) dairy cattle specialized vs. 2) average mixed farm systems showed that there is space for improving farm configurations by minimizing trade-offs between livestock intensification (profit) on the one hand and N losses and leisure time in the specialized farm on the other hand. This is associated to the farm larger landholding size. In a scenario of higher crop productivity, total costs would increase due to a lower crop gross margin and associated increase of costs of improved technologies.

Finally, in Chapter 6, the findings are summarized, key themes are discussed, and the main conclusions and recommendations are presented.

Samenvatting

Kleinschalige boerderijen spelen een belangrijke rol in het voorzien van voedsel van plattelandsgemeenschappen in landen met een laag inkomen en een lager midden-inkomen, door midde van de productie van basisproducten. De bijdrage van kleinschalige boeren aan gemeenschappen in b.v. Zuid-Azië wordt geschat op ongeveer 30%. Kleinschalige boerderijen worden vaak geclassificeerd als gemengde agroecosystemen, maar de algehele productiviteit van gewassen in combinatie met veeteelt is echter meestal laag. Als gevolg hebben deze boerderijsystemen vaak te maken met voedselonzekerheid. Daarnaast stijgt de vraag naar dierlijke eiwitten snel als gevolg van een snelle bevolkingsgroei en heerst er de behoefte om deze voedselproductiviteit te verhogen. De productiviteit moet echter op een duurzame manier worden gecreeerd, bijvoorbeeld door minder afhankelijk te zijn van een externe aanvoer van voedingsstoffen en meer in balans met de natuur. Daarom onderzoekt dit proefschrift opties om een duurzame intensivering te bereiken in kleinschalige boerderijsystemen in Nepal.

In Nepal zijn de meeste boerderijsystemen kleinschalig van aard. Deze boerderijsystemen zijn gemengd, omdat ze gebaseerd zijn op graanproductie (maïs, tarwe en rijst) in combinatie met veeteelt. Graan en veeteelt zijn beiden een inkomensbron en kunnen worden gebruikt als buffer tegen voedseltekorten. Bovendien levert vee zowel mest op om de gewassen te bemesten evenals trekkracht om de akkers te ploegen. Toch zijn Nepalese boerderijen vaak niet zo productief als gedacht. Verder worden Nepalese boerenbedrijven steeds kleiner door landfragmentatie vanwege culturele redenen. Het belang van een betere integratie van gewas- en veeteelt subsystemen voor intensivering van de landbouw kan dus veelbelovend zijn in deze context van agroecosystemen in Nepal. Geïntegreerde veehouderijsystemen kunnen bijdragen aan een efficiënt ontwerp van een duurzaam landbouwsysteem, omdat ze zich richten op het bereiken van synergie tussen bodem, plant, dier en atmosfeer.

Dit proefschrift onderzoekt en evalueert de integratie van het verbouwen van gewassen en het houden van vee als een manier om duurzame intensivering te bereiken voor deze op graanteelt gebaseerde landbouwsystemen in Nepal, vanuit het perspectief van de agrariër. De doelstellingen van dit proefschrift (zoals gepresenteerd in hoofdstuk 1) zijn: 1) Het beschrijven van de diversiteit van op graanteelt gebaseerde agro-ecosystemen en het identificeren van de huidige knelpunten binnen de stikstof (N) stromen die gewasteelt-veehouderijsystemen belemmeren in hun functioneren (hoofdstuk 2); 2) Het verrichten

van onderzoek naar de perceptie van boeren ten aanzien van landbouwinnovaties voor de integratie van het telen van gewassen en het houden van vee (hoofdstuk 3); 3) Het onderzoeken en verklaren van afwegingen van agrariërs die rechstreeks verband houden met de integratie van vee- en gewasteelt, en de potentiële reacties van componenten van landbouwsystemen op externe factoren (hoofdstuk 4 en 5); en om de veranderingen te verklaren die zich naar verloop van tijd hebben voorgedaan in deze landbouwsystemen in de Mid-hills en de factoren die hebben gezorgd voor intensivering van de landbouw die als lijdraad kunnen dienen om potentiële toekomstige trajecten te kunnen begrijpen (hoofdstuk 5).

Dit proefschrift maakt gebruik van een verscheidenheid aan methoden uit de zogenaamde “harde” beta en “zachte” alpha wetenschappen, waaronder kwantitatieve methoden zoals intercrop-veldexperimenten, ecologische netwerkanalyse, en biofysisch-sociaal-economische modellen; en daarnaast met semi-kwantitatieve methoden: Fuzzy Cognitive Mapping, interviews en discussiegroepen met boeren op het erf van hun boerderijen.

Hoofdstuk 2 onderzoekt het concept van robuustheid van nutriëntenstromen. De belangrijkste resultaten laten zien dat de bedrijven in de verschillende agro-ecosystemen slechts een klein deel van de totale N-invoer hergebruiken (<15%) met hoge N-verliezen tot gevolg (63-1135 kg N per ha per jaar). Bovendien zijn ze sterk afhankelijk van de invoer van N in de vorm van voer (zelfvoorziendheid 11-43%). Bovendien zijn deze boerderij N-stromen redelijk tot goed georganiseerd (hoge productiviteit), maar niet flexibel (lage veerkracht) en als gevolg daarvan onevenwichtig (lage robuustheid). Scenario's van een beter management van deze N-stromen tonen aan dat de gewasproductie verder kan worden verbeterd, wat leidt tot minder invoer van veevoer en minder N-verliezen op de boerderijen zelf. N-netwerken kunnen de flexibiliteit verhogen, wat resulteert in een hoger niveau van robuustheid van het het netwerk van N stromen in de onderzochte boerderijsystemen in Nepal.

De resultaten zoals gepresenteerd in hoofdstuk 3, op basis van een tweejarig onderzoeksproject gericht op de participatie van boeren, tonen aan dat: 1) substantiële productiviteitsverbeteringen kunnen worden bereikt door specifieke intensiveringsmethoden, 2) de actieve betrokkenheid van boeren bij de experimenten op hun boerderijen helpt bij het begrijpen van onderliggende factoren die de beslissingen beinvloeden om verbeterde werkwijzen al dan niet aan te nemen, en 3) het betrekken van boeren heeft een positieve invloed op hun perceptie ten aanzien van het wel of niet volgen van innovatieve, vooruitstrevende werkwijzen. Hoewel wordt aangetoond dat de productiviteit aanzienlijk toeneemt door de voorgestelde verbeterde werkmethoden, beperken sociale en culturele factoren de snelle acceptatie ervan.

Hoofdstuk 4 laat zien hoe boeren afwegingen kunnen maken tussen enerzijds de voordelen van een verhoogd inkomen en de productie van mest op de boerderij zelf door een intensivering van de veehouderij en anderzijds een toename van de arbeidsbehoeften die komen kijken bij de aanvoer van voer voor hun dieren. Het is aangetoond dat boeren niet bereid zijn om extra te investeren in de productie van voer op het bedrijf zelf, omdat ze deze niet als een werkbare oplossing beschouwen om de groeiende vraag als gevolg van extra vee te overbruggen. Dezelfde beperkingen worden genoemd, ongeacht het niveau van toegang tot natuurlijke hulpbronnen van de boeren. Bovendien toont een gevoeligheidsanalyse gericht op de percepties van de boeren zelf aan, dat een toename van de vraag op de melkmarkt de situatie t.a.v. de veehouderij en het boerderij inkomen zou kunnen verbeteren.

Hoofdstuk 5 identificeert de belangrijkste factoren die verband houden met de landbouwintensificatie die zich sinds 1985 in de landbouwsystemen in de Mid-hills van Nepal hebben voorgedaan. Deze factoren zijn gebaseerd op de toegang tot landbouwinputs zoals bijvoorbeeld verbeterde variëteiten van zaden en vee. Dit was een gevolg van een verbeterde infrastructuur en een betere toegang tot commerciële markten, die werden gestimuleerd door landbouwbeleid en ontwikkelingsprojecten. Bovendien toonde de trade-offs analyse van twee contrasterende scenario's, namelijk 1) landbouwbedrijven gespecialiseerd in melkvee of 2) gemiddelde gemengde bedrijfssystemen aan dat er ruimte bestaat voor het verbeteren van bedrijfssituaties door gebalanceerde afwegingen te maken om trade-offs te minimaliseren tussen enerzijds een intensivering van vee (winst) en anderzijds N verliezen en tijd die vrij komt op een gespecialiseerde boerderij. Deze trade-offs zijn geassocieerd met de grootte van de boerenbedrijven. In het scenario van een hogere gewas productie, de totale kosten die gemoeid zijn met het runnen van zo’n boerderij zullen stijgen door een kleinere winst marge op het gewas zelf en een hogere kostenpost t.a.v. verbeterde technieken die toegepast moeten worden.

In hoofdstuk 6 worden de resultaten samengevat en worden de verschillende hoofdthema’s bediscussieerd. Ook worden de algehele conclusies en aanbevelingen voor vervolgonderzoek gepresenteerd.

Resumen

Las fincas de pequeña escala juegan un rol importante en la alimentación de las familias rurales en los países de ingreso bajo y de bajo-medio contribuyendo con productos de consumo básico. La contribución de las fincas de pequeña escala a las comunidades de por ejemplo Asia del Sur está estimada en 30%. Las fincas de pequeña escala están usualmente clasificadas como agroecosistemas mixtos; sin embargo, la producción de cultivos y ganado tienen un nivel de bajo a medio de intensidad. Como resultado, estos sistemas agrícolas están comúnmente afectados por la inseguridad alimenticia. Por otra parte, se estima un crecimiento rápido de la demanda de proteína animal como consecuencia del acelerado crecimiento de la población mundial.

Por lo tanto, existe la necesidad de incrementar la productividad de la comida. Sin embargo, la productividad debe ser incrementada de una manera sustentable con menos insumos externos y en balance con la naturaleza. Por consiguiente, esta tesis investiga opciones para alcanzar la intensificación sostenible en fincas de pequeña escala en Nepal. La mayoría de sistemas agrícolas en Nepal son de pequeña escala. Estos sistemas agrícolas son mixtos, puesto que están basados en la producción de cereales (maíz, trigo y arroz) y ganado. Tanto los cereales como el ganado son fuente de ingresos y reserva en caso de escasez de comida. Además, el ganado proporciona abono para fertilizar los cultivos y tracción animal para labranza. Sin embargo, los sistemas cultivo-ganado en Nepal tienen una productividad baja. Así mismo, el tamaño de las fincas está continuamente decreciendo al ser estas fragmentas por razones culturales. Por lo cual la importancia de integrar mejor los subsistemas ganado y cultivo para conseguir intensificación sostenible puede ser una estrategia promisoria en el contexto de los agroecosistemas en Nepal. Los sistemas integrados de cultivo-ganado podrían contribuir en un diseño eficiente para un sistema agrícola sostenible porque producen sinergismos entre el suelo, la planta, el animal y la atmosfera.

Esta tesis explora y evalúa la integración cultivo-ganado como ruta para alcanzar la intensificación sostenible de sistemas agrícolas basados en cultivos de cereales en Nepal. Esto lo hace desde la perspectiva del agricultor. Los objetivos de la tesis (Capítulo 1) son 1) describir la diversidad de agroecosistemas basados en cereales e identificar problemas que puedan restringir el funcionamiento de los sistemas cultivo-ganado en función de los flujos de N (Nitrógeno) (Capítulo 2); 2) explorar las percepciones de los agricultores acerca de las innovaciones asociadas con la integración cultivo-ganado (Capítulo 3);

explorar y explicar compensaciones asociadas con la integración de la integración cultivo-ganado; y respuestas potenciales de los componentes de los sistemas agrícolas a causantes externos (Capitulo 4 y 5). Finalmente, explicar los cambios históricos que han ocurrido en los sistemas agrícolas de las colinas y los causantes que han producido la intensificación agrícola para explorar potenciales trayectorias futuras (Capítulo 5).

Esta tesis utiliza una diversidad de métodos de ciencias duras y suaves combinando métodos cuantitativos: experimentos de cultivo intercalado/mixto en campo. Análisis de Redes Ecológicas, uso de modelos biofísicos y socio-económicos; y métodos cuantitativos como: Mapeo Cognitivo Difuso, entrevistas y grupos de discusión en finca con los agricultores.

El Capítulo 2 explora el concepto de robustez de los flujos de nutrientes. Los resultados principales demuestran que las fincas de diferentes agroecosistemas reciclan solo una pequeña porción de los ingresos de N (<15%) y por consiguiente producen grandes cantidades de pérdidas de N (63-1135 kg N por ha por año). Además, las fincas muestran gran dependencia a importaciones de N en forma de forraje (autosuficiencia de forraje 11-43%). Así mismo, las redes de N son organizadas (alta productividad) pero inflexibles (baja resiliencia) y consecuentemente desequilibradas (baja robustez). Sin embargo, los escenarios de manejo mejorado muestran que la producción de cultivo puede ser mejorada produciendo disminución en la importación de forraje y por consiguiente menos pérdidas de N. Consecuentemente, las redes de N aumentan su flexibilidad, lo que resulta en niveles más altos de robustez de las redes de N en las fincas estudiadas.

En el capítulo 3, los resultados de un proyecto de dos años de duración que incluyó investigación participativa orientada al agricultor muestran que: 1) la productividad se puede incrementar sustancialmente mediante métodos de intensificación; 2) el involucramiento activo de los agricultores en experimentos en sus fincas, contribuyen a un mayor entendimiento de importantes factores para la toma de decisiones para adoptar o no prácticas mejoradas.; y 3) el involucramiento de los agricultores influenció positivamente sus percepciones acerca de la adopción de prácticas innovadoras. A pesar de que un incremento significativo de la productividad fue demostrado gracias a las prácticas mejoradas, los factores sociales y culturales limitan la efectiva adopción de las prácticas.

El capítulo 4 muestra como los agricultores identifican compensaciones entre los beneficios del aumento de ingresos y de abono gracias a la intensificación de ganado versus incrementos en los requerimientos de trabajo para la importación de forraje. Aquí se demuestra que los agricultores no están dispuestos a hacer inversiones adicionales en producción de forraje en sus fincas, porque perciben a esta producción insuficiente para cerrar la creciente brecha de alimentación que involucra el incremento de ganado. Las mismas limitaciones fueron mencionadas independientemente del nivel de dotación de recursos de los agricultores. A si mismo, un análisis de sensibilidad demuestra que dada la percepción de los agricultores, un aumento en la demanda del mercado de la leche podría tener efectos positivos sobre la producción ganadera y los ingresos en la finca.

El capítulo 5 identifica los principales causantes asociados a la intensificación sostenible que han ocurrido en los sistemas agrícolas de las colinas desde 1985. Estos causantes están basados en el acceso a insumos agrícolas como variedades mejoradas de semillas y ganado. Este acceso ha sido consecuencia de la mejora en conectividad y acceso a los mercados; la misma que ha sido estimulada por políticas agrícolas y proyectos de desarrollo. De forma similar, el análisis de compensaciones de dos escenarios contrastantes: 1) finca especializada en producción de ganado de leche versus 2) típica finca mixta, mostraron que hay más espacio para mejorar la configuración de estos sistemas agrícolas minimizando la compensación entre la intensificación de ganado (ganancia)por un lado, y perdida de N y el tiempo de descanso por otro lado en la finca especializada. Esto es asociado al mayor tamaño de la esta. En el escenario de mayor productividad de cultivo, los costos totales aumentarían debido a un menor margen bruto asociado con el aumento de costos de las tecnologías mejoradas.

Finalmente, en el capítulo 6, los resultados son resumidos, se discuten temas claves y se presenta las principales conclusiones y recomendaciones.

कम र कम-मध्यम आय भएका देशहरुमा ग्रामिण समुदायलाई खुवाउन स-साना खेति प्रणालीले मुख्य खाद्यवस्तुहरुको योगदानको माध्यमबाट महत्वपुर्ण भुमिका खेल्दछन् । साना किसानको योगदान (जस्तै दक्षिण एशियाली देशहरुमा) समुदायमा बढि भन्दा बढि ३०% जति अनुमान गरिएको छ । साना खेतिकिसानीलाई मिश्रित कृषि प्रणाली भनि बर्गिकरण गरिएतापनि बालीनाली र पशुवस्तुको उत्पादन सामान्यता कम देखि मध्यम स्तरको सघन्तामा हुन्छ । नतिजा स्वरुप यी खेती प्रणाली प्रायजसो खाद्य असुरक्षाले प्रभावित हुन्छन् । यस बाहेक दुर्त गतिमा बढि रहेको जनसंख्यालाई पशुजन्यबाट पाइने प्रोटिनको माग पनि बढ्ने अनुमान गरिएको छ । तसर्थ खाद्य उत्पादकत्व बृद्धि गर्न अति आवश्यक छ । जबकि दिगो उत्पादकत्व हासिल गर्नका निम्ति प्राकृतिक श्रोतहरु संतुलनमा राखि बाह्य कृषि सामाग्रीको प्रयोग कम गर्दै लैजानुपर्दछ । तसर्थ यो शोधपत्रले नेपालको साना खेति प्रणालीहरुमा दिगो सघन खेति हासिल गर्न आवश्यक विकल्पहरुको अध्ययन गरेको छ ।

नेपालमा गरिने धेरै जसो खेति प्रणाली सानो आकारको खेतिको रुपमा चिनिन्छ । यी खेति प्रणाली मिश्रित छन किनभने यी अनाज (मकै, गहुँ र धान) र पशुपालनको संयोजनमा आधारित छन् । दुवै (अनाज र पशुपालन) आयआर्जनका श्रोतको साथै खाद्य अभावको बेला खाद्य भण्डार हो । यसबाहेक पशुपालनबाट बालीलाई उर्वर गर्न मल र खेत जोत्नको लागि हलको रुपमा प्रदान हुन्छ । यद्यपि नेपालमा बालीनाली र पशुपालन प्रणालीहरुका उत्पादकत्व कम छन् । थप रुपमा भुमि खण्डिकरणका कारण खेतियोग्य जमिन निरन्तर आकारमा कम हुदैछन् । त्यसैले कृषि सघन्ता प्राप्त गर्नका लागि उत्तम एकिकृत बालीनाली र पशुपालन उपप्रणालीको महत्व नेपालको कृषि पारिस्थितिकी प्रणालीको सन्दर्भमा आशाजनक हुनसक्छ । एकिकृत बालीनाली र पशुपालन प्रणालीले दिगो खेति प्रणालीको प्रभावकारी योजना बनाउनमा योगदान पुरयाउन सक्छ किनभने तिनीहरुले माटो, बोटबिरुवा, जनावर र वातावरण बीचको सहकार्य प्राप्त गर्ने लक्ष्य राख्दछन् ।

यस शोधपत्रले एकिकृत बालीनाली र पशुपालनलाई किसानको दृष्टिकोणबाट नेपालमा खाद्यान्नमा आधारित खेति प्रणालीमा दिगो सघन खेति प्राप्त गर्ने मार्गको रुपमा अन्वेषण र मुल्याङ्कन गरेकोछ ।

शोधपत्रको उदेश्य (अध्याय १) १) खाद्यान्नमा आधारित कृषि प्रणालीको विविधताको वर्णन गर्ने र नाइट्रोजन प्रवाह हुने बालीनाली र पशुपालन खेति प्रणालीमा बाधा पुरयाउने कारक तत्वहरु पहिचान गर्ने , (अध्याय २) २) एकिकृत बालीनाली र पशुपालन प्रणालीका लागि नविन कृषि प्रविधिहरुमा किसानहरुको धारणा अन्वेषण गर्ने (अध्याय ३) ३) एकिकृत बालीनाली र पशुपालन प्रणालीसँग सम्बन्धित समझौताकारी समन्यवयहरुको साथै बाह्य कारक तत्वहरुमा कृषि प्रणाली घटकहरुको सम्भावित प्रतिक्रियाहरु पत्ता लगाउने र व्याख्या गर्ने, (अध्याय ४ र ५) मध्यपहाडी खेति प्रणालीमा भएका विगतका परिवर्तनहरु र कृषि सघन्तालाई प्रभाव पार्ने कारक तत्वहरुको वर्णन गर्ने, (अध्याय ५) सम्भावित भावि मार्गनिर्देशनहरुको अन्वेषण गर्ने ।

यस शोधपत्रले बिज्ञानहरुको विविध मापन विधिहरुको प्रयोग गरि अध्ययन गरेको छ : घुसुवा बाली प्रविधिको प्रयोग, पारिस्थितिकिय संजाल विश्लेषण, जैविकभौतिक तथा सामाजिकआर्थिक विश्लेषण तथा प्रक्षेपण र अर्ध मापन विधिहरु : फजी कगनिटिभ नक्शांकन, अनतरवार्ता र किसानहरुसँगको छलफल ।

अध्याय २ ले खाद्यतत्व प्रवाहको लागि बलियो अवधारणाको खोजी गरेको छ । विभिन्न कृषि प्रणालीमा प्रयोग गरिएका नाइट्रोजन मध्ये थोरै मात्रामा (<१५%) उक्त नाइटोजन पुन : प्रयोगमा ल्याइएको छ र धेरै मात्रामा (६३ - ११३५ नाइट्रोजन प्रति हेक्टर प्रति वर्ष) नोक्सान भइरहेको यस अध्ययनले देखाउँछ । यसबाहेक, घाँसको रुपमा नाइट्रोजन आयातमा उच्च निर्भरता देखिन्छ (दाना आत्मा निर्भता ११-१३ %) । यसबाहेक, खेतबारीमा नाइट्रोजन संजाल संगठनात्मक (बढि उत्पादकत्व) भएतापनि नाइट्रोजन प्रवाह असंतुलित देखिन्छ । यद्यपि सुधारिएको व्यवस्थापनको परिदृष्यले बाली उत्पादनलाई सुधार गर्न सकिन्छ भनेर देखाउँदछ जसले घाँसको आयात र नाइट्रोजन क्षति घटाउँछ । फलस्वरुप, अनुसंधान गरिएको खेति प्रणालीमा उच्च स्तरको नाइट्रोजन प्रवाह पाइएको छ ।

सारांश

अध्याय ३ मा दुई वर्ष किसान उन्मुख सहभागितामुलक अनुसंधान परियोजनाको माध्यमबाट गरिएको परिणामहरु देखाइएको छ : १) सघन्ताका विधिहरु मार्फत प्रयाप्त उत्पादकत्व सुधार गर्न सकिन्छ , २) किसानहरुको सकृय सहभागितामा खेतबारीमा गरिने अनुसंधानले कुनै पनि उन्नत प्रविधि अपनाउने वा नअपनाउने भनि किसानहरुले लिने निर्णयका कारक तत्वहरुको बुझाइमा वृद्धि हुन्छ र ३) किसानहरुलाई प्रत्यक्ष संलग्न गराउनाले नविन प्रविधि अपनाउने तर्फ कृषकहरुको धारणामा सकरात्मक प्रभाव पार्दछ । उन्नत प्रविधि अपनाउदा उत्पादकत्वमा बृद्धि देखिएता पनि सामाजिक र सांस्कृतिक कारक तत्वहरुले गर्दा अझै पनि प्रविधिहरु छिटो अभ्यासमा ल्याउदैनन् ।

अध्याय ४ ले सघन पशुपालनबाट हुने बढ्दो नगदी आमदानीका लाभहरुको साथै मल आपुर्ति र घाँस आयात गर्दा लाग्ने श्रमको आवश्यक्ता वीच सम्झौतारी समन्वयन किसानहरुले कसरी पहिचान गर्दछन् भनि देखाउँछ । किसानहरु खेतबारीमा घाँस उत्पादनमा थप लगानी गर्न इच्छुक हुदैनन् किनभने उनीहरुलाई यी अतिरिक्त पशुवस्तुहरुको परिणामस्वरुप चाहिने घाँस प्रयाप्त मात्रामा पुग्दैनन् भन्ने सोँच किसानहरुमा छ भन्ने यस अध्ययनले देखाउँदछ । किसानहरुको लगानीयुक्त श्रोतको अवस्था जस्तो भएतापनि यी बाधा समान छन् भनि उल्लेख गरिएको छ । यसबाहेक, संवेदनशीलता विश्लेषणले किसानको धारणालाई ध्यानमा राख्दै दुध बजारको माग बढेमा पशुपालन उत्पादन र कृषिमा हुने आयमा सकरात्मक प्रभाव पार्न सक्छ भनि देखाउँदछ ।

अध्याय ५ ले सन् १९८५ देखि मध्य पहाडको खेति प्रणालीमा भएको कृषि सघन्ताका मुख्य कारक तत्वहरु पहिचान गर्दछ । यी कारक तत्वहरु उन्नत वीउ र पशुपालन जस्ता कृषि सामाग्रीको पहुँचमा आधारित छन् । यो सुधारिएको बजार संजाल र बजारमा पहुँचको एक परिणाम हो , जुन कृषि निति र विकास परियोजनाहरुले प्रोत्साहित गरेका छन् । यसबाहेक, दुई विरोधाभासी परिदृश्यहरुको विश्लेषण देखाइएको छ : १) विशेषत दुग्धगाई पालन र २) औसत मिश्रित खेति प्रणाली । एकातर्फ पशुपालन सघनता (नाफा) र अर्कोतर्फ नाइट्रोजन क्षति र फुर्सदमा गरिने विशेष खेति बीचको समझौताकारी समन्यवयलाई घटाएर खेति प्रणालीमा सुधार ल्याउन सकिन्छ । यो ठूलो आकारको जग्गा भएकाहरुसँग सम्वन्धित छ । उच्च बाली उत्पादकत्वको परिदृष्यमा, उन्नत प्रविधिको लागतमा वृद्धि र धेरै मात्रामा नाफामुलक हुने भएकोले कुल लागत बढ्ने छ ।

अन्तमा, अध्याय ६ मा निष्कर्षहरु सारांशमा राखिएका छन् ,मुख्य विषयवस्तुहरु छलफल गरिएका छन् र मुख्य निष्कर्ष र सिफारिसहरु प्रस्तुत गरिएका छन् ।

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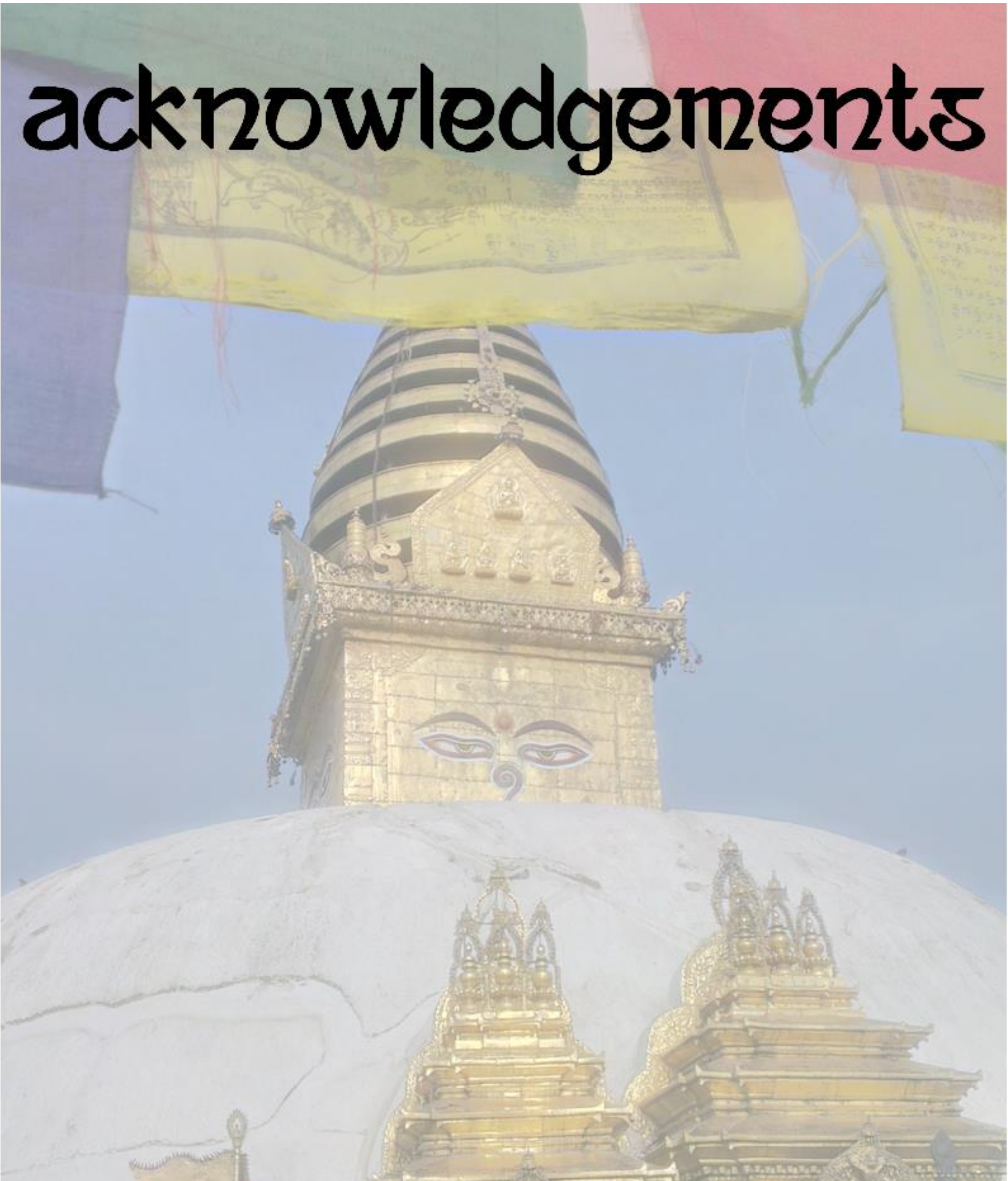

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María Victoria Alomia Hinojosa was born in Quito, Ecuador, on August 6, 1983. She started her BSc studies in Agribusiness Engineering at the Universidad San Francisco de Quito (USFQ) in Ecuador. In 2003, she received a scholarship to study her junior year in Oregon State University, USA. In 2006, she graduated cum laude at USFQ. Following her graduation, she worked as an assistant manager at Sande Ecuador, where she was responsible for the sustainable social-environmental programs and labels certification processes of this (Dutch) flower company.

In 2010, she was awarded a full fellowship from the Netherlands Fellowship Programme (NFP-NUFFIC) to pursue her MSc studies at Wageningen University where she enrolled in the Plant Sciences programme with a specialization in Natural Resources Management. During her MSc studies, she completed her major MSc thesis at the former Biological Farming Systems Group at Wageningen University. Her major thesis focused on determining yield gaps due to water limitation and soil fertility, for which she performed field experiments in Hawassa, Ethiopia.

For her MSc internship at the Royal Tropical Institute (KIT) in Amsterdam, she focused on gender equity in certified coffee, cocoa and tea value chains. Her research revolved around the position of women in value chains, and the role of socio-certifications addressing and supporting gender equity. Upon completion of her MSc studies in 2012, she continued working at the KIT and similar projects, and facilitated a stakeholder workshop in Yogyakarta, Indonesia.

In 2013, María Victoria started her PhD studies at the Farming Systems Ecology Group (FSE) at Wageningen University, of which this thesis is the result. She focused on the sustainable intensification of cereal-based agro-ecosystems through crop-livestock integration and diversification in the Terai and Mid-hills of Nepal. For this project, she performed extensive field campaigns in Nepal in 2013, 2014 and 2015. She presented the outcome of her research at scientific conferences in Montpellier (France 2015), Vienna (Austria 2016), and Guayaquil (Ecuador 2018).

In 2018, María Victoria returned to Ecuador where she became the mother of Nina Sofie.

List of Publications

Peer reviewed journal articles

Alomia-Hinojosa, V., Speelman, E.N., Thapa, A., Wei, H.-E., McDonald, A.J., Tittonell, P., Groot, J.C.J., 2018. *Exploring farmer perceptions of agricultural innovations for maize-legume intensification in the mid-hills region of Nepal*. International Journal of Agricultural Sustainability 16, 74-93. https://doi.org/10.1080/14735903.2018.1423723

Alomia-Hinojosa, V., Groot, J.C.J., Speelman, E.N., Bettinelli, C., McDonald, A.J., Tittonell, P., 2020. *Operationalizing the concept of robustness of nitrogen networks in mixed smallholder systems: A pilot study in the mid-hills and lowlands of Nepal*. Ecological Indicators 110, 105883. https://doi.org/10.1016/j.ecoloind.2019.105883

Conference/Symposium Proceedings

Alomia-Hinojosa, V., Groot, Bettinelli, McDonald, Alvarez, Tittonell (2015); Crop-livestock integration of cereal-based mixed farming systems in the Terai and Mid-hills of Nepal. In: Farming Systems Design 5; Montpellier- France. *Poster presentation*

Alomia-Hinojosa, V., Speelman, Thapa, Wei, McDonald, Tittonell, Groot (2016); Participatory maize-legume experiments as a tool to explore social-ecological niches for innovation adoption in small scale farming systems. In: Tropentag; Vienna-Austria. *Poster and oral presentation*

Alomia-Hinojosa, V., Groot, Bettinelli, McDonald, Alvarez, Tittonell (2018); Operacionalización del concepto de robustez de las redes de nitrógeno en sistemas agrícolas de pequeña escala. In: “VII Congreso Latinoamericano de Agroecolgía”; Guayaquil-Ecuador. *Oral presentation*

PE&RC Training and Education Statement

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Overview of frameworks for socio-ecological analysis of agro-ecosystems to support sustainable intensification and adaptation

Writing of project proposal (4.5 ECTS)

- Sustainable intensification of cereal-based agro-ecosystems through crop-livestock integration and diversification in the Terai and Mid-hills of Nepal

Post-graduate courses (5.1 ECTS)

- Sampling in space and time for survey and monitoring of natural resources; PE&RC (2013)
- Companion modelling; ForDev group, ITES, ETHZ (2014)
- R statistics introduction; PE&RC (2014)
- The art of Modelling; PE&RC (2015)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Fields Crop Research: soil fertility and annual crops nutrition and grain yields in a tropical region (2013)
- Agricultural Systems: bridging the gap between scientists' theory and farmers' practise (2016)

Competence strengthening / skills courses (2.4 ECTS)

- Competence assessment; WGS (2013)
- Teaching and supervising thesis students; WGS (2013)
- Project and time management; WGS (2014)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.1 ECTS)

- PE&RC First years weekend (2013)
- PE&RC Last years weekend (2016)
- PhD Carrousel (2017)
- PhD One day symposium (2017)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- SIAS-Sustainable Intensification of Agricultural Systems (2013-2016)

International symposia, workshops and conferences (6.6 ECTS)

- International Symposium for Farming Systems Design; Montpellier, France (2015)
- Tropentag; Vienna, Austria (2016)
- VII Latin American Congress of Agroecology; Guayaquil, Ecuador (2018)

Lecturing / supervision of practicals / tutorials (1.8 ECTS)

- Analysis and design of biological farming systems (2013)
- Integrated natural resource management in organic agriculture (2014)

Supervision of MSc students (5 ECTS)

- Quantification of crop-livestock integration and diversity of farm-household systems using ecological network analysis in two regions of Nepal: Terai valley and mid-hills
- On-farm evaluation of maize and legume intercropping for improved crop productivity in the mid hills of Nepal
- Field evaluation of maize-legume intercropping systems in the mid-hills of Nepal
- Exploring options to reduce nutrient losses in the mid-hills of Nepal
- Trajectory of change in cereal-based farming system in Terai and mid-hills of Nepal

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FARMER PESRPECTIVES ON SUSTAINABLE CROP- LIVESTOCK INTEGRATION IN CERAL BASED FARM SYSTEMS OF NEPAL

VICTORIA ALOMIA - HINOJOSA