Piecing together complexity:

the co-evolution of agroecosystem patterns & natural resource management

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Contents

Chapter 1: Introduction

1. Background

Walking through rural landscapes in the Ecuadorian Andes one is struck by the complex and intricate relationship between the farming families who live there and the agroecosystems upon which they rely for their livelihoods. Not only do the agroecosystems of the these landscapes provide a means for agricultural production, they also provide a range of other critical ecosystem 'services' for broader society, such as watershed protection (Buytaert et al., 2009), carbon storage (Henry et al., 2013; Lorenz and Lal, 2014), and the conservation of regional biodiversity (Lawler et al., 2009). Despite their importance, these agroecosystems are threatened by severe land degradation processes and the risks associated with climate change (Fonte et al., 2012).

Specifically, the steep slopes of these mountainous agroecosystems mean that the landscapes are inherently susceptible to erosion. Two studies in the Ecuadorian Andes, one located close to the main study site in this thesis, found sediment loss in rural landscapes to range from 0.26 to 151 Mg ha^{-1} $year^{-1}$ with an overall average soil loss of between 22-27 Mg ha^{-1} $year^{-1}$ (Henry et al., 2013; Molina et al., 2008). In addition to the loss of important soil nutrients required for agricultural production, soil erosion also leads to the loss of soil structure and biological activity, which play a critical role in soil water retention, nutrient recycling, root penetration and the overall productivity of agricultural lands (Bronick and Lal, 2005; Lal, 2001). While the loss of soil nutrients can be compensated for through the incorporation of more fertilizers, the rehabilitation of overall soil health and productivity is a much slower process (Fonte et al., 2012).

In addition to the inherent erosion processes of these mountainous landscapes, land degradation in the rural Andes is also being driven by negative nutrient balances where small-scale farmers are unable to replace the macronutrients (nitrogen (N), phosphorus (P) and potassium (K)) lost through the harvest and export of crops away from fields (Bahr et al., 2014; De Koning et al., 1997; Vanek and Drinkwater, 2013). A major reason for the pervasive trend of negative nutrient balances within the rural Andes is that the smallholder farmers that live there generally have limited access to agricultural inputs, due to both a low financial resource base to invest in agricultural inputs and their remoteness from population centres (Fonte et al., 2012).

SOM balances are often also reported to be negative under agricultural land-use as a result of agricultural management techniques that accelerate degradation by increasing the aeration of soils through ploughing for example. Indeed, in a study undertaken in the Southern Ecuadorian Andes, SOM levels under annual agricultural land-use were observed to be 15% lower than those of forest sites, which, according to the authors, pointed towards a non-sustainable management of the land (Bahr et al., 2014). SOM, in particular is critical to maintaining soil health, by supporting biological activity and diversity (Moore et al., 2004) and regulating soil processes linked to agroecosystem functions such as nutrient cycling, plant growth, soil aggregation (structure), and water storage (Barrios, 2007; Bronick and Lal, 2005; Lavelle et al., 2006).

Given the strong influence of climate on productivity and key soil processes, climate change must also be considered as a major risk to these agroecosystems in the future. Air temperatures along the Andean Cordillera have already increased at faster rates than those at lower elevations (Bradley et al., 2009; Diaz et al., 2003). As a consequence, vegetation in Peruvian mountain regions has shifted to higher elevations (Lutz et al., 2013). Moreover, Kohler et al., (2014) suggested that the freezing point may rise several hundred meters over the next century and that this phenomenon may affect tropical mountain ecosystems more than those at higher latitudes. While a slight increase in temperature in these relatively cool climates high in the Andes may increase the productivity potential, it is also important to highlight that climate change is also likely to bring more erratic precipitation patterns, increased risk of hail damage, and greater evapotranspiration rates (Kohler et al., 2014), posing major threats to these rain-fed farming systems.

Coupled with these pervasive threats to the agroecosystems of the region of study, rural Andean landscapes are characterised by high levels of socio-ecological heterogeneity where elevation-induced climate gradients create many different environmental niches (Mayer, 2002). SOM, for example, generally increases with elevation in mountainous regions (e.g., Leifeld et al., 2009; Nottingham et al., 2015) due to the greater accrual of SOM in cooler, moister climates that slow organic matter decay (Lavoie and Bradley, 2003; Zehetner and Miller, 2006).

These biophysical and associated agroecosystem patterns, in turn, shape farmers' agricultural practices and often result in different agricultural management zones across the landscape, where farmers' fields located in each zone are managed distinctly in terms of crops grown, resource allocation, soil preparation, among other factors (Li et al., 2013; Mayer, 2002). Such differentiated farming practices then feedback into the agroecosystems patterns of the landscape generating complex patterns, often with non-linear responses to landscape gradients.

Understanding such complex socio-ecological relationships between farming practices and landscape dynamics is critical to the development of more successful developmental and natural resource conservation intervention strategies that are required to address the challenges of land degradation and climate change (Rammel et al., 2007). Unfortunately, these relationships still remain underexplored and poorly understood (Benoît et al., 2012). While a number of conceptual models, such as the Household Lifecyle Theory (Thorner et al., 1986); the Forest Transition Theory (Mather, 1992); the New Economics of Labour Migration (Stark and Bloom, 1985), have been posited to shed light on the social and environmental trends and relationships found between farm and land management and agroecosystems, the scientific literature often uncovers inconsistent and even contradictory findings, suggesting that the theoretical frameworks to date may be overly rigid or deterministic.

Based on a framework of Complex Adaptive Systems (CAS) for the purposes of understanding critical environmental challenges within a social context (Cumming, 2011), the recently emerging Socio-Ecological Systems (SES) framework represents great promise in terms of providing deeper insights into the inter-relationships between farm and land management, agroecosystems and associated socio-ecological factors. With its origins in complexity theory, the CAS framework can better account for inconsistencies found in land and farming systems, and agroecosystem research literature, as the framework posits that localised responses are context-specific and therefore variables are non-deterministic (i.e., instrumentally dependent on interactions and relationships with other variables). Instead of purporting direct linear relationships, this framework also postulates phenomena such as non-linearities, thresholds, alternative stable states, feedbacks and self-organization (Norberg and Cumming, 2008).

The overall objective of this PhD project was therefore to contribute to the understanding of some of the main relationships between land and farm management, agroecosystems and socio-ecological variables, shed a new light on how farm and land management and agroecosystems patterns have co-evolved within this particular socio-ecological context in the Ecuadorian Andes, and provide an empirical case-study as to how the SES and CAS frameworks could be used to inform more contextualised (and arguably effective) natural resource management and intervention strategies. In line with the SES framework, a diverse range of methodologies from different disciplines was employed. Critical to the CAS management approach, the research was conducted as part of a broader process of co-learning and co-evolution (Rammel et al., 2007) with a group of farmer 'researchers' as well as professors and students from a local university and key policy makers and intervention agents who became intricately involved in this action-research, from planning to data collection and analysis. The work of this group culminated in the co-development of a "Landscape Level Natural Resource Management Plan" that aimed to identify and outline pathways for more contextualised natural resource management and intervention strategies for the main community of study.

2. Complex adaptive systems

2.1. Panarchy

One of the central concepts to CAS is that of '*panarchy*', which seeks to describe how complex systems, comprised of people and the natural environment, are dynamically organised and structured in 'context' – i.e., in space and time (Gunderson and Holling, 2002; Holling, 2001). The concept postulates that component systems or adaptive cycles come to be organised in a nested hierarchy, in such a way that allows for cross-scale interactions, whereby top-down and bottom-up processes may occur. A simplified example of such a structure in a socio-ecological system found in the rural context could be one that envisages the interconnections between national policies with regard to food and agriculture; local market demand for agricultural products and accessibility; the agroecosystems of the landscapes upon which the farming families rely for their livelihoods; the farm; and individual field fertility (Figure 1).

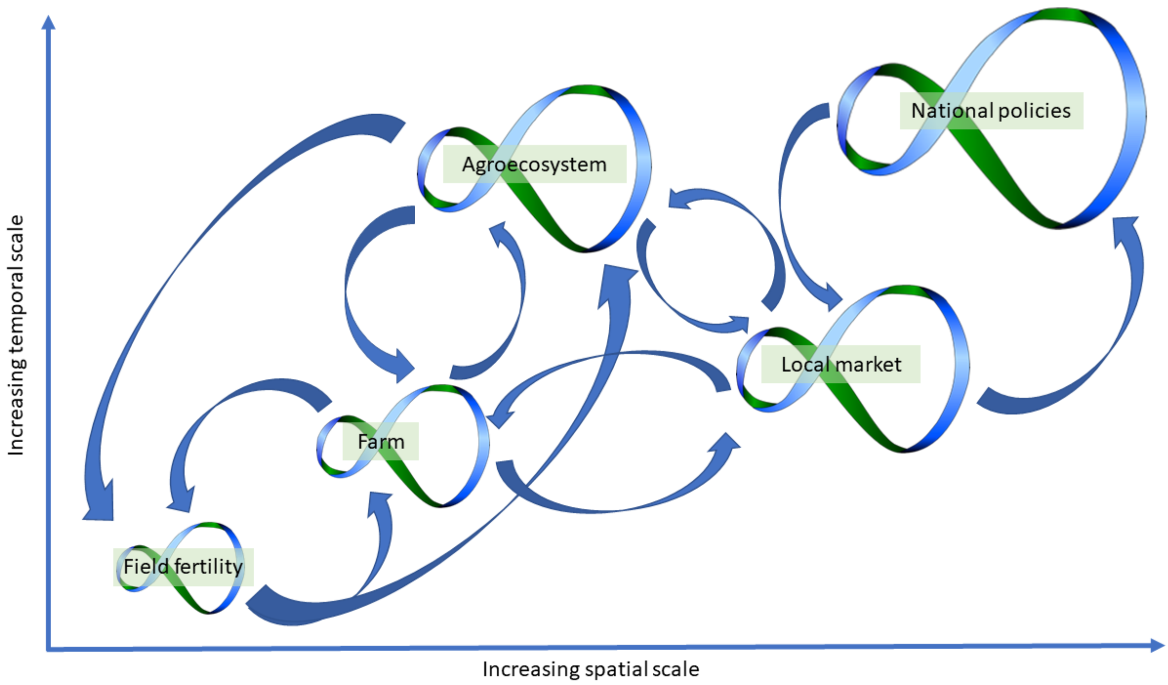

Figure 1: *Panarchy of nested hierarchies depicting the interactions between different adaptive cycles across space and time.*

In this example (Figure 1), farms are moulded by agroecosystems and local markets, which are influenced by national policies with regard to agriculture and food. It also indicates that the fertility of individual fields on a farm are both influenced by the farm (management) and the broader agroecosystem. However, it also suggests that the influence is not unidirectional but that feedback loops exist such that individual fields and farms also influence the agroecosystem, and farms affect local markets and local markets may influence national policies. Identifying these cross-scale relationships and interactions is not only critical to scientifically testing the theoretical concepts of panarchy, CAS and SES, but it provides critical insight into the points in the complex adaptive system where transformation is most easily implemented – through strategic interventions to enable more sustainable management of a landscape (Allen et al., 2014).

2.2. Asymmetries, feedback loops and self-organisation

Another important concept for SES and CAS theory is that of asymmetry, in that asymmetries are expected to be found in such systems (Cumming, 2011). As understood in CAS theory, asymmetries are characterised as non-random or systemic variation. This definition is an important point of differentiation with the term 'heterogeneity', which also refers to variation, but to a variation that does not necessarily have to be asymmetric in character (Van Apeldoorn et al., 2011). Heterogeneous variation would therefore apply to the case where the cropping choices of a rural family, for example, varies randomly across a landscape. However, in the case that cropping system differentiation is tied to a particular factor or set of factors, an asymmetrical 'pattern' may emerge where, for example, farmers at lower elevations of the landscape organize around a certain cropping system, while those at higher elevations develop an alternative cropping approach.

In this example, asymmetries are not only present in the responses to an elevation gradient (cropping patterns adopted by farmers), and the emergent properties resulting from the responses to the elevation gradient in the landscape patterns (spatial distribution of cropping systems across the landscape), but are also inherent to the system in that the climate associated elevational gradient is a 'driver' of the observed patterns. This observation is important within the concept of CAS as it demonstrates how the concept of a panarchy of nested hierarchies links pattern to process.

Taking this point a step further, the presence of asymmetric patterns also suggests that system features may emerge from a process of self-organisation (Green and Sadedin, 2005). The key to self-organisation is the existence of feedback loops between the nested hierarchy of adaptive cycles. Again, taking the elevation gradient within a landscape as an example, the climatic suitability for the cultivation of a certain crop and the elevation induced climate gradient, can temporarily drive diverging cropping dynamics, where the crops grown at higher elevations are different to the ones grown at lower elevations. If, for example, the market value for one of these crops is higher than the other crop, farmers growing the first crop (crop 1) may be incentivised to invest more in fertilizer inputs to maximise production, than those growing the second crop (crop 2). This differentiated farm management may in turn lead to important differences in soil fertility between farms in the different parts of the landscape which will eventually feedback into the cropping patterns, farm management and income generated by farmers. The farmers originally growing crop 1 for instance, with greater returns on their investment due to the higher value of their crops, may become more prosperous and therefore able to continue to invest in soil fertility, further increasing productivity and prosperity. The farmers originally growing crop 2 on the other hand may fall into a 'poverty trap' (Tittonell and Giller, 2013) where, due to the lower return on investment from the crops they can cultivate, their lower investment in soil fertility leads to decreasing soil fertility and productivity, meaning less financial resources to invest in soil fertility management, further aggravating the decrease in soil fertility and productivity. Such feedback loops across scales can be characterised as self-organisation, where the cross-scale interactions between adaptive cycles lead to the co-evolution of the overall system.

2.3. Regimes (stability landscapes) & regime shifts (transformations)

The result of the self-organising systems located within a panarchy of nested hierarchies discussed above can be conceived of as the development of a system regime, a set of characteristics or features that best describes the behaviour of a particular adaptive cycle at a particular level of granularity in space and time (Tittonell, 2014). Figure 1, for example, draws on the concept of panarchy to stylistically summarise how the 'farm', as a system regime, is constrained and influenced by the nested hierarchies above and below it. The 'robustness' or 'resilience' to change of these system regimes are therefore constrained by the linkages with the nested hierarchies. Accordingly, if there are very strong constraining factors at each level, it is less likely that the characteristic features of the system regime will change should a 'perturbation' occur in the system (e.g., a drought or a crash in the market price of a cash crop). In other words, the system regime can be considered 'resilient' to change, or where the 'threshold' needed to instigate a regime change is large. However, if the constraining factors found in the levels above and below the system regime in focus are weak, only a small perturbation in the system may initiate a 'regime shift' or 'transformation' whereby the characteristic features of the system regime change into another 'alternate' regime (e.g., the abandonment of farming or the re-orientation of livelihood strategies to rely on out-migration labour opportunities). Such regimes may be considered 'vulnerable' (Adger, 2006).

These ideas have been conceptualised in a seminal paper by Scheffer et al. (2001) using the concept of landscape stability (stylised in Figure 2 below). The 'basins of attraction' can be compared to system regimes that have co-evolved from a panarchy of nested hierarchical influences. The deeper the basins, the more robust or resilient their system regime. Each ball in the figure depicts an individual system that moves between these basins of attraction adopting the same characteristics and features common to the basin of attraction. The concept of 'thresholds' is also important here, for regime shifts to occur the balls must move out of the basin of attraction to a point where the ball finds itself in another basin of attraction. The point at which the ball passes from one basin of attraction to another can be said to be a threshold (Tittonell, 2014).

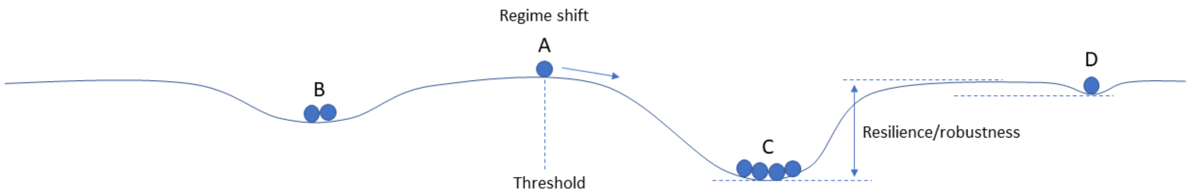

Figure 2: *A stylisation of Scheffer et al. (2001) Stability Landscapes concept. Basins of attraction (regimes) are depicted by troughs, in which individual systems gather. Ball A represents the process as a system experiences a regime shift moving beyond the threshold of the basin of attraction where Balls B are located into the basin of attraction where Balls C are located. The basin of attraction in which Ball D is located represents a system regime with very low resilience (to change), whereas the basin of attraction in which Balls C are located represents a system regime with high resilience.*

Research questions associated with SES, especially those related to natural resource management and rural development, sit within a social context that can generate important recommendations that can affect people's livelihoods (Cumming, 2011). Normative questions may therefore also arise, such as whether certain system regimes are preferable to others. Indeed, depending on one's perspective, one system regime may be preferable to one person, while another preferable to a different person. It is therefore important to highlight that a system regime's resilience or robustness to change is not associated with desirability. In some cases, it may be preferable to instigate regime shifts, while in others it may be preferable to increase 'resilience'. When aiming to increase the resilience of a (preferred) system regime, it is of particular importance to explore mechanisms to enhance its 'adaptive capacity', or its ability to recover performance after perturbations to the system or when new elements have been introduced into the system (Groot et al., 2016).

3. Application of SES and CAS in research related to farming and agroecosystems

Some notable examples exist where the theoretical frameworks of SES and CAS have been applied and tested in empirical research related to farming and agroecosystems (e.g., Downey, 2010; Easdale et al., 2016; Vallejo-Rojas et al., 2016). One such example is that of a study conducted in a traditional rural landscape in the north of the Netherlands (Van Apeldoorn et al., 2013). This study found that landscape patterns and agricultural intensification co-evolved such that production intensity was found to differ with the landscape pattern of clay content and groundwater hydrology, and with farming system differences (such as larger fields, fewer hedgerows, fewer grazing days, higher use of N-fertilizer and a decrease of nutrient cycling). Van Apeldoorn et al. (2013) speculated that the largest differences observed between fields (found for similar values of clay content, groundwater hydrology and fertilizer use) represented potential tipping points or thresholds.

Another study used the SES and CAS frameworks to assess the vulnerability and resilience of two dairy farms in Michoacán State, Mexico (Groot et al., 2016). Using the FarmDESIGN model (Groot et al., 2012) which explores alternative farm configurations using a Pareto-based multi-objective optimization algorithm, the authors assessed the adaptive capacity of the two farms following a perturbation to the farming systems as a result of a forage maize yield loss. The results of the study demonstrated how a system reconfiguration could play an important role in increasing the potential adaptive capacity of agricultural systems as well as reducing the impact from disturbances (Groot et al., 2016). Notwithstanding these examples however, while the use of the SES and CAS frameworks have been steadily increasing in peer-reviewed literature over the past decade or two, their use remains primarily descriptive and abstract (Allen et al., 2014).

Two recent papers, in particular, explore how the SES and CAS frameworks may be better tested empirically and operationalised in the future. The first, authored by Allen et al. (2014), outlines three core propositions related to the structure of complex systems that follow from the Panarchy Theory. These propositions state that: complex systems are discontinuously structured; complex systems undergo cycles of renewal and collapse; and cross scale linkages are critical to system structure. Under these propositions Allen et al. (2014) suggest different hypotheses for empirical investigation such as “small scale variables should, sometimes, control system dynamics (bottom-up control)” and “functions should be distributed non-randomly with respect to scale”.

Descheemaeker et al. (2016) focus on how the SES and CAS frameworks may be better operationalised in order to facilitate the co-development of more contextualised agricultural improvement options. In this paper the authors outlined different participatory methodological approaches that should be used in parallel in a process of co-learning to develop a richer contextual understanding of the challenges and opportunities faced by farmers thus facilitating the co-development of agricultural improvement options at different scales (regional, village, farm and field) (Descheemaeker et al., 2016). Such an approach helps reveal constraints and risks faced by farmers that often can prove to be important barriers to the adoption of technocratic blanket recommendations. The authors also highlight the importance of creating enabling policies and institutions that may improve the larger-scale context (Descheemaeker et al., 2016).

4. Methodology and hypotheses

4.1. Study sites description

The field work for the research took place between April 2015 and September 2017 in four indigenous Kichwa communities (Basquitay, Carillos, Naubug, and Tzimbuto) located in the Central Ecuadorian Andes. The main study site was the community of Naubug located in the parish of Flores, Chimborazo Province (1°51'24.0"S, 78°39'15.6"W). All communities are found on a steep topographic gradient with a maximum elevation among communities of around 3600 masl and a minimum elevation of around 2800 masl. Annual precipitation and average temperatures vary with elevation. During the period of research, at the highest point in Naubug, the average annual precipitation was measured to be 640 mm and the average annual temperature was 9.0°C. A public weather station located at a similar elevation to the lowest point in the communities (2850 masl) a couple of km away from Naubug, recorded an average annual precipitation rate of 592 mm and an average annual temperature of 14.2°C. Rain mostly falls between December and May with a drier, windier period from June to November (GAD de Flores 2015).

The pedogenic processes of the region are dominated by long-term volcanic activity with pyroclastic deposits which gave rise to the formation of relatively uniform, thick layers of hardened volcanic ash upon which lie volcanic (Andisol) soils. The A horizon of the soils is usually rich in organic matter having developed under cool, moist conditions and natural dense vegetation (either grass páramo at the higher elevations; sub-páramo between 3000-3500 masl or Andean forest below 3000 masl) (De Noni et al., 2001; Zehetner et al., 2003; Zehetner and Miller, 2006). However, in these intensively farmed rural landscapes, nearly all remnants of natural vegetation types have been removed resulting in erosion and exposure of low organic matter sub-soils composed of hardened volcanic ash, known locally as 'cangahua' (Podwojewski and Germain, 2005). In these areas where significant erosion has occurred, soils can be classified as either inceptisols or entisols.

Small-scale, often subsistence, farming dominates the landscapes with only small quantities of crops and livestock being sold at the local markets. Potato (*Solanum tuberosum L.*) often comprises the most important cash crop in the communities and usually receives the largest investment in terms of area and agronomic inputs (e.g., manure, fertilizer, pesticides). Other crops cultivated include cut forages such as annual barley (Hordeum vulgare L.) and vetch (Vicia) or perennial alfalfa (Medicago sativa), quinoa (*Chenopodium quinoa*), maize (*Zea mays*), rye (Secale cereale) and barley (*Hordeum vulgare L.*).

4.2. Methods

4.2.1. Co-developing an understanding of the socio-ecological context

The overall research objective of this PhD project was to contribute to the understanding of some of the main relationships between land and farm management, agroecosystems and socio-ecological variables, shed a new light on how farm and land management and agroecosystems patterns have co-evolved within this particular socio-ecological context in the Ecuadorian Andes, and to provide an empirical case-study as to how the SES and CAS frameworks could be used to inform more contextualised natural resource management. As summarised in Table 1, the research followed the DEED cycle (Describe, Explain, Explore, Design) (Descheemaeker et al., 2016; Giller et al., 2011), in order to co-develop a contextualised "Landscape Level Natural Resource Management Plan" with a group of farmer researchers and local stakeholders for the main study site. The empirical research outlined in Chapters 2, 3, 4 and 5 in this thesis lay the foundations for the 'Design' stage in the DEED cycle, by attempting to describe, explain and explore the main socio-ecological drivers and feedbacks at different scales for the current socio-ecological systems of the main study site as well as some neighbouring communities. In addition, in Chapter 5 I aimed to describe, explain and explore a novel technique that farmers had identified to address their concerns with regard to land degradation, access to organic resources and agricultural intensification.

Specifically, in Chapter 2 I set out to investigate the complex relationships and impacts of how a broader societal trend such as rural out-migration affected farm and land management. By using a novel type of statistical analysis for these types of investigations (structural equation modelling) I aimed to tease out linkages between underlying/indirect causes and proximate/direct causes reflecting the different adaptive cycles that are expected to be found under Panarchy Theory. The statistical modelling was complemented by a role-play game to provide a more qualitative appreciation of the potential adaptations (regime shifts) farmers would make should their broader socio-economic circumstances (access to labour and financial resources) change.

In Chapter 3 the aim was to investigate asymmetric patterns of organic matter inputs at three scales of analysis (community, farm and within farm), and their interactions with soil chemical properties. The research used methodologies from both the social and biophysical sciences (resource flow mapping, a farming system survey and soil sampling). Mixed linear regression model (with fixed and random effects) were applied to the data to explore the different interactions hypothesised.

In Chapter 4 I used participatory community land-use mapping to identify the main land-uses and three separate within-farm 'system regimes' (agricultural management zones) within the community of Naubug. Based on this map, soil and agroecosystem sampling was undertaken across the landscape and across land-uses (and agricultural management zones). Interactions between the underlying environmental context, driven largely by the elevation induced climate gradient, and management were analysed using multivariate linear regression analyses.

Chapter 5 was undertaken to assess the potential of hedgerows, identified by farmers in Naubug, as a technique for reducing erosion and enhancing productivity through the incorporation of organic amendments harvested from the hedgerows. Experimental plots comprising three replicates of four treatments (canary grass; canary grass and Andean alder; Andean alder; and a control treatment with no hedgerow) were established in the community in two different environmental contexts, one in the upper elevations of the landscape, the other in the lower elevations. Overall biomass production, grain yield, soil moisture, soil water erosion and soil chemical properties were measured and analysed using ANOVA.

4.2.2. Co-developing a landscape level natural resource management plan

As outlined in Chapter 6, based on the enhanced understanding of the socio-ecological context of the main study site and neighbouring areas co-developed in Chapters 2-5, a series of three workshops were developed to complete the last step in the DEED cycle, Design, by identifying opportunities and challenges for enabling pathways to more sustainable landscape natural resource management in the main study site, using key concepts from the SES and CAS frameworks.

Through discussion groups and the use of scenario land-use mapping, the first workshop aimed to co-develop a common understanding of the research findings from Chapters 2-5 as well as to identify potential future land-use change scenarios based on current land-use, past socio-economic and cultural trends and current challenges and opportunities, reflecting the Narrative methodology proposed by Cumming (2011). The second workshop aimed to explore and design more sustainable and productive farming systems in the community of Naubug, using a role-play game that took inspiration from the FarmDESIGN model and conceptual framework (Groot et al., 2010, 2007). The role-play game used data adapted from the research conducted in Chapters 2-5 to make the trade-offs and interactions involved in designing alternative farms in the community as explicit and as real as possible to participants.

The third workshop aimed to bring together the learning co-developed from the research and the previous workshops in order to co-design a landscape level natural resource management plan for the community of Naubug based on the qualitative assessment of key concepts from the complex adaptive systems framework. In groups, participants were asked to discuss and agree whether the current system regimes (the upper, middle and lower agricultural management zones) were desirable, taking into account productivity and agroecosystem health, as well as assessing their vulnerability (Adger, 2006). Based on this analysis, groups were then requested to discuss what could and should be done either to ensure the resilience of these system regimes or how to instigate transformation to an alternate (preferred) state (Cumming and Collier, 2005). The final task groups had to undertake was to evaluate the proposals from the previous step (building resilience or instigating transformation) within the broader socio-ecological context, gauging the adaptive capacity of the regimes (Fabricius and Cundill, 2010; Groot et al., 2016). The findings for each methodological step in the workshop for each of the groups were presented in plenary where participants could clarify and discuss the findings further. A landscape level natural resource management plan was then compiled and presented at a seminar with farmers and local stakeholders and policy-makers.

4.3. Hypotheses

Through the application of the SES and CAS frameworks, it is hypothesised that:

- farm management and agroecosystem patterns are driven by multiple interacting socio-ecological factors at different scales;
- feedback loops exist across scales and between adaptive systems, such that farm management and agroecosystem patterns co-evolve;
- system regimes are evident at different scales; and
- insights developed through the application of the SES and CAS theoretical frameworks facilitate the co-development of more contextualised development strategies.

Table 1: *Summary of the Chapters, the level of analysis, steps in the DEED cycle, objectives and main methodological and analytical tools.*

Chapter	Levels of analysis	Steps of DEED cycle	Objectives	Main methodological and analytical tools
2	Broader socio-economic Farming system	Describe, explain, explore	Investigate how and why out-migration trends, prominent in the study region, affect farming systems	Household survey; semi-structured interviews; role play game; structural equation modelling
3	Broader socio-economic Farming system Within farm Agroecosystem	Describe, explain, explore	Investigate between community, between farm and within farm variability in organic matter inputs and their effects on soil chemical properties.	Resource flow mapping; farming system survey; soil sampling; mixed linear regression models
4	Environment context Farming system Within farm Agroecosystem	Describe, explain, explore	Investigate interactions between environmental context, landscape patterns and within farm system regimes	Community land-use mapping; agroecosystem and soil sampling;

Chapter	Levels of analysis	Steps of DEED cycle	Objectives	Main methodological and analytical tools
				multivariate linear regression analysis
5	Environmental context Farming system Agroecosystem	Describe, explain, explore	Investigate a farming technique to tackle common concerns of farmers (land degradation, lack of organic matter inputs, productivity) in different ecological contexts within a landscape	Experimental plots to measure soil erosion and moisture and crop productivity; ANCOVA
6	Environment context Broader socio-economic Farming system Within farm Agroecosystem	Explore, design	Co-develop a landscape natural resource management plan for the main study site using key concepts from the theoretical frameworks of SES and CAS	Participatory workshops involving role play games

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Chapter 2: How rural out-migrations drive changes to farm and land management – a case study from the rural Andes

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Abstract

Rural-urban migrations are one of the most conspicuous patterns in global population shifts in recent decades and can have considerable impacts on land-use and management in the rural migrant-sending communities. To better understand these impacts, we employed household surveys and semi-structured interviews to generate a small, but detailed and relatively complete set of data (43 out of a total of 57 households) from a rural indigenous Kichwa community in the Andean highlands of Ecuador. We conducted linear regression analyses (LR) between migration-related attributes of each household and farm management variables in order to provide greater insight into the complex relationships and impacts of rural out-migration on farm and land management. Our findings indicated that reduced household labour availability was associated with a decrease in the use of physical soil and water conservation (SWC) techniques ($p = <0.01$), while remittances received from rural out-migrations were associated with an increase in the use of pesticides and chemical fertilizers ($p = <0.01$). The results of the LRs were used to develop a Structural Equation Model (SEM) to elucidate the direct and indirect effects between increased access to financial resources (as a result of temporary out-migrations) and the use of agro-chemicals and mechanized tillage (industrialized farming techniques). Our analysis suggests that temporary out-migrations were indirectly related to the use of industrialized farming techniques through their effects on household financial resources and subsequent farm-level decisions to increase the proportion of potato cash crops. As a consequence, it is probable that the effects of out-migration, at least in this case-study, are negatively affecting the agroecosystems of the landscape. However, the results of the SEM suggest that this response may be specific to this particular socio-ecological context. Rural development policies, programmes and projects must therefore explicitly recognise and better understand these broader socio-ecological contexts and their effects on farm-level decisions in view of rural out-migration in order to develop more effective intervention strategies.

1. Introduction

Population mobility has long been a significant driver of change in rural areas (Milbourne and Kitchen, 2014). Rural population mobility, including rural out-migrations, may take many forms across different spatial and temporal scales contributing to the inherent complexities of rural change (Milbourne, 2007). Rural-urban migrations are not only transforming the social relations of the families sending these migrants, but are strongly associated with changes to farming practices and livelihood strategies in response to the opportunities and challenges presented by migration (de Haas, 2006; Greiner and Sakdapolrak, 2013; Maharjan et al., 2013). Moreover, given the intricate socio-ecological relationships in rural landscapes, the effects, both direct and indirect of out-migrations, appear to lead to important feedback loops with the biophysical environment of the agroecosystems of these rural landscapes (Qin, 2010; VanWey et al., 2012).

Understanding the causes and impacts of rural out-migrations has therefore become an important area of study in the past three decades, as governments and civil society grapple with how to manage this challenging and complex trend. In particular, a number of studies have attempted to shed-light on how high population mobility has been driving changes in rural households and landscapes (Bhandari and Ghimire, 2016; Davis and Lopez-Carr, 2014; Li and Tonts, 2014; Radel et al., 2012; VanWey et al., 2012 among others). However, despite this rich body of research, the effect of out-migrations on land-use change, agricultural management and livelihood strategies remains unclear and many studies present inconsistent findings, revealing a complex and at times a seemingly contradictory picture (Qin, 2010; Gray and Bilsborrow, 2014).

One of the early dominant narratives that developed in this area of research is that population dynamics are strongly associated with vegetation cover change (Cropper and Griffiths, 1994; Ehrhardt-Martinez, 1998; Mather and Needle, 2000). In particular, it was asserted that vegetation cover, specifically forest cover, changed in predictable ways as a result of economic development, industrialisation and urbanization. This pattern of land-use change, coined as ‘Forest Transition’ by

Mather (1992), claimed that as societies developed economically there would be a parallel process of deforestation until a certain point was reached whereby the trend would reverse leading to a slow increase in forest cover either as a result of rural out-migrations or perceived economic opportunities in the timber industry creating economic incentives to invest in forestry (Li et al., 2013; Robson and Berkes, 2011; Rudel et al., 2005).

In contrast to the assertion that vegetation cover and land-use changes follow a common pathway however, other studies have found that deforestation and rural land-use change occur as a result of multiple causative factors with no distinct universal pathway (eg, Angelsen, 2010; Enuoh and Ogogo, 2018; Geist and Lambin, 2002; Imai et al., 2018; Perz, 2007). In a meta-analysis of 152 sub-national case studies located in Asia, Africa and Latin America, Geist and Lambin (2002) identified both proximate and underlying causes for tropical deforestation concluding that no universal causal link exists. Instead they argued that loss of forest cover was determined by different combinations of proximate and underlying forces, varying in geographical and historical contexts. They further contested that the underlying national and global drivers for deforestation were mediated by local-scale institutional factors, found at the proximate level of analysis (Geist and Lambin, 2002).

While much of the work undertaken under the framework of Forest Transition Theory is focused at land-use change at the regional and landscape level, other researchers have attempted to unpick the nuances of factors affecting land-use and farm management change at the household level. In particular, the theoretical framework of 'Household Lifecycles', first developed by A.V. Chayanov following the Russian revolution in 1917, has been adapted and used to analyse the effect of household level dynamics on farm management (Perz and Walker, 2002; Walker et al., 2002). The original Household Lifecycle Theory contended that, over time as members of a farming household aged, farming strategies changed to adapt to the new family structure. In the early years, in the presence of young infants and children, farmers would tend to cultivate less land, but as the children grew older and began participating in on-farm work, the amount of land farmed would expand

(Thorner et al., 1986). Evidence for the effect of farm household lifecycle and the role of access to family household labour in shaping farm management can be found in research assessing the maintenance of soil and water conservation (SWC) structures. According to research undertaken in Peru (Collins, 1988), Bolivia (Zimmerer, 1993) and Nepal (Jaquet et al., 2015) decreased labour availability has been shown to result in decreased effort in soil and water conservation measures within farming systems.

However, the early formulations of Household Lifecycle Theory have been criticised due to assumptions made with regard to migration patterns, access to agricultural inputs, credit and product and labour markets (Perz and Walker, 2002). Indeed, the consequences of rural population dynamics and population mobility go beyond simple variations in rural population density or labour availability. Rural out-migrants often send remittances to their families thus impacting the financial resource base of the migrant-sending communities and contributing significantly to rural household incomes (eg, Deininger and Olinto, 2001; Reardon et al., 2001; Sana, 2008). When factoring in remittances, it has been found that the loss in farm household labour availability is often compensated for by increased access to capital, leading to overall improvements in both agricultural and total incomes (McCarthy et al., 2006). This perspective, coined the 'New Economics of Labour Migration' provides an 'optimistic' view on the consequences of rural out-migration, arguing that migration may enhance economic development of impoverished rural households by lessening production and investment constraints (Taylor, 1999; Bloom and Stark, 2016).

The adoption of more 'industrialized' agricultural practices in rural communities with out-migrations has been observed. For example, a study in Bangladesh found that remittances influenced the uptake of high-yielding seed technology (Mendola, 2008). Another study in the southern Ecuadorian Andes revealed that agrochemical inputs increased with international remittances (Gray, 2009). Similarly, a study from three rural regions in Ecuador found that decreased labour availability associated with out-migration led to an increase in farm cropping area, while remittances had a countervailing effect decreasing the farm cropping area per household (Gray and Bilsborrow, 2014). While the overall use of chemical inputs in this study did not exhibit significant differences between migrant and non-migrant households across these three regions, the proportion of agricultural chemical inputs were seen to increase with increasing remittances.

However, while a number of findings appear to support the hypothesis that off-farm income compensates the loss of household-labour availability with the adoption of labour-saving ‘industrialized’ farming techniques, the effects may not be so simple or direct. For example, a study in Cañar Province of Ecuador found that income from remittances was not used to improve agricultural productivity, but rather invested in housing and land acquisition (Jokisch, 2002). The authors suggested that while semi-subsistence agriculture remained an important risk averse economic and cultural activity, it represented a poor investment for families with relatively limited financial resources. In another study, conducted in Chongqing Municipality of Southwest China, households with migrants used land less intensively and cultivated smaller areas of land with fewer agrochemical inputs (Qin, 2010).

Such complex and, at times, inconsistent findings regarding the effects of rural out-migration, suggest that multiple interrelated factors may be responsible for the observed effects (Gray, 2009; Qin, 2010; Greiner and Sakdapolrak, 2013). Moreover, it is likely that the changes brought about by rural out-migration are a result of not only direct effects, but occur through indirect mechanisms as well, whereby changes in farm management and land-use, is mediated by local, regional and global socio-ecological contexts, which are, by definition, context specific (Caldas et al., 2007; de Sherbinin et al., 2008).

It is important to recognise that while the current research uses ‘out-migration’ as an important variable to assess the effects of population mobility on land-use and farm management changes, the other side of the coin is of equal importance, that of ‘staying’ (Stockdale and Haartsen, 2018). Indeed, the act of migrating may be a mechanism for others to stay. As Stockdale and Haartsen

(2018) point out, the migrant who lives elsewhere during the week to earn off-farm income for the farming household but returns 'home' at weekends, may be better considered a stayer rather than a mover. This analysis is supported by two recent studies from China (Ye, 2018) and Mexico (Mata-Codesal, 2018) which highlight the role migrants play in enabling families to remain put.

The objective of this study was therefore to build on this growing body of research to provide insight on the relationships that govern the impacts on farm and land management that the challenges and opportunities of rural population mobility pose. In particular, we aimed to shed further light on the question whether the processes leading to land-use and farm management change in the tropics are driven by universal causal factors leading to common pathways as suggested by the earlier formulations of the Household Lifecyle Theory (Thorner et al., 1986) and the Forest Transition Theory (Mather, 1992) or a result of interacting factors at multiple levels as suggested by subsequent authors (de Sherbinin et al., 2008; Geist and Lambin, 2002; Walker et al., 2002).

In order to gain greater insight on these relationships, we focused on one rural community in the Andean highlands of Ecuador selected based on key-informant discussions in order to ensure a representative community from the area of work of the local NGO with whom the research was conducted. As such, the community in which the study was undertaken was an indigenous Kichwa community, Carrillos, with 57 farming households located at low to mid-elevation ranges in the parish of Cusubamba, Cotopaxi Province, Ecuador. According to the key-informant discussions, the community, like other communities in the area, is characterised by important rural out-migration flows, but still retains a significant population of farming households. Compared to other communities in the parish, the number of migrants in Carrillos (61) falls mid-way through the range of migrants per community, 22-108 (Gobierno Autónomo y Decentralizado de la Parroquia de Cusubamba, 2011).

As in Mendola (2008), in our study we define three types of rural out-migration; permanent or long-term, long-distance out-migrations to third countries (international migration); permanent rural out-migration within Ecuador, where migrants have left the community with the aim of establishing a life and livelihood elsewhere (permanent national migration); and short-term temporary or seasonal out-migrations within Ecuador where the migrant returns on a regular basis to the farming household (usually at weekends, for a week once a month or who only spends a few months a year living outside the community – temporary migration).

We used household surveys and semi-structured interviews to begin to unravel the relationships between increased access to financial resources, as a result of out-migrations, and industrialized farming techniques. We also considered the implications of out-migrations in the environmental context of these rural landscapes by placing it in a framework of natural resource management policies and interventions.

As outlined in the adapted Household Lifecycle Theory by Walker et al. (2002), which integrates demography with market-based factors ,we hypothesize that rural out-migration leads to changes in land management and farming practices, as a result of its influence on farming household labour availability and off-farm income from migrants. Specifically, we postulate that a loss in farming household labour will lead to the use of fewer physical SWC techniques (eg, hedgerows, drainage ditches etc.) as per Collins (1988); Jaquet et al. (2015); and Zimmerer (1993). We also suspect that greater off-farm income from out-migrations will provide farming households with a larger financial resource base with which to invest more in labour-saving agricultural intensification practices (as in Gray, 2009; and Mendola, 2008). However, in contrast to theories that suggest universal causal factors or pathways, we predict in line with other authors (eg, de Sherbinin et al., 2008; Geist and Lambin, 2002; Walker et al., 2002), that the relationships observed between out-migrations and changes to farm management practices will be mediated by different level factors influencing livelihood decisions.

2. Materials and methods

2.1. Study site description

This research was conducted between the months of April-June, 2016 in an indigenous Kichwa community, Carrillos, located in the parish of Cusubamba, Cotopaxi Province, Ecuador (1°04'09.1"S 78°40'40.8"W). The total population of the parish of Cusubamba in 2011 was 7200, of which 3490 were male and 3710 were female (Instituto Nacional de Estadística y Censos Ecuador (INEC), 2010). The community itself has 453 registered inhabitants, and 57 farming households according the community president. Its elevation ranges from 3050 to 3200 masl and is characterised by gentle slopes (slopes of usually < 15°) enabling easier agricultural production than communities located at higher elevations, with steeper slopes. Annual precipitation varies between 250 to 600 mm , with most rain occurring between September-May and a dry season from June to August (Gobierno Autónomo y Decentralizado de la Parroquia de Cusubamba, 2011; Martínez, 2006). The average annual precipitation reaches only 50% of the potential evapotranspiration, which results in a high hydric deficit (Martínez, 2006). Access to irrigation water (via a network of canals) and generally constant temperatures permit year-long agricultural production. There are no areas of forest cover in the community, except for eucalyptus trees bordering mostly inaccessible terrain close to a steep canyon.

The geology of the area is dominated by a long history of volcanic activity with pyroclastic deposits that have given rise to the formation of volcanic soils (Andosols), whose characteristics vary according to land-use, management, elevation and climate (Zehetner et al., 2003; Zehetner and Miller, 2006; Chapter 4). As found in the farmer interviews, farmland is privately owned and households have on average 2.4 ha under agricultural production. No communal land exists in the community. The land is generally divided into several relatively small plots (roughly 40 x 40m), spread throughout the landscape. Generally, farmers do not own land outside the community. Crop rotation is pervasive throughout the community with the dominant crops being potato (*Solanum* *tuberosum L.*), maize (*Zea mays*), broad beans (*Vicia faba*), peas (*Pisum sativum*), and Andean lupine (*Lupinus mutabilis*) (Gobierno Autónomo y Decentralizado de la Parroquia de Cusubamba, 2011). A significant part of the crop rotation is also dedicated to the cultivation of forages, either annual barley (*Hordeum vulgare L.*) and vetch (*Vicia*) or perennial alfalfa (*Medicago sativa*) crops.

According to key-informant interviews on-farm income is generated largely through dairy production, with milk being sold to a dairy company at a fixed price ($0.37 l^{-1}; 2016 prices). Potatoes provide the other main source of farm income. Households sell their harvest at a local market (40 minutes drive) negotiating a price between $10 and $30 per quintal (100 pounds or 45.4kg), meaning that this income source, while potentially large, is also riskier.

2.2. Data collection and analysis

2.2.1. Access to (household) farm labour and off-farm income from out-migrations

A household survey was conducted in Spanish by a Master's student from Europe who worked in close collaboration with the local NGO field officer to collect information regarding family structure, profession, farming activities (types of activities and time dedicated to each) and migration patterns (frequency and duration of the migration periods as well as money earned from remittances). The surveys usually lasted around 30 minutes. In total 43 of the 57 households in the community were interviewed. The remaining households either declined to participate or were unavailable at the time fieldwork was taking place.

The contribution of the different members of the household to the total labour availability was calculated as follows: Permanent household members dedicated to agriculture were considered to allocate 365 days per year to farming activities. The time that migrants (temporary, national and international) allocate to farming was estimated as the number of days they are present in each community, since all households indicated that migrants participate in farm activities when they come back. Children and students of more than 8 years old were considered to dedicate one third of their time to farm tasks, between afternoons, weekends and holidays (ie, 120 person-days per year). This follows the observation that children dedicate a large part of their free time to cutting forage or helping with weeding or harvest of potatoes. Women of more than 65 and men of more than 70 were considered at 0.5 of their reported time due to the observation that elderly workers are considerably slower at completing their farm tasks.

The definition of 'migration' includes a diversity of sub-categories including national permanent migration; temporary (often seasonal) migration; and international migration (Mendola, 2008; van Naerssen et al., 2008). The effect of these migration patterns on farm management practices has been analysed in recognition of these different types of migration. However, due to the small number of international migrants in this community (n = 6), statistical analyses could not be conducted on this category. Remittances received from international migrants are however included in total off-farm income from migrants and their contribution to overall farming household labour availability is also considered.

2.2.2.Farm management practices

The data on farm management practices was collected during semi-structured interviews by the same Master's student who conducted the household survey. The interview and the subsequent exploration of future scenarios (see description below) usually took around 90 minutes. The semi-structured interview asked questions on the following topics: land tenure, crop rotations and associations, soil preparation, fertilisation practices, pest management, livestock management, irrigation and water management, utilization of live barriers, deviation ditches, water harvesting ponds and other physical soil and water conservation (SWC) techniques. The farmers' responses to farm-management practices questions were recorded in the field and input into an excel file at a later date.

In addition, farmers participated in an analysis of how they would change their farming practices in the case of potential changes to their labour and financial resources in the future. To elicit these responses, cards with drawings of the different farm management practices were placed in front of the interviewee. The cards were grouped into practices they regular undertake and practices they currently do not undertake. Farmers were then asked to verify that the groupings of the cards correctly depicted their usual farming practices. They were subsequently asked what three things they would do differently in case of increased or decreased labour availability; and in the case of increased or decreased access to financial resources. The scenarios were presented to farmers in a randomised order and the responses to each scenario recorded in the field and later digitalized into an Excel file.

2.2.3.Statistical analysis

Descriptive statistics were applied to the household data to provide insight on the general patterns of the community regarding migration patterns, access to labour, off-farm income from migration and farming activities. Linear regressions were used to assess relationships between migration and farm-management-related variables. Log transformations were applied as needed to address issues of normality and homoscedasticity. In order to tease out the direct and indirect relationships inherent in these associations, a structural equation model was developed. This model was developed to test whether temporary out-migration led directly to more industrialized farming techniques, or whether this path was mediated by the effect of increased off-farm income from migrants on cropping patterns. All analyses were undertaken within the RStudio environment Version 0.99.902 for R, using openxlsx, ade4, agricolae, doBy, lavaan, semPlot and ggplot2 packages.

3. Results

3.1. Descriptive statistics and linear regressions

Survey results indicated that the number of temporary migrants in each household ranged from 0-3, while the number of permanent national migrants ranged from 0-8, accounting for the majority of the out-migrations (Table 1). Nine households did not have members who had temporarily or permanently migrated, 19 had no member who had migrated on a temporary basis and 27 had no permanent migrants. While more permanent national migration was observed in this community, on average temporary migrants contributed much larger amounts to off-farm income, $2082 compared to $78.17 a year. Overall off-farm income from migration contributed on average $3359 in additional income a year per household (Table 1). Temporary migration was undertaken mainly by male members of the household, while a similar amount of female (26) and male (36) were found to have permanently emigrated from the community. Temporary migration was undertaken by the same number of heads of household as non-heads of households (18). On the other hand, non-heads of households accounted for all permanent national migration (Table 2). The number of temporary migrants correlated negatively with the number of permanent household members (Table 2).

Table 1: *Descriptive statistics of the migration-related and farm management characteristics of the households of the community of Carrillos, Cotopaxi Province, Ecuador. Means, standard deviation and range (minimum and maximum) are presented*

Variable	Mean	SD	Min	Max
Number of permanent farming household members	1.8	1.2	0	6.0
Number of temporary migrants	0.7	0.8	0	3.0
Number of permanent national migrants	1.2	2.0	0	8.0
Number of international migrants	0.1	NA	0	1.0
Total off-farm income generated by migrants (temporary and permanent) ($ year-1)	3359.0	3656.7	0	13200.0
Off-farm income generated by temporary migrants ($ year-1)	2082.0	2809.8	0	10400.0
Remittances from permanent national migrants ($ year-1)	78.0	298.5	0	1560.0

Variable	Mean	SD	Min	Max
Total farm land (ha²)	2.4	1.2	0.7	6.4
Proportion of potatoes (cash crop) in crop rotation (%)	16.5	11.1	0	50.0
Proportion of forage crops in crop rotation (%)	69.7	14.9	30.3	93.0
Proportion of 'other crops' in crop rotation (%)	13.8	6.7	0	39.4
Heads of cattle owned	5.5	3.0	1.0	14.0
Chemical fertilizer applications (field/year)	0.8	0.5	0	2.0
Pesticide applications (field/year)	1.7	1.1	0	4.8
Number of (physical) SWC techniques used	1.5	1.4	0	5.0

Table 2: *Descriptive statistics of the characteristics of the migrant categories of the community of Carrillos, Cotopaxi Province, Ecuador*

Migration Status Characteristic	Permanent Household Members	Temporary Migrants	Permanent National Migrants	International Migrants
Gender (F/M)	70 F / 29 M	2 F / 34 M	26 F / 36 M	3 F / 3 M
Age (mean)	47.31	34.56	34.24	40.00
Position in household (Head of HH or partner (HH)/non-head of HH (NHH))	66 HH / 33 NHH	18 HH / 18 NHH	0 HH / 62 NHH	3 HH / 3 NHH
Permanent household members - coefficient (SE)	NA	-0.647 (0.213)**	0.033 (0.091)	NA
Household labour availability - coefficient (SE)	NA	-94.92 (82.84)	-5.048 (32.312)	NA

** p-value = <0.01

Linear regression analyses revealed a significant negative relationship between the number of permanent farming household members and the proportion of potato cultivated within the overall crop rotation (Table 3). A similar inverse relationship was observed between number of permanent farming household members and the use of pesticides and chemical fertilizers. Conversely, positive correlations were observed between the number of permanent farming household members and total cropping area, proportion of forage crops in rotation and the use of physical SWC techniques

(Table 3). The number of temporary migrants in the household displayed a significant positive correlation with the proportion of potatoes in the crop rotation and the use of agro-chemicals and mechanized tillage; and a strong negative correlation with the proportion of forage crops. The number of permanent national migrants exhibited no significant relationship with any of the farm management practices assessed (Table 3). Farming household labour availability (the number of working days of household members available to undertake farming activities) displayed a positive significant relationship only with cropping area and the number of physical SWC techniques used (Fig. 1).

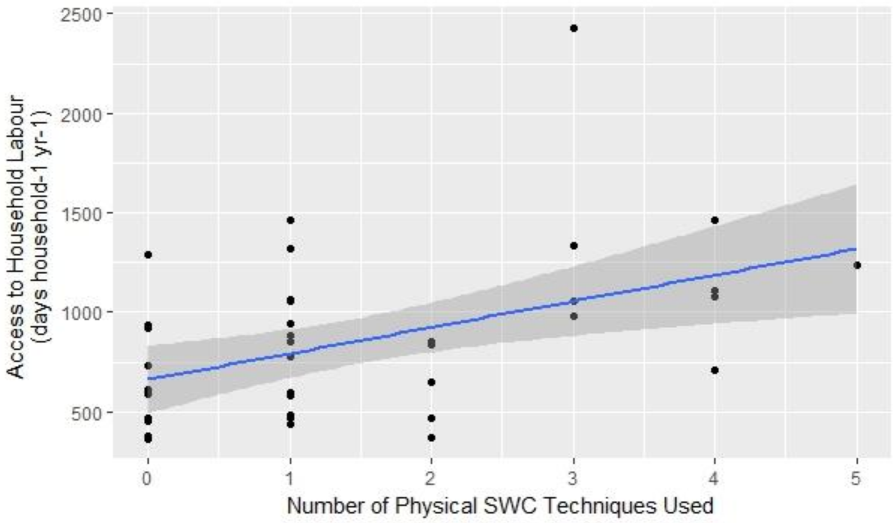

Figure 1: *Linear regression analysis for the effect of household labour availability on the number of physical SWC techniques used by each farming household. 95% confidence region highlighted in the shaded area. p = 0.003, Adj. R² = 0.17*

Off-farm income from temporary migrants was positively correlated with the proportion of potato and 'other' crops in the overall crop rotation of the farm, as well as agrochemical use. It displayed a negative correlation with the proportion of forage crops in the cropping rotation. Remittances from permanent national migrants were only found to have a significant positive correlation with mechanised tillage. On the other hand, total off-farm income from migration displayed positive correlations with the proportion of potato (Fig. 2) and 'other' crops in the cropping rotations, agrochemical inputs and the use of mechanised tillage, while it exhibited a negative relationship with the proportion of the forage crops in the crop rotations.

Table 3: *Correlations between household and farm management factors. Results presented include coefficient and the standard error in parentheses and significance of the correlations. Permanent farming household members; temporary migrants and permanent national migrants are presented on a 'number of individuals per household' basis*

Variable	Perm. farming HH members	Temp. migrants	Perm. national migrants	HH labour availability (days)	Off-farm income (temp. migrants - $1000)	Off-farm income (perm. migrants - $1000)	Total off-farm income ($1000)
Proportion of Potato in Crop Rotation (%)	***-2.92 (1.43)****	***6.735 (2.01)*****	-0.64 (0.86)	-0.005 (0.004)	***1.547 (0.568)*****	6.833 (5.714)	***1.423 (0.419)*****
Proportion of Forage Crops in Crop Rotation (%)	***4.63 (1.87)****	***-9.03 (2.68)*****	0.98 (1.15)	0.01 (0.01)	***-1.8393 (0.775)****	-8.146 (7.673)	***-2.060 (0.547)******
Proportion of 'Other' Crops in Crop Rotation (%)	*-1.70 (0.87).*	*2.29 (1.33).*	-0.35 (0.52)	*-0.004 (0.002).*	0.293 (0.372)	1.312 (3.519)	***0.637 (0.270)****
Proportion of Associative Cropping in Crop Rotation (%)	1.28 (3.36)	0.23 (5.08)	0.32 (1.95)	0.003 (0.009)	-0.331 (1.3853)	10.18 (12.95)	-0.189 (1.00)
Heads of Cattle (nb)	0.21 (0.40)	-0.57 (0.60)	-0.08 (0.23)	0.000 (0.001)	*-0.295 (0. 159).*	1.090 (1.549)	-0.159 (0.125)
Cropping land (ha)	***0.153 (0.064)****	-0.083 (0.103)	0.008 (0.040)	***0.0005 (0.0002)****	-0.038 (0.028)	-0.022 (0.265)	-0.010 (0.022)
Use of Physical SWC Techniques (nb)	***0.43 (0.17)****	-0.10 (0.28)	0.07 (0.11)	***0.001 (0.000)*****	-0.110 (0.074)	-0.0005620 (0.0007109)	-2.345e-05 (5.835e-05)
Pesticide Use (nb of applications/ year/field)	***-0.33 (0.14)****	***0.63 (0.21)*****	-0.05 (0.09)	-0.0006 (0.0004)	***0.152 (0.058)****	0.244 (0.591)	***0.137 (0.043)*****

Variable	Perm. farming HH members	Temp. migrants	Perm. national migrants	HH labour availability (days)	Off-farm income (temp. migrants - $1000)	Off-farm income (perm. migrants - $1000)	Total off-farm income ($1000)
Chemical Fertilizer Use (nb of applications/ year/field)	*-0.12 (0.06).*	***0.28 (0.09)***	-0.02 (0.04)	-0.0002 (0.0002)	***0.071 (0.024)***	0.145 (0.252)	***0.055 (0.019)***
Mechanized tillage (nb of applications/ year/field)	-0.150 (0.145)	***0.431 (0.211)****	0.060 (0.085)	<-0.001 (<0.0001)	0.069 (0.059)	***1.323 (0.530)****	*0.082 (0.045).*

****** P <0.001, ** P <0.01, * P <0.05***, *. P = <0.1*

3.2. Structural equation model

The structural equation model developed (Fig. 2) specifically aimed to investigate whether the correlation observed between temporary migration and industrialized farming techniques (mechanized tillage, pesticide and chemical fertilizer use) was a direct association or whether it was associated indirectly through effects on crop rotation patterns and increased off-farm income. In the model we hypothesised that temporary migrants increased off-farm income through remittances and that this increased financial resource base enabled households to adopt riskier cropping rotations (because of price fluctuation) through increased cultivation of potato cash crops. Furthermore, we expected that the cropping of higher proportions of potato as cash crops to be positively correlated with the use of mechanized tillage, chemical fertilizers and pesticides.

As can be seen in Fig.2, the structural equation model we developed proved to be a good to reasonable fit for the data (Root Mean Square Error of Approximation (RMSEA) = <0.001 and Standardized Root Mean Square Residual (SRMR) = 0.079, with a 90% Confidence Interval of 0.000-0.154). As hypothesised, the model revealed that temporary migration was associated with the use of industrialised farming techniques mediated by significant positive relationships between: temporary migration and off-farm income from migration; off-farm income from migration and the proportion of (potato) cash crops; and the proportion of (potato) cash crops and the use of mechanized tillage, chemical fertilizers and pesticides.

No significant direct relationship was observed between off-farm income from migrants and the use of mechanized tillage, chemical fertilizers or pesticides. P-values, standard errors, R^2, variance and standardised coefficients are presented in Fig. 2, while actual coefficient effects can be seen in Figs. 3, 4, 5 and 6.

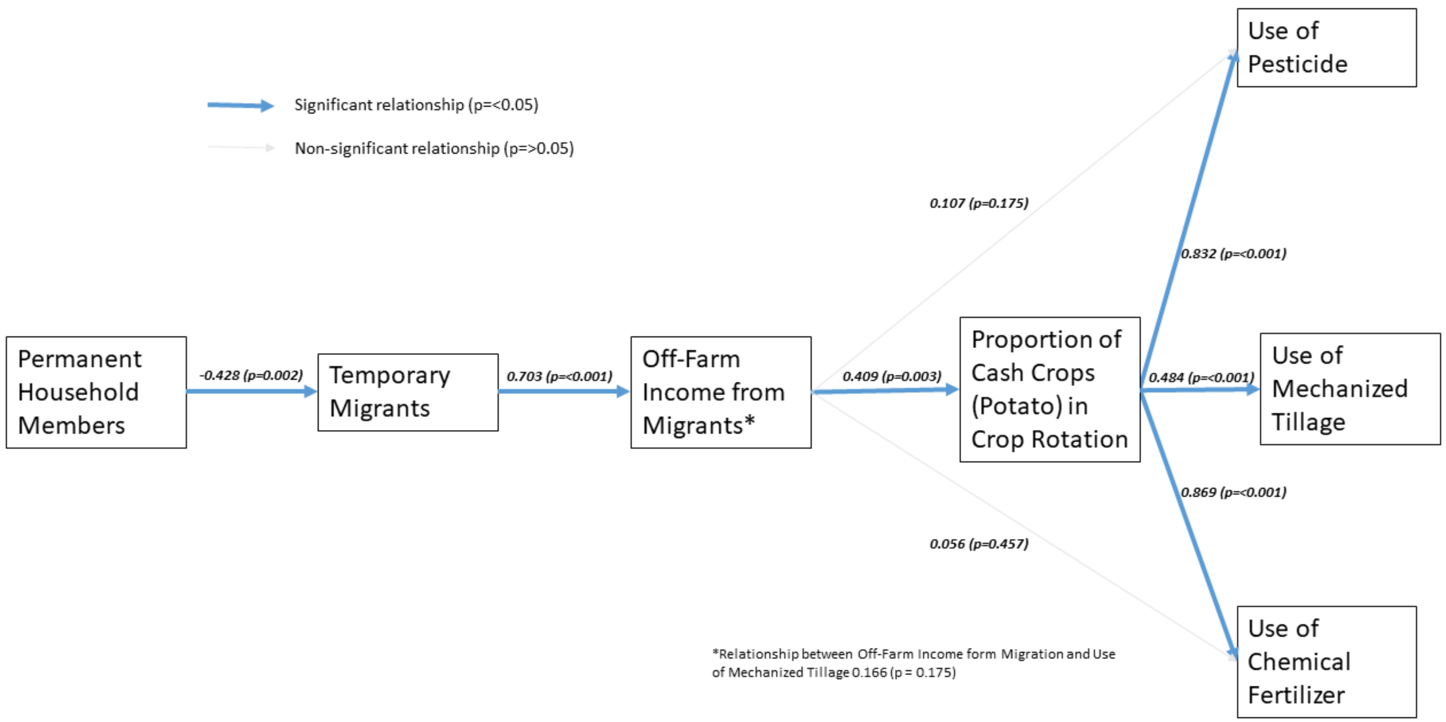

Figure 2: *Structural Equation Model displaying the indirect relationship between temporary migration and the use of pesticides, chemical fertilizers and mechanized tillage via increased off-farm income from migration and higher proportions of potato cultivation in the cropping rotation. The standardised coefficient estimate and the p-value is presented next to each "path". The standardised coefficient estimate refers to the regression coefficient that has been standardized so that the variances of dependent and independent variables are equal to 1 enabling comparability between SEM variables in terms of strength of effect. Root Mean Square Error of Approximation (RMSEA) = <0.001; 90 Percent Confidence Interval: 0.000-0.154; p-value RMSEA: 0.643; Standardized Root Mean Square Residual (SRMR): 0.079*

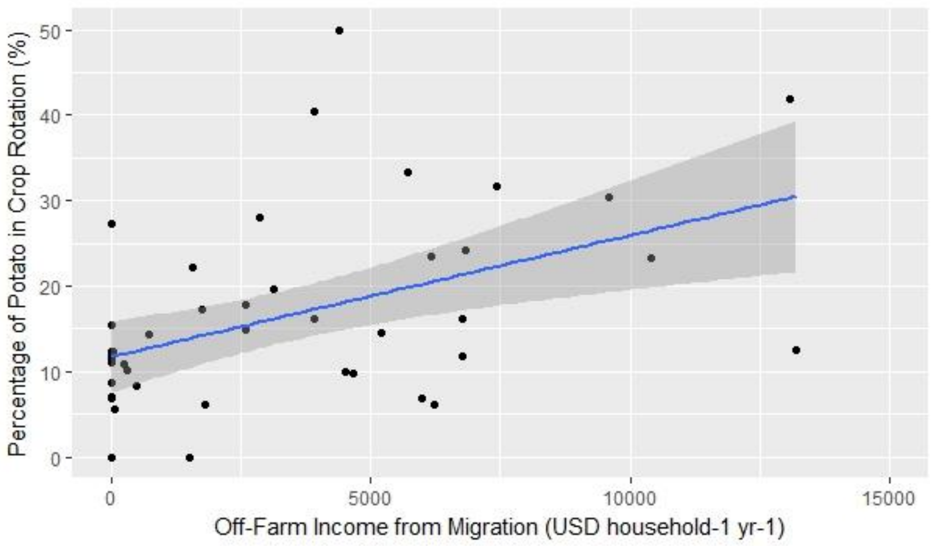

Figure 3: *Linear regression analysis for the relationship between off-farm income from migration on the proportion of potato (as a cash crop) in the overall cropping rotation. 95% confidence region highlighted in the shaded area.* $p = 0.002$*, Adj.* $R^2 = 0.20$

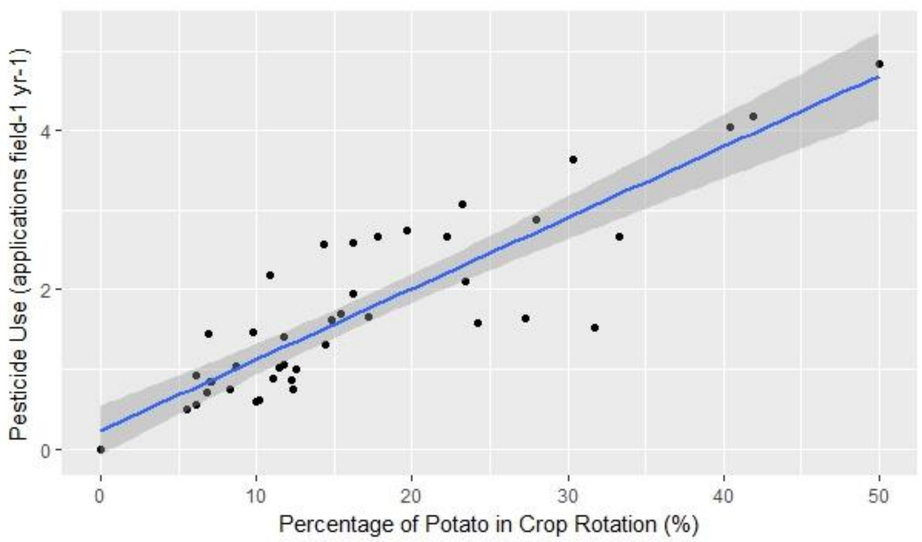

Figure 4: *Linear regression analysis for the relationship between the proportion of potato (as a cash crop) in the overall cropping rotation and the number of pesticide applications per field per year. 95% confidence region highlighted in the shaded area.* $p = <0.001$*, Adj.* $R^2 = 0.76$

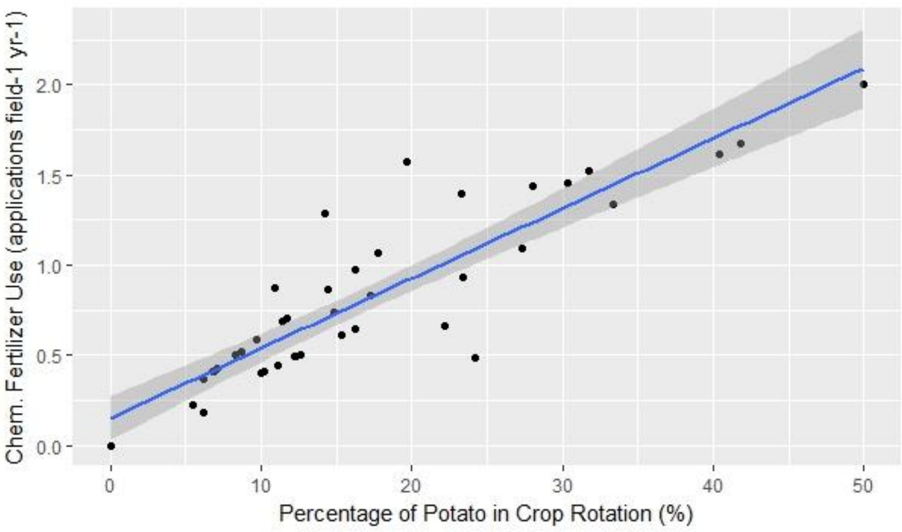

Figure 5: *Linear regression analysis for the relationship between the proportion of potato (as a cash crop) in the overall cropping rotation and the number of chemical fertilizer applications per field per year. 95% confidence region highlighted in the shaded area. p = <0.001, Adj. R² = 0.79*

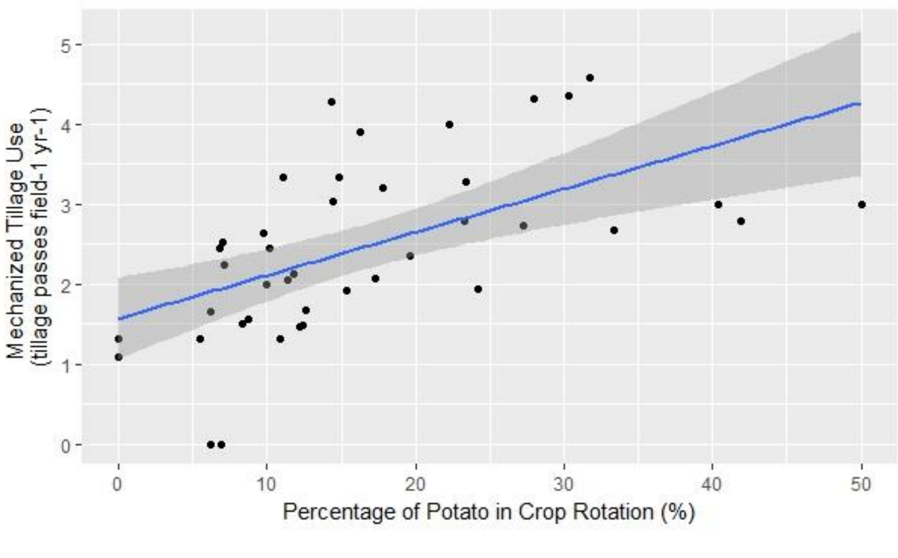

Figure 6: *Linear regression analysis for the relationship between the proportion of potato (as a cash crop) in the overall cropping rotation and mechanized tillage use per field per year. 95% confidence region highlighted in the shaded area. p = <0.001, Adj. R² = 0.29*

3.3. Farmer predictions of farm management changes as a result of changes to labour and financial resources

The responses from farmers when asked about how they would change farming practices as a result of increased or decreased access to labour or financial resources provided complementary insights on the statistical analyses of current farming practices in the community. The most recurrent responses given by farmers in the scenarios of changes to both labour availability and financial resources addressed issues of increasing and decreasing potato and milk production (Fig. 7). Specifically, in the scenarios looking at changes to labour availability, farmers tended to respond that they would decrease potato and milk production in case of decreased labour availability (Fig. 7a). In the case of greater labour availability, it appeared that farmers tended to respond that they would increase livestock production (omitting the potential to increase potato production). Moreover, in the case of greater labour availability a number of farmers also indicated that they would increase their maintenance of “living” hedgerows and install a water harvesting pond (Fig. 7b).

In the scenario of decreased financial resources farmers most often responded that they would decrease potato production. They also indicated that they were likely to reduce the use of artificial fertilizers and increase pasture production (Fig. 7c). On the other hand, in the case of an increase in financial resources, farmers responded that they would increase potato production, install water harvesting ponds and increase the use of chemical fertilizers (Fig. 7d).

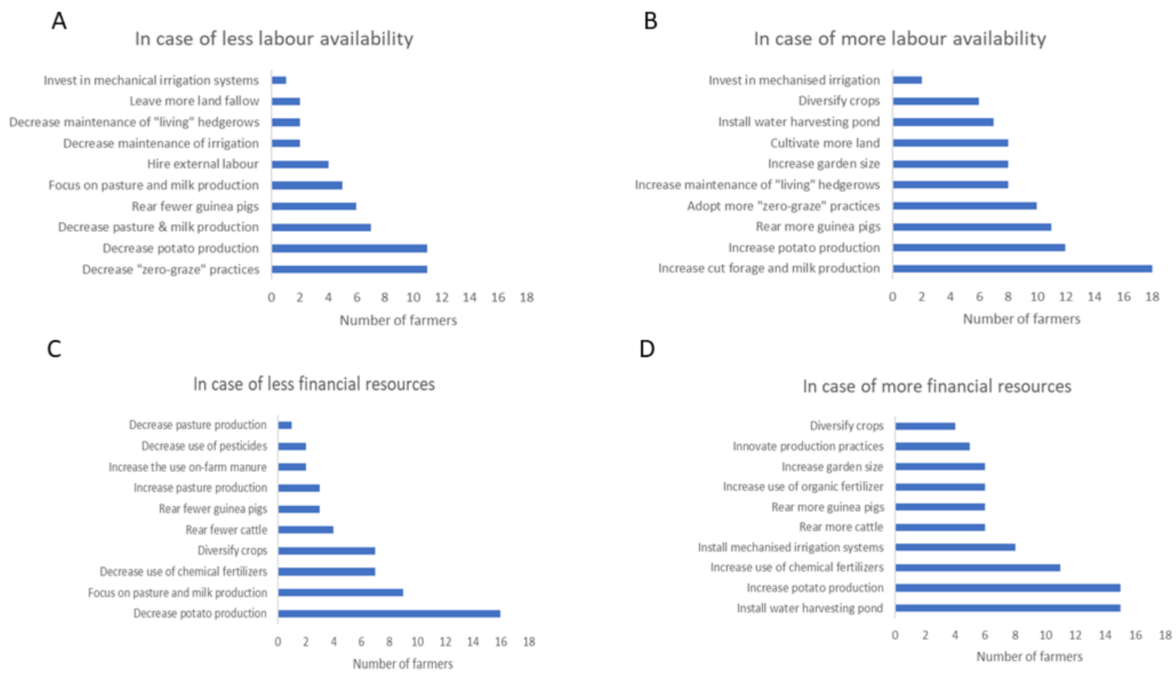

Figure 7: *Ten most popular farmer responses of how they would change their farming practices in case of A) less labour availability; B) more labour availability; C) less financial resources; D) more financial resources*

4. Discussion

4.1. Household labour availability

One of the most obvious consequences of rural out-migrations is the loss of household labour availability. As hypothesised, we found evidence that physical SWC techniques tended to be neglected with less household labour availability. Specifically, we found that the use of physical SWC techniques is positively correlated to both the number of permanent members of the household and household labour availability (Table 3). Moreover, in the changes to resources scenarios interview, farmers indicated that in case of increased labour availability they would increase their maintenance of “living” hedgerows and install a water harvesting pond. They reported the opposite in the case of a potential decrease in labour availability (Figs. 7a and 7b). This finding corroborates other studies such as Zimmerer (1993) who found that 46% of households in the Calicanto watershed in Bolivia stopped practicing at least one type of soil conservation technique in the face of a growing labour shortage. Similarly, Jaquet et al. (2015) found that decreases in population led to land abandonment and lack of terrace management in a sub-watershed in Nepal (Jaquet et al., 2015).

We note that the number of migrants was not significantly correlated with the use of physical SWC techniques. The reason for this may be two-fold; when considering permanent national migrants, we observed no significant relationship with any of the labour availability variables, which explains the absence of a correlation with the use of SWC techniques. With regard to temporary migration, the overall numbers of migrants negatively correlated with the number of permanent household members. However, the relationship is not significant with the total labour availability of the households (Table 2). This would indicate that the time spent by temporary migrants on their return to the community may be sufficient to influence the household labour resource base, and thus their capacity to implement and maintain the physical SWC techniques.

Beyond these observations, given the strength of the relationship between both permanent household members and the overall household labour availability to the number of physical SWC techniques and the responses given by farmers to scenarios involving variations in access to labour, we can assume that any general trend that will exert a downward pressure of labour availability, such as out-migration, is likely to exhibit a tendency for a decreased use of physical SWC techniques in this community.

Similar to the use of physical SWC techniques, the total area of land used for cropping per household is positively correlated to both the number of permanent members of the household and household labour availability (Table 3). This, along with the observation that the proportion of potato crop in the rotation (cash crop) is negatively correlated with permanent farming household members (Table 3), as is agro-chemical use and mechanized tillage (Table 3), suggests that households with fewer migrants generally adopted less intensive cropping strategies relying more on livestock production.

Indeed, farmers indicated in the scenario analyses that in the case of greater labour availability they would be most likely to increase cut forage and milk production (Figs. 7b).

Past findings examining the effect of labour availability on management decisions are not entirely consistent with regard to this finding. For example Gray and Bilsborrow (2014), found that households experiencing decreases in labour availability through out-migration tended to 'de-intensify' their agricultural activities using fewer agricultural inputs on an increasing amount of farm land. While, Hull (2007) in north-east Thailand and Taylor et al. (2003) in east China, found that households with labour-migrants were able to intensify their agricultural production. As we will discuss below, these inconsistent findings may be related to an inter-play between the general direct consequences of migration (loss of labour availability and increase in remittances) and other indirect relationships, such as livelihood strategies, which are influenced by the broader socio-ecological context.

4.2. Access to financial resources (remittances)

As observed in the linear regression analyses, the greater the amount of remittances provided by temporary migrants, the larger the proportion of potatoes grown in the overall crop rotation (Table 3, Fig. 3). It was also observed that both higher remittances and production of potatoes were associated with a greater use of chemical fertilizers, pesticides and mechanized tillage. These findings reflected the responses provided by farmers in the scenario interviews asking how their farm management would change in the case of more or less access to financial resources. The most popular response by farmers in case of less access to financial resources was to decrease potato production followed by the use of fewer chemical fertilizers. In the case of more financial resources, the joint-top response from farmers was to increase potato production followed by an increase in the use of chemical fertilizers. As such our findings support our original hypothesis and corroborate others who have suggested additional financial resources received from remittances compensates for the loss of available family labour (Mendola, 2008; Gray, 2009; Gray and Bilsborrow, 2014).

In order to further investigate the relationships between out-migration and farm management and to potentially better understand the inconsistent results found in the literature, we used structural equation modelling to tease out direct and indirect effects. This analysis suggested that temporary out-migrations (as the main contributors to off-farm income) were not directly related to an increased use of more industrialized farming techniques, but were indirectly related to their use through their effects on access to greater financial resources and farm-level decisions to increase the proportion of potato cash cropping (Fig. 2). As such, we can conclude, that households with temporary out-migration in this community appear to be adapting their livelihood strategies to bet on higher risk cash crop production based on the opportunities (greater financial resources) out-migration presents within this particular socio-economic context.

This finding reflects the conclusions of Qin (2010) who found that rural livelihood strategies were an integrative mediating factor in the way in which migrant-sending households responded to the opportunities and challenges brought by out-migrations. Moreover, Qin argued that broader social and economic issues at national and regional levels, such as property rights, influenced these household livelihood decisions, (Qin, 2010). The conclusions also reflect those of other authors who postulate that the effects of rural out-migrations are dependent, for example, on the overall suitability for the expansion of commercial agriculture (Gray, 2009) or mediated in varying degrees by socioeconomic conditions, gender dynamics, and cultural factors (Greiner and Sakdapolrak, 2013).

Taking these observations into consideration, as posited by Mata-Codesal (2018); Stockdale and Haartsen (2018); and Ye (2018) we also argue that temporary out-migration (in contrast to permanent national migration), in this particular socio-ecological context, may be better viewed as a mechanism for farming families to remain in the community by integrating the opportunities presented by mobility into their livelihood strategy. In particular, we note that temporary migrants contributed much more money to the household income than permanent national migrants (Table 1), and the gender balance for temporary migrants was more skewed towards male migrants than female migrants when compared to permanent national migrants (Table 2). The financial contribution of temporary migrants to the household appears to suggest they were heavily invested, and played an important role, in the overall household livelihood strategy (ie, a mechanism to stay). The reason for the skewed gender balance in temporary migration on the other hand may reflect the off-farm employment opportunities available regionally and nationally.

4.3. Implications for research and development

Based on these conclusions, in line with our hypothesis and the work of Geist and Lambin (2002) we argue that the results of the current study seem to imply that land-use change does not necessarily follow a universal pathway of development as may have been suggested in the early formulations of the Forest Transition Theory. Moreover, as with de Sherbinin et al, (2008) and Caldas et al. (2007) these results also appear to suggest that the relationships between land use and farm management change and rural population mobility are mediated by interactions between both proximate and underlying factors that are broader than the original formulation of the Household Lifecycle Theory.

In the current socio-ecological context of the community of Carrillos, access to financial resources and labour played important roles in household-level decisions regarding livelihood strategies and farming practices. However, broader contextual factors must also have played a part in shaping farmers’ decisions. Market opportunities (access and distance from market, market demand etc) and agricultural inputs availability were obvious important factors in farmers’ decisions as regards how to benefit from the opportunities presented by temporary migration, as was also concluded by Perz and Walker (2002) in their adaptation of the Household Lifecycle Theory. If the market demand for potatoes, for example, was non-existent or inputs for potato production unavailable, remittances in

Carrillos may have been invested outside agriculture (eg, in housing or real estate), as observed by Jokisch (2002).

Beyond the context of the market, other factors may also have played an important role in shaping the pathways adopted by farmers in the face of the opportunities and challenges posed by increasing population mobility. In the mountainous landscapes of the study site in particular, biophysical constraints and opportunities must also be considered as important underlying factors that mould farming practices and should be considered in future empirical research. For example, elevation and its associated climate and precipitation gradient clearly influence farm management and cropping choices in mountainous regions (Chapter 4).

Moreover, while Carrillos enjoys relatively shallow slopes, in other communities in the parish, the average slope gradients can be much steeper. In these areas SWC practices may be perceived as critical by farmers and therefore we may not observe the same correlation between labour availability and the use of SWC practices. Instead, we may observe a decrease in cultivated land in the case of decreased labour availability, or a trend to farming systems including fallows (Perz and Walker, 2002).

Human and social resources are also likely, in this current context, to have played a role in the processes leading to changes in farm and land-use management. Cultural habits and practical agronomic knowledge in this Andean community may be contributing to the increased production of potatoes as households gain access to greater financial resources as a result of temporary migration. Potato is both a staple and a cash crop. As a staple crop, farmers' potato production knowledge is well developed and therefore the shift toward commercializing the product may be somewhat easier than other crops with which farmers in the community have less experience. Associated with this factor, is the potential role of social networks in promoting the production of certain crops. The more farmers see and hear success stories of certain practices, the more likely they are to copy such practices (Bandiera and Rasul, 2002; Conley and Udry, 2001).

The findings highlighted above have important implications for governmental and non-governmental rural development policies and interventions. As observed here, out-migration patterns can lead to significant within-community heterogeneity in terms of farming systems and livelihood strategies. Households with higher levels of temporary out-migration invested more in (riskier) potato cash crops and as a consequence also more in agro-chemicals and mechanized tillage; agricultural practices which may be associated with land degradation (Fonte et al., 2012). Moreover, the loss in household labour availability appeared to be associated with a tendency to use fewer physical SWC techniques. As such, we argue, that in this instance, migration is likely leading to less sustainable farming strategies, particularly in the case of tillage and the use of physical SWC techniques, with important implications for long-term agricultural production and land degradation. Indeed, given the importance of potato as a cash-crop throughout the highlands of Ecuador and the fragile nature of the mountainous landscapes, continued rural out-migrations that generate greater financial resources and lead to the cultivation of more potatoes with greater management intensification poses serious land degradation threats to the sustainability of the Ecuadorian Andes.

Intervention strategies to address these threats must explicitly recognise within community heterogeneity in out-migration patterns and livelihood strategies. For example, a farming household with reduced labour availability may not respond well to intervention strategies promoting the use of labour intensive physical SWC techniques or production methods. At the same time, farming households with little or no temporary migration may respond better to the promotion of physical SWC techniques or even to the diversification of cropping patterns. Intervention strategies therefore need to consider the disparities of labour availability and income among the households, focusing on integrated farm management and the inclusion of more sustainable farming practices on the farm. Hence, similar to conclusions of research done in a comparable setting in Bolivia (Kessler, 2007) training, awareness raising on soil fertility management, and transfer of knowledge should be core issues in any agricultural intervention strategy in this area.

More broadly, it will be important to explore future perspectives and alternative, endogenous development pathways that may lead to farming households 'stepping-up' their agricultural production or indeed 'stepping-out' of agriculture (Tittonell, 2014). In this respect, the opportunities all types of population mobility presents should be considered as mechanisms to empower rural households to 'stay put' or 'move-out' should they so wish.

Secondly, intervention strategies must also explicitly recognise that out-migration patterns may lead to contrasting responses in farming systems and livelihood strategies in different communities due the inherently unique socio-ecological contexts. As observed above, farming households in this study responded to the challenges and opportunities of rural out-migration through the intensification and commercialization of their agricultural practices. However, as observed in other studies, this is not always the case (Jokisch, 2002; Qin, 2010; Shi et al., 2011). Hence, addressing the challenges and opportunities of rural out-migrations in different regions and communities requires significantly different approaches. Moreover, we would argue that attention should also be given to the macro socio-economic and cultural factors that are influencing the responses to potential increases in financial resources or losses of household labour availability.

From a research perspective we argue that greater attention should be placed on trying to better understand the direct vs. indirect relationships between rural out-migrations, farm management and agroecosystem health. This will enhance our understanding of the effects of migration on farming and the rural environment. Moreover, we suggest conducting more cross-site studies that can empirically compare different socio-economic and cultural contexts, so as to generate a better understanding of the macro-level influences on the farming responses to out-migration patterns.

5. Conclusions

Rural out-migrations from the community of Carrillos and elsewhere in Ecuador are clearly an important social trend, with many households experiencing both temporary and permanent migration of family members. These out-migrations are having a profound effect on the farming systems of rural communities as migrant-sending households adapt their farming practices and livelihood strategies in the face of new challenges and opportunities associated with migration. We have observed that temporary migration, in particular, generated important increases in the financial resources of sending farming-families leading to investments in potato cropping and hence greater use of agro-chemicals and mechanized tillage. Furthermore, decreased household labour availability was associated with decreased use of physical SWC techniques. Therefore out-migration may be leading to significant land and soil degradation processes in this case study.

However, it is important to recognise that the current research is limited in spatial scope comprising of a case-study in a unique socio-ecological context. Furthermore, the lack of a temporal, inter-generational perspective within the case study limits our ability to observe changing patterns and causal relationships over time. Nevertheless, the study does provide important generalisable insights into the effect of population mobility on land-use and farm management change providing evidence that responses to out-migration are not always direct, but mediated by indirect relationships within a socio-ecological system. This implies that rural out-migrations will lead to alternative responses in communities in different socio-ecological contexts, explaining to a great extent the inconsistent findings in the research literature. It is argued that more research is necessary to develop a greater appreciation of these direct and indirect socio-ecological relationships within rural communities to better understand the processes behind land-use and farm management change. Importantly, rural development policies, programmes and projects must explicitly recognise these broader socio-ecological contexts and their effects on farm-level decisions in view of migration in order to develop more effective intervention strategies.

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Chapter 3: Between community and within farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape

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Abstract

Organic matter (OM) inputs play a critical role in the sustainability of farming systems in the highland tropics. However, asymmetric allocation patterns of these resources among communities and within individual farms can lead to important soil fertility gradients. The objective of this study was to document and better understand the underlying causes for such asymmetric allocation patterns and their consequences in order to inform natural resource management strategies. The study was carried out in three indigenous Kichwa communities located in Chimborazo Province, in the Central Ecuadorian Andes. The communities are located in close proximity to one another, but differ in terms of biophysical contexts, linkages to local markets, farming strategies, and access to resources. Field variables 'distance from homestead' and 'perception of fertility' were associated with asymmetric OM allocation patterns to fields and were also significantly associated with soil fertility gradients within farms. For example, soil organic carbon (SOC), total nitrogen (N), available phosphorus (P) and exchangeable potassium (K) all decreased with distance from the homestead ($p < 0.001$) while SOC, total N and available P were positively correlated with farmers´ perception of soil fertility ($p < 0.001$). We note that these fertility gradients were not diminished by increased farm-level OM inputs. Overall OM allocation patterns differed significantly among communities ($p = 0.003$), and were associated with significant differences in soil fertility, with the highest levels of available P and exchangeable K found in the community with the highest OM inputs ($p<0.001$). The results of this study demonstrate the importance of asymmetric OM allocation patterns that may be encountered at different scales, both within farms and among neighbouring communities, in rural Andean landscapes and their significant interactions with soil fertility gradients.

1. Introduction

Organic matter (OM) inputs play an important role in the sustainability of farms in the tropics, both in terms of providing nutrients to support productivity and in the longer-term maintenance of soil organic matter (SOM), and associated agroecosystem functions (Craswell and Lefroy, 2001; Palm et al., 2001). SOM is essential for promoting a range of ecosystem services such as improved soil structure (Bronick and Lal, 2005), water capture and storage (Franzluebbers, 2001; Nissen and Wander, 2003), carbon (C) sequestration (Chapter 4; Takimoto et al., 2008) and the maintenance healthy soil food webs (Moore et al., 2004).

Crop residues, manure and other OM resources produced on farm represent important nutrient sources in smallholder farming systems, as severely constrained financial resources limit the purchase of alternative sources of nutrients, such as commercial composts or mineral fertilizers (Fonte et al., 2012; Palm et al., 2001). Waste streams from existing industries, such as poultry farming, however, offer promising fertility sources for many peri-urban farming communities with severe nutrient deficits (Fonte et al., 2012). Poultry manure, in particular, is highly valued as a source of organic nitrogen (N) and phosphorus (P) in many regions (Moore et al., 1995).

While soil properties vary naturally within a landscape due to varying pedogenic conditions such as climate, topography and the underlying geology, land and farm management are also important drivers (Caulfield et al., in prep; Van Apeldoorn et al., 2013). In rural areas patterns of organic matter resource allocation can create management-induced soil fertility gradients both within and among farms (Tittonell et al., 2013), thus driving processes of soil degradation or aggradation (Van Apeldoorn et al., 2011).

A number of socio-economic factors have been observed to influence agricultural inputs (e.g., Berkhout et al., 2011; Chikowo et al., 2014; Tittonell et al., 2013). Household wealth, in particular, has featured as an important factor that influences organic and inorganic nutrient inputs. Cobo et al.

(2010), in a meta-analysis of 57 nutrient balance studies in East Africa, found that wealthier farmers typically present higher N and P balances than poorer farmers.

In addition to farmer wealth different financial, natural, social and human resources have also been shown to influence nutrient inputs. For example, in a study in the central highlands of Ethiopia organic nutrient inputs into fields were directly related to the number of livestock holdings (Haileslassie et al., 2007). In another study in Uganda it was found that larger farms with greater off-farm income displayed the most positive nutrient balances (Ebanyat et al., 2010). Access to labour has also long been considered one of the main constraints to improved natural resource management (Barrett et al., 2002; Marenya and Barrett, 2007; Zimmerer, 1993).

In addition to socio-economic drivers of resource allocation, within-farm factors can also determine farm resource allocation at the field level (Chikowo et al., 2014). For example, a number of studies have found that 'home' or near-fields of farms receive greater inputs and as a consequence are more fertile compared to remote fields (eg, Kamanga et al., 2010; Zingore et al., 2007). Although it is noteworthy that the reverse has also been found in a case study Zimbabwe, where due to the more recent conversion of this land from forest to agricultural land-use, improved fertility was found in remote fields (Masvaya et al., 2010).

Perception of a field's inherent quality has also been found to be associated with resource allocation patterns with those fields perceived as more productive (and fertile) often receiving greater inputs than less productive fields (e.g., Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2005a). In the Andes, one study on field nutrient balances has demonstrated similar within-farm gradients (Vanek and Drinkwater, 2013), while noting fewer between-farm differences in nutrient management than in African cases. However, this single study from a remote Bolivian context suggests the need for more examination of Andean systems, including the important aspect of community to community variation.

While farm management is an important driver of soil patterns in rural landscapes, the underlying biophysical context is also a critical factor (Pennock and Veldkamp, 2006). The strength of influence of farm management on the soil patterns of a rural landscape compared to the underlying biophysical conditions appears to differ between the main soil chemical properties. For example, while it appears that farm management can induce important fertility gradients for P and K (Tittonell et al., 2005c; Zingore et al., 2007), it is not always the case for soil organic carbon (SOC) due to the influence of longer-term, biophysical drivers such as soil texture, climate and hydrology (van Apeldoorn et al., 2014).

Based on crop productivity differences, fertility gradients in the Ecuadorian landscapes considered here seem conspicuous. Our objective was to develop a better understanding of these landscape patterns of soil fertility and the drivers behind them in order to contribute to improved farm and natural resource management. To achieve this, we examined socio-economic, cultural and farm management factors that influence OM inputs, and the association of these factors with soil fertility gradients across three Andean communities.

We hypothesised that community and farm-level variables as well as within-farm differences such as distance from homestead and perception of fertility would significantly influence OM inputs. We further anticipated that asymmetric allocation of OM inputs would be associated with soil fertility gradients between communities and within farms and that these patterns would also be related to the differing underlying biophysical contexts found between the three communities.

2. Materials and methods

2.1. Site description

The study was carried out between February-April 2016, in three indigenous Kichwa communities located in the parishes of Flores (communities of Basquitay and Naubug) and Licto (community of

Tzimbuto), Chimborazo Province, in the Central Ecuadorian Andes. The communities are situated in close proximity to one another, but differ significantly in terms of elevation ranges, linkages to local markets, farming strategies, and access to resources (Fig. 1 and Table 1). The climate enables nearly year-long production with average temperatures ranging between 10 and 18°C. Average annual precipitation ranges from 250–500 mm in the parish of Licto and 400-500 mm in the parish of Flores, with greater rainfall at higher elevations and most rain falling between December and May and a drier, windier period from May to November (GAD Parroquial Rural de Flores, 2015; GAD Parroquial Rural de Licto, 2014).

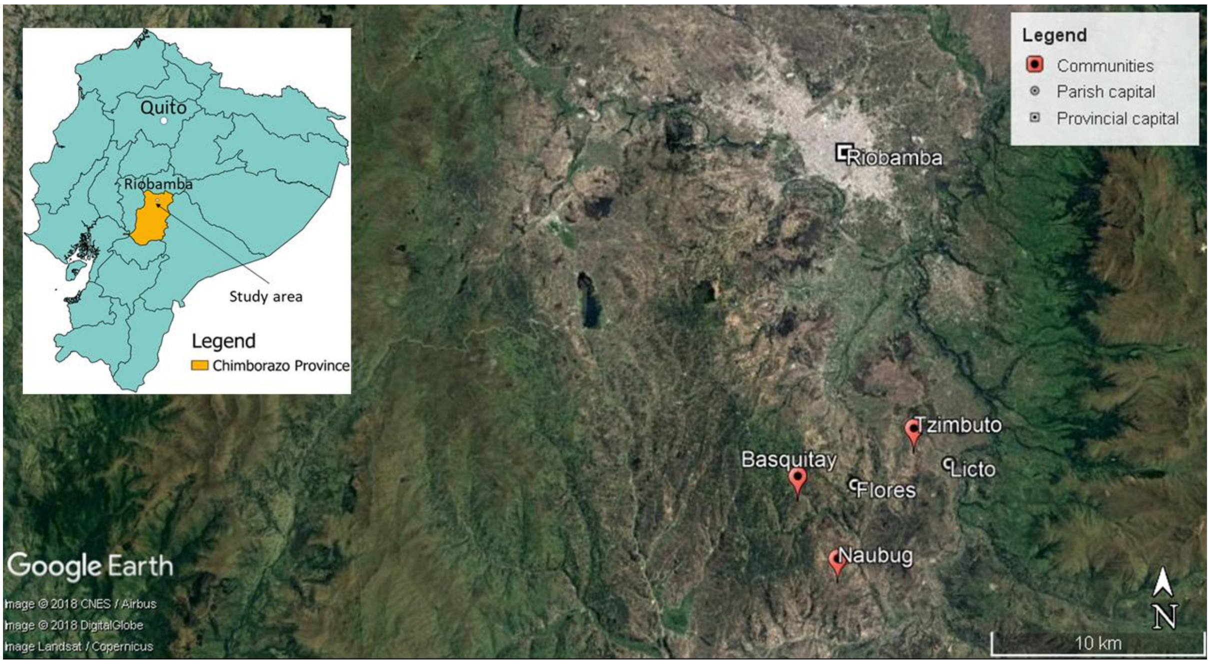

Figure 1: *Location of the three communities of study in relation to provincial and parish capitals. Inset: map of Ecuador, the Province of Chimborazo and the location of the communities of study, Basquitay, Naubug and Tzimbuto.*

The diverging elevation ranges mean that the three communities developed under ecosystems dominated by different vegetation types. The natural vegetation of Basquitay, as the highest community (3400-3650 m.a.s.l.), is characterised as páramo grassland with some significant patches still remaining in the community. Tzimbuto (2800-3250 m.a.s.l.) on the other hand likely developed under sub-páramo and Andean forest conditions, while Naubug, with the greatest range in elevations (2800-3600 m.a.s.l.), likely comprised the three different ecosystems. Remnants of these “natural” ecosystems no longer exist in either Naubug or Tzimbuto. Soils in the study area are generally classified as Andosols developed on deep ash deposits. Where management has been less intense, surface soil horizons are deep and high in SOM, while intense management in many other areas has denuded the A horizon, revealing SOM-poor sub-soils composed of hardened volcanic ash known locally as ‘cangahua’ (classified as inceptisols or entisols; USDA soil taxonomy). These soils are especially prevalent in the communities of Naubug and Tzimbuto (Fig. 2).

Figure 2: *Photos of the varying landscapes of Basquitay (A), Naubug (B) and Tzimbuto (C), Province of Chimborazo, Ecuador.*

Major crops grown in the communities include potato (*Solanum tuberosum L.*) and other Andean tubers (e.g., Oca (*Oxalis tuberosa*), Mashua (*Tropaeolum tuberosum*) and Ulluco (*Ullucus tuberosus*)), cereals such as maize (*Zea mays*), quinoa (*Chenopodium quinoa*), barley (*Hordeum vulgare L.*) and oats (*Avena sativa*). Cereals are cultivated both for human consumption and cut forage. Alfalfa (*Medicago sativa*) and vetch (*Vicia*) are also grown for forage. More market-oriented farms, mainly in Tzimbuto (which has irrigation access), grow high-value vegetables. At higher elevations (above 3400m.a.s.l.) forage crops, quinoa and faba bean (*Vicia faba*) are most common. At lower elevations cereals dominate along with high-value cash crops (where irrigation is available). Farmers at all elevations rotate other crops with potato as a linchpin crop which receives the greatest amount of OM inputs. Farming families usually have at least two heads of cattle (for animal traction and milk) as well as pigs, sheep, and smaller animals such as chickens and guinea pigs. Some farms gain income from selling milk and livestock, though both herd composition and the market role of livestock varies among communities (Table 1). Farmer-owned livestock supply most of the OM inputs in these communities, although Tzimbuto imports significant amounts of chicken manure from industrial chicken farms in the region.

Table 1: *Socio-economic and farming characteristics of the studied communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador.*

Community Characteristics	Basquitay	Naubug	Tzimbuto
Population	120	641	415
Area (km^2)	3.73	8.11	3.73
Population density (persons km^{-2})	32.17	79.04	111.26
Elevation range (m.a.s.l.)	3400-3650	2800-3600	2800-3250
Maximum walking distance of fields from homestead (min.)	60	90	60
Average number of livestock (excluding small livestock)	15.1 (se: 1.86)	5.2 (se: 0.80)	11.1 (se: 1.90)
Main crops cultivated	Forage, tubers	Forage, cereals (for human consumption), tubers	Forage, cereals, vegetables, tubers
Import of manure from outside community	Rare	Rare	Regular
Import of cut forage from outside community	Rare	Regular	Regular
Access to irrigation	No	No	Yes
Market orientation	Livestock, milk production	Few or no products sold	Agricultural products, vegetables, milk and livestock
Main source(s) of income	Social security, livestock (milk and animals), and off-farm income	Social security and off-farm income	Social security, livestock (milk and animals), sale of agricultural produce and off-farm income
Diversified Sources of Income*	4/10	3/10	10/10
Income generated from livestock**	8/10	4/10	7/10

Community Characteristics	Basquitay	Naubug	Tzimbuto
Income generated** from sale of agricultural production	1/10	4/10	10/10

*Number of farmers out of 10 interviewed gaining income from at least 2 significant income sources (sale of agricultural production; sale of livestock or livestock products; off-farm income)
**Number of farmers out of 10 interviewed gaining regular income from the sale of agricultural production or the sale of livestock or livestock products

2.2. Farm and livelihood analysis

Workshops were held in the communities with ten volunteer farming households from each community selected to participate in this research. A farming systems survey based on ImpactLite (Rufino et al., 2013) and adapted for the Andean context was then conducted individually with the main labourer of each farming family to provide household data on family composition, market orientation and income.

Due to the high variability in monthly and yearly income from crop and livestock sales, these variables were expressed as categorical variables. When the farmers were able to sell crops or livestock on a regular basis, this was classified as 'regular' income; while 'irregular' income was applied when farmers only sporadically engaged in opportunistic sales of their crops or livestock in times of surplus. The 'diversified income sources' variable was set as diversified when the household received income from at least two significant income sources (sale of agricultural production; sale of livestock or livestock products; or off-farm income).

The survey was supplemented by working individually with farmers to develop a farming resource-flow diagram for each household, which depicted the main resource flows to and from each field, as well as the main characteristics of these fields.

2.3. Soil and field data collection

Four fields per farm were selected together with farmers to encompass a range of soil and environmental conditions as well as distances to the homestead. Soils were sampled in each field by combining 20 sub-samples (0-20 cm) from each field to generate a composite sub-sample of around 2 kg. Soils were air-dried and transported to the laboratory of the Ecuadorian National Institute for Agricultural Research (INIAP) for analysis. Each soil sample was analysed for texture (Bouyoucos, 1962), SOC (Walkley and Black, 1934), total N (Kjeldahl, 1883) as well as available P and exchangeable K (modified Olsen method, pH 8.5; Olsen et al., 1954).

Additional data collected for each field included: elevation (using a GPS), slope (using an inclinometer), distance from homestead (in min. walking time), the farmers' perception of relative soil fertility (categorized as 'very good', 'good', 'average' and 'poor'), field size, current and historical (past four crop cycles) data on crop rotations and organic fertilizer inputs (according to a short farmer questionnaire). Where appropriate, this information was cross-referenced with the data generated from the farming systems survey and resource-flow diagrams, and any discrepancies were rectified by the farmer at a field workshop that took place a few weeks later. Mean fresh weight of OM inputs (Mg ha^{-1} cropping cycle^{-1}) were calculated based on the inputs over the past three cropping cycles in order to take into account the differences in inputs according to the different crops present in a field crop rotation pattern.

2.4. Statistical analysis

Between community differences in soil chemical and textural parameters were evaluated using ANOVAs with a Post-hoc Tukey's Honest Significant Difference Test. To examine for the relative influence of "community" on the quantity of OM inputs to fields, the mean OM inputs across the four fields were calculated for each farmer and analysed using multiple linear regression models, with OM inputs being the response variable and community being used as a categorical explanatory variable. A Post-hoc Tukey's Honest Significant Difference Test was also applied to compare OM inputs among the three communities.

To further assess the potential effects of more granular, between farm, socio-economic variables on OM inputs, a mixed linear regression model was fitted for OM inputs against fixed effects for community and each socio-economic explanatory variable. Income from livestock; income from crops; off-farm income; and diversified income sources were treated as categorical explanatory variables while number of family members dedicated to farming; and average age of active farm workers were treated as continuous explanatory variables.

To assess the potential effects of within-farm variables on OM inputs (per field) mixed linear regression models were fitted for OM inputs against the explanatory variables, with nested random effects for community and farm within community included. Distance from homestead was treated as a continuous explanatory variable, while perception of fertility was treated as categorical explanatory variable.

Finally, to assess the relationships between OM inputs and soil chemical properties; and within farm variables and soil chemical properties, regression models for four soil parameters (SOC, total N, available P and exchangeable K) were produced in a stepwise process for each explanatory variable (OM inputs; distance from homestead; and perception of fertility). Initially a mixed linear regression model was fitted for each soil parameter against fixed effects for community, the explanatory variable and the interaction between community and the explanatory variable. In addition, because of the structure of the data collection procedure with four fields sampled within a single farm, a random effect was included within this model for farm. Where the interaction term was significant, separate models were then fitted within each community, with a random effect for farm. Where the interaction was not significant then a single model was fitted, with nested random effects for community and farm within community.

Data for OM inputs, sand content, SOC, total N, available P, and exchangeable K were log-transformed to meet the assumptions of homoscedasticity and normality. All analyses were carried out within the RStudio environment Version 0.99.902.

3. Results

3.1. Differences in soils between community

Of the three communities studied, Basquitay's soils displayed significantly higher levels of clay, total N and SOC, and lower levels of sand, available P, and exchangeable K than soils of Naubug and Tzimbuto (Table 2).

Table 2: *Soil texture and chemical characteristics for the communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. Standard errors are presented in parentheses, while different letters indicate significant differences (p = <0.05) according to the Post-hoc Tukey's Honest Significant Difference Test.*

Soil Characteristics	Basquitay	Naubug	Tzimbuto	P-Value
Clay (%)	18.06 (1.60)a	12.19 (2.07)b	12.81 (1.56)b	***<0.001***
Silt (%)	46.11 (2.01)a	42.88 (2.74)b	44.90 (2.21)ab	***0.002***
Sand (%)#	35.99 (2.01)b	45.11 (3.94)a	42.33 (2.00)a	***<0.001***
SOC (%)	4.07 (0.66)a	1.66 (0.56)b	1.09 (0.28)c	***<0.001***
Total N (%)	0.35 (0.06)a	0.14 (0.04)b	0.12 (0.05)b	***<0.001***
Available P (mg kg-1)#	17.80 (14.77)b	39.88 (32.96)a	55.77 (30.89)a	***<0.001***
Exchangeable K (cmol kg^{-1})#	0.61 (0.65)b	0.88 (0.47)a	1.02 (0.34)a	***<0.001***

log transformations were applied to the data for ANOVA and the Post-hoc Tukey's Honest Significant Difference Test to adhere to the assumptions of normality and homoscedasticity. Mean values and SE are calculated based on non-transformed data.

3.2. Drivers of organic matter inputs

The only socio-economic and cultural variable to display significant differences in OM inputs was that of 'Community' (Table 3). As shown in Fig. 3a, farmers in the community of Tzimbuto applied significantly more OM inputs to their fields compared to Basquitay and Naubug, according to the Tukey Tests.

Table 3: *P-values and R^2 values for multiple linear regression analyses assessing the relationships between OM inputs and between community, between farm, and within farm explanatory variables in the communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador.*

Explanatory variable	P-value	$R^{2\#}$
Between community		
Community	***0.003***	***0.29***
Between farm		
Number of family members dedicated to farming	0.513	0.01
Average age of active farm workers	0.294	0.02
Income from livestock	0.962	<0.01
Income from crops	0.348	0.03
Off-farm income	0.320	0.05
Diversified income sources	0.585	0.01
Within farm		
Walking distance from homestead (per 10 mins)	***<0.001***	***0.22***
Perception of fertility	***0.002***	***0.13***

#Pseudo R^2 values are presented for linear regressions with fixed and nested random effects.

Distance from homestead and perception of fertility displayed significant relationships with OM inputs (Table 3), such that OM inputs decreased with distance from homestead (Fig. 3a); and with decreasing perception in the fertility of fields (Fig. 4a).

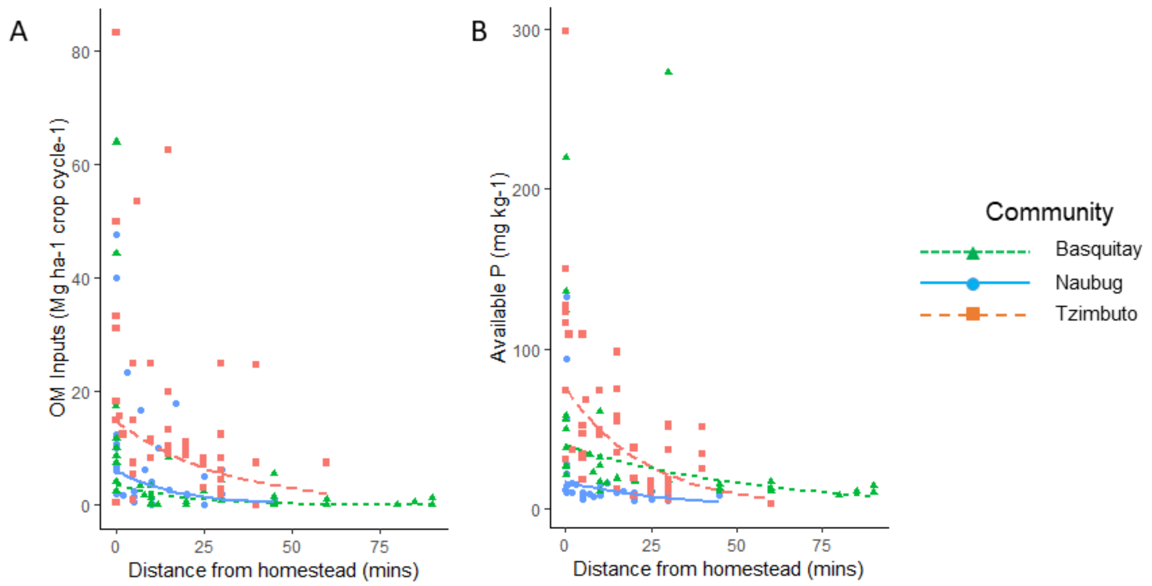

Figure 3: *Relationship between field walking distance from homestead and organic matter inputs (A) and available P (B) for fields of the communities of Basquitay, Naubug and Tzimbuto, Chimborazo province, Ecuador.*

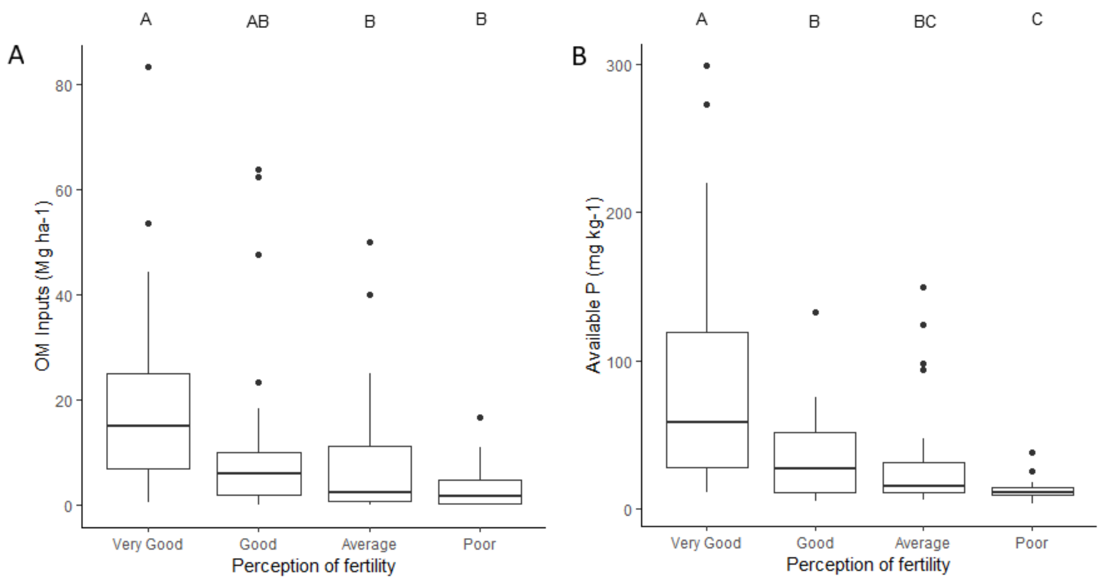

Figure 4: *Differences in organic matter (OM; A) inputs and available P (B) based on farmers' perception of field fertility in the communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. Points located outside the "whiskers" of the boxplots are considered outliers (≥1.5*

interquartile range). Post-hoc Tukey's Honest Significant Difference Test results are presented above each box at the top of the plots, with different letters significantly different at the P < 0.05 level.

3.3. Organic matter inputs, within farm variables and soil chemical properties

OM inputs were positively related with total N, available P and exchangeable K. A significant interaction between inputs and communities was observed for SOC, such that the effect of OM inputs on SOC was significant for the communities of Naubug and Tzimbuto, but not for the community of Basquitay (Table 4).

Distance from homestead displayed significant negative relationship with total N. Significant interactions between distance from homestead and communities were observed for SOC, available P and exchangeable K. SOC only displayed a significant negative relationship with distance from homestead in the communities of Naubug and Tzimbuto. Tzimbuto displayed the strongest negative relationship of distance from homestead for available P between communities, while Basquitay exhibited the strongest negative relationship for exchangeable K (Table 5).

Perception of fertility displayed significant relationships with total N and available P, but not for exchangeable K. A significant interaction between communities was observed for SOC, such that fertility of perception was only associated with SOC in the communities of Naubug and Tzimbuto. For all soil chemical properties, including exchangeable K, but with the exception of SOC in the community of Basquitay, fields that farmers perceived to be most fertile ("very good" or "good") displayed the highest levels of the macronutrients measured. Conversely, those fields that were perceived to have "poor" fertility exhibited the lowest levels of macronutrients (Table 6).

Table 4: *Coefficients, standard errors (in parentheses) and p-values for mixed model linear regression analyses testing the relationship between OM inputs and four different soil chemical properties (SOC, total N, available P and exchangeable K) in Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. In the case where a significant interaction was found between 'OM inputs' and 'communities', the mixed model linear regression analyses were applied separately by community with a random effect included for 'farm'. Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for 'community' and random effect for 'farm'.*

Soil chemical property	Coefficient (standard error)	Interaction between inputs and community (P-value)	Basquitay	Naubug	Tzimbuto
SOC (%)	-	***0.049***	0.015 (0.074)	***0.192 (0.055)*****	***0.125 (0.057)****
Total N (%)	***0.10 (0.03)*****	0.388	-	-	-
Available P (mg kg^{-1})	***0.27 (0.05)******	0.397	-	-	-
Exchangeable K (mmol kg^{-1})	***0.24 (0.06)******	0.240	-	-	-

*p < 0.05; **p < 0.01; ***p < 0.001.

Table 5: *Coefficients, standard errors (in parentheses) and p-values for mixed model linear regression analyses testing the relationship between distance from homestead and four different soil chemical properties (SOC, total N, available P and exchangeable K) in Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. In the case where a significant interaction was found between 'distance from homestead' and 'communities', the mixed model linear regression analyses were applied separately by community with a random effect included for 'farm'. Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for 'community' and random effect for 'farm'.*

Soil chemical property	**Coefficient (standard error)**	***Interaction (P-value)***	***Basquitay***	***Naubug***	***Tzimbuto***
SOC (%)	-	***0.031***	<0.001 (0.004)	***-0.009 (0.003)****	***-0.020 (0.004)******
Total N (%)	***-0.005 (0.002)*****	*0.124*	-	-	-
Available P (mg kg^{-1})	-	***0.010***	***-0.039 (0.009)******	***-0.018 (0.004)******	***-0.043 (0.007)******
Exchangeable K (cmol kg-1)	-	***0.024***	***-0.056 (0.017)*****	***-0.018 (0.005)*****	***-0.015 (0.006)****

*p < 0.05; **p < 0.01; ***p < 0.001.

Table 6: *Mixed model linear regression results testing the relationship between perception of fertility and four soil chemical properties (SOM, total N, available P and exchangeable K) in the communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. In the case where a significant interaction was found between 'perception of fertility' and 'communities', the mixed model linear regression analyses were applied separately by community with a random effect included for 'farm' (Supplemental Table 1). Otherwise, the results are presented for the three communities combined (with the interaction term for community removed), but including a fixed effect for 'community' and random effect for 'farm'. Means of each soil chemical property are presented by perception of fertility. Different letters to the right of the means (a, b, c) signify significant differences at the P <0.05 level.*

Soil chemical property	**p-value**	**Interaction (p-value)**	**Fertility perception category**			
			Very good	**Good**	**Average**	**Poor**
SOC (%)	***<0.001***	***0.023*** [#]	-	-	-	-
Total N (%)	***<0.001***	0.255	***0.252a***	***0.160b***	***0.162b***	***0.102c***
Available P (mg kg^{-1})	***<0.001***	0.275	***46.610a***	***25.782b***	***18.889bc***	***11.306c***
Exchangeable K (cmol kg-1)	0.251	0.738	0.587a	0.598a	0.456a	0.370a

[#] Perception of fertility was found to be significantly associated with SOC in the communities of Naubug (P <0.001) and Tzimbuto (P <0.001), but not in Basquitay (P = 0.894). Full results of the mixed model linear regression analyses for the relationship between perception of fertility and SOC by community are displayed in Supplemental Table 1.

4. Discussion

4.1. Within farm heterogeneity in organic matter inputs

The results from this study confirm our hypothesis and previous research reporting that agricultural inputs vary significantly due to field-distance from homestead and perception of fertility. It also provides evidence that these asymmetric patterns of organic matter resource allocation could be accentuating existing gradients of soil fertility across the landscape (e.g., Diarisso et al., 2016; Vanek and Drinkwater, 2013; Vanlauwe et al., 2006). Furthermore, the results seem to also suggest that the type and quality of manure inputs used by farmers in each community may be influencing these within farm soil spatial patterns.

The effect of distance from homestead was observed to be strongest in the community of Basquitay for exchangeable K, but strongest in Tzimbuto for available P (Table 5). Unlike in the other two communities, Tzimbuto imported considerable amounts of poultry manure, which is particularly rich in available P relative to the other types of manure or common OM inputs (e.g., crop residues). On the other hand, cow and sheep manure tend to have higher proportions of exchangeable K (Moore et al., 1995). Such differences in manure types may help explain the contrasting soil fertility gradients, whereby available P accumulates most in near-fields of the community using imported poultry manure and exchangeable K accumulates most in the near-fields of the communities only using on-farm generated manure.

Another noteworthy finding is that the fertility gradients are not necessarily prevented or reduced when farmers have higher farm OM inputs. While Tzimbuto's farmers incorporated nearly twice as much OM inputs into their fields on average compared to the farmers in Basquitay and Naubug (Fig. 3a), the effect of distance from homestead on available P was, in fact, stronger than for the other two communities (Table 5, Fig. 3b). This is an important finding, as it indicates that fertility gradients may not be reversed by a simple increase in access to OM inputs. Indeed, it may be that the observed effect of distance from homestead is not only a result of constrained OM resources, but a complex combination of different factors including, for example, field accessibility, farming habits and strategies, access to different agricultural fertilizer types, labour use efficiency, transport and logistics etc.

This conclusion reflects the findings of Vanek and Drinkwater (2013) who concluded in their study that asymmetric allocation of organic matter inputs were, at least partly, due to the inaccessibility of far-fields in the mountainous Andean terrain. Access to inorganic fertilizers was also found to be an important factor in asymmetric allocation patterns in a study in the Central Highlands of Ethiopia, where near-fields received greater quantities of organic matter, but far-fields received greater quantities of inorganic fertilizer as these types of fertilizer were easier to transport (Haileslassie et al., 2007). Meanwhile two other studies undertaken in Zimbabwe presented cases where the fertility gradient was found to be the reverse. In these cases the cropping conditions were either more favourable in the far-fields for the main cash crop suggesting that the asymmetric allocation patterns were strategic or the far-fields were only recently converted into agricultural land (Chuma et al., 2000; Masvaya et al., 2010).

This has important implications for development as it means that simple intervention strategies, such as the free or subsidised provision of nutrient and/or OM inputs, will not necessarily lead to the improvement of fertility in the most distant and least fertile fields. Further research is necessary to explore the drivers behind these well-recognised asymmetric resource allocation patterns in agricultural landscapes so as to develop more contextualised pathways for improving the overall fertility and productivity of farms. For example, if the main constraint on increasing soil fertility of distant fields is one of logistics and labour rather than access to resources, a better solution for improving productivity may be *in situ* methods of nutrient and OM inputs, such as green manures or forage rotations with direct grazing, or possibly alternative cropping systems that reduce nutrient export and require fewer inputs. Or in the case that the asymmetric OM allocations reflect broader risk management strategies whereby the fertile infields are used for reliable crop production while the outfields are used as low investment ‘bets’, a deeper discussion may be more fruitful around risk management and sustainable land management.

4.2. Between community differences in organic matter inputs

Turning to between community and between farm heterogeneity in OM inputs, our results revealed large differences in OM inputs among communities located in close proximity to one another, such that farmers from the community of Tzimbuto incorporated nearly twice the quantity of OM inputs than farmers in Naubug and also significantly more than in Basquitay. However, our findings did not find evidence for significant differences in OM inputs between farms based on individual socio-economic variables. This diverges from previous research, undertaken mostly in east Africa, where such socio-economic factors have been found to be significantly correlated to inputs and positive nutrient balances (e.g., Barrett et al., 2002; Cobo et al., 2010; Haileslassie et al., 2007; Marenya and Barrett, 2007).

Part of the reason for this finding may be that the small sample size considered here may have been insufficient to detect clear OM input patterns based on these more granular socio-economic factors. However, it may also suggest that the individual socio-economic factors considered do not provide the whole explanation as to how farmers manage their resources. In this regard, this research agrees with Vanek and Drinkwater (2013) who observed no association between manure application rates and farmer wealth in the Bolivian Andes.

As others have also suggested, no single indicator variable appears to be sufficient to account for the diversity found in land and farm management within or between communities; instead differences are a result of interactions between the biophysical and socio-economic and cultural trajectories unique to each individual context (Caldas et al., 2007; de Sherbinin et al., 2008; Tittonell, 2014). In our case-study, these formative interactions may be best encapsulated at the level of the community where the biophysical contexts and socio-economic and cultural differences may be greater between communities than between farmers.

Despite the proximity of the three communities (Fig. 1), they represent distinct biophysical contexts (soil, climate, vegetation), and these are likely to have shaped multiple farming systems attributes, including OM inputs (Chapter 4). Socio-economic and cultural differences are also likely to have contributed to the between community differences in OM inputs. For example, Tzimbuto is the only community with access to irrigation, due to construction of an irrigation canal over 20 years ago. Tzimbuto also has stronger links with regional markets since it is located close the Parish capital Licto and enjoys better transport links with the provincial capital of Riobamba. It appears that these improved opportunities may have allowed farmers in Tzimbuto to invest more deeply in agricultural production than those in Naubug or Basquitay, hence the observed higher OM inputs observed.

4.3. Community level organic matter inputs and soil fertility gradients

It appears that the observed differences between communities in OM inputs may be contributing to greater heterogeneity in soils of this landscape of the Andes. As mentioned above, the use of different types of organic inputs between communities may be driving different within farm fertility gradients for available P and exchangeable K. Moreover, it is noteworthy that Tzmibuto displayed, on average, the highest levels of available P and exchangeable K compared to the other two communities, despite exhibiting the lowest levels of SOC (Table 2). Macronutrients such as P and K have been suggested to be more responsive than SOC to differences in agricultural inputs (Tittonell et al., 2005b; van Apeldoorn et al., 2014; Van Apeldoorn et al., 2013; Zingore et al., 2007). The larger additions of organic resources in Tzimbuto could potentially help explain the greater accumulation (or reduced loss) of these nutrients in this community.

On the other hand, SOC generally reflects longer-term processes related to soil texture, climate and hydrology and is generally less sensitive to short-term management influences (van Apeldoorn et al., 2014; Zingore et al., 2007). The cooler climate and high moisture levels found at higher elevations supports SOM accumulation through faster accumulation and slower decomposition (Lavoie and Bradley, 2003; Zehetner and Miller, 2006), while higher clay content is also known to stabilize SOM (Chivenge et al., 2007; Six et al., 2002). This is reflected in our finding that Basquitay, the community with the highest SOC, but significantly lower levels of OM inputs than Tzimbuto, was also the community with the highest elevation range and soil clay content (Fig. 3a, Table 2). Furthermore, it is noteworthy that Basquitay was the only community where no evidence was found for an association between OM inputs and SOC, distance from homestead and SOC, and perception of fertility and SOC (Tables 4-6). We suspect that the high baseline levels of SOC likely eclipse any influence that farmer OM inputs may have in this community.

This differential response of soils in each community to OM inputs suggests that it is critical to consider biophysical and management context specific intervention strategies. For example, in Tzimbuto one could argue that continued soil aggradation measures using OM inputs would continue to prove beneficial for farmers in the future. On the other hand, in Basquitay, where SOC levels were less responsive to OM inputs, but already exhibited high background levels, soil conservation measures may be more effective. Meanwhile Naubug, with its greater SOC variability compared to Tzimbuto, but with, on average, lower SOC levels than Basquitay, may require a more of a hybrid approach conserving the richer soils and aggrading the soils with lower levels of SOC.

5. Conclusion

The results of this study demonstrate the importance of the diversity in organic matter inputs that may be encountered within farms and between neighbouring communities in rural Andean landscapes and their potential impacts on and interactions with the underlying biophysical contexts found between communities due to a steep elevation gradient. We found that asymmetric allocation patterns of OM appear to be accentuating existing soil fertility gradients and that greater overall OM inputs did not prevent or reduce the development of these commonly observed fertility gradients. We also found that despite the close proximity of the three communities, differences in infrastructure and access to markets may be driving differences in OM input quantity and quality. These differences in OM inputs between communities may be associated with important differences in soil fertility, with the highest levels of available P and exchangeable K found in the community with the highest OM inputs. We also suspect that differences in the underlying biophysical context (soil and climate) between communities is contributing to the observed variability in soil fertility, with the community located at the highest elevation range and with the highest baseline levels of SOC, being the only community to display no significant association between OM inputs and SOC and the only one not to display significant within farm SOC gradients. This suggests that intervention strategies need to take into account smaller scale, within-farm variability and the complex social and ecological factors that determine farmer investment in their soils.

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Chapter 4: Agroecosystem patterns and farm management co-evolve from environment, management and land-use interactions

Submitted as: Caulfield, M.; Fonte, S., Groot, J.; Vanek, S.; Sherwood, S.; Dumble, S.; Borja, R.; Oyarzun, P.; Tittonell, P. Environment, management and land-use interactions drive soil and agroecosystem patterns in a rural Andean landscape. Ecosphere.

Abstract

A poor understanding of the interactions between biophysical and social elements within rural mountainous landscapes can lead to suboptimal management and recommendations. The objective of this study was to contribute to more contextualised natural resource management in a rural landscape in the Ecuadorian Andes by: (i) identifying biophysical patterns in soil properties, biodiversity and C stocks that emerge from 'natural' landscape pedogenic processes, resulting from elevation-induced climate gradients, erosion and soil textural patterns; and (ii) assessing farm management and land-use effects on and their interactions with these biophysical patterns. Our findings revealed that the climate and soil texture gradients within the landscape led to an exponential increase in SOC with elevation ($P < 0.001$) moderated by slope gradient ($P < 0.004$), indicating significant erosion processes. Farmers adapted their farm management according to the observed environmental patterns creating three distinct management 'zones'. Differentiated agricultural management in these zones and land-uses in turn were observed to significantly influence soil and agroecosystem properties. For example, available P was found to be significantly higher in the upper and middle agricultural management zones (24.0 and 28.7 mg kg^{-1} respectively) where agricultural inputs were higher compared to the lower agricultural management zone (8.9 mg kg^{-1}, $P < 0.001$). Mixed hedgerows on the other hand displayed significantly higher Shannon Index scores for ground vegetation (1.8) and soil macrofauna (2.0) compared to agricultural land-uses (1.0 and 1.7, $P < 0.05$). Our results provide important insights into how the agroecosystem patterns and farm management of the landscape co-evolved from environment, management and land-use interactions.

1. Introduction

Mountainous rural landscapes in the Andes exhibit biological, physical and social components that interact within multiple dimensions (spatial, temporal, and organizational) and result in complex coupled human-natural systems (Pickett and others 2005; Cadenasso and others 2006). While such socio-ecological relationships have long been recognised, the nature and complexity of their interactions remain poorly characterised (Liu and others 2007). Insufficient understanding of these interactions can result in suboptimal management, unsound policies, and poor decision making frameworks (Ascher 2001).

In rural Andean landscapes families often manage fields dispersed throughout a large geographical area that is comprised of diverse topography and micro-climates (Buytaert and others 2007; Fonte and others 2012; Zehetner & Miller, 2006). These biophysical contexts are shaped by dynamic pedogenic processes that drive the emergence of patterns in soil properties and soil-based agroecosystem components. This perspective reinforces the idea that soils should be studied as dynamic entities within a landscape, in recognition of the role of landscape processes in shaping and changing soils (Pennock and Veldkamp 2006).

One important natural driver of soil properties within mountainous landscapes is elevation and associated climatic gradients in temperature and precipitation. For example, soil organic matter (SOM) generally increases with elevation in mountainous regions (eg, Leifeld and others 2009; Nottingham and others 2015). Underlying these landscape-level patterns are local pedogenic processes. For example, the accrual of SOM is often associated with cooler, moister areas that slow organic matter decay (Lavoie and Bradley 2003; Zehetner and Miller 2006) and/or higher clay content that supports both the physical and chemical stabilization of SOM (Chivenge and others 2007). These patterns of soil physical and chemical properties across the landscape, in turn, drive multiple aspects of soil health and biological function. For example, in providing energy resources for soil food webs, SOM supports a range of soil biological activity and diversity (Moore and others 2004), including soil macrofauna communities.

These biophysical contexts shape farmers' agricultural practices and often result in different agricultural management zones across the landscape, where farmers' fields located in each zone are managed distinctly in terms of crops grown, resource allocation, soil preparation, among other factors (Mayer 2002; Li and others 2013). Farming practices then interact with the biophysical context of the landscape generating complex patterns, often with non-linear responses to landscape gradients. For example, research in the highlands of East Africa has revealed significant socio-ecological interactions, where existing soil fertility gradients determined farmer resource allocation within the farm (Tittonell and others 2010, 2005a, 2005b). As such, farmers would tend to allocate more resources to fields perceived to be more fertile creating a feedback loop where the increased inputs would improve soil fertility, which would consequently increase (perceived) fertility.

While this growing body of work aims to tease out the complexity in a variety of coupled human-natural systems, much remains to be learned (Ellis and Ramankutty 2008). In this study we sought to understand different environmental (elevation, geomorphology and soil texture), farm management (agricultural inputs and cropping patterns) and land-use effects on and interactions with key agroecosystem components related to soil fertility and ecosystem functions that are commonly impacted by management and land degradation processes in rural mountain landscapes (soil chemical and physical properties, soil macrofauna communities, ground vegetation and C storage). Specifically, the objective of this research was to contribute to more contextualised and nuanced natural resource management in the region of study by: (i) identifying the biophysical patterns in soil quality, biodiversity and C stocks that emerge from multiple 'natural' landscape pedogenic processes, resulting from elevation-induced climate gradients, erosion and soil textural patterns; and (ii) assessing farm management (agricultural inputs and cropping patterns) and land-use effects on and their interactions with these biophysical patterns. We hypothesised that biophysical patterns emerge within a rural mountainous landscape as a result of an elevation-induced climate gradient as well as geomorphology (slope) and soil textural patterns, which are then influenced by human activities such as farm management and land-uses. We further postulated that important feedbacks exist between the biophysical patterns of the landscape and farm management and land-uses in so much that the biophysical patterns influence and, in turn, are influenced by human activities (farm management and land-uses) within the landscape.

2. Materials and Methods

2.1. Site Description

The study was carried out between April-May 2015 in an indigenous Kichwa community (Naubug) located in the parish of Flores, Chimborazo Province in the Central Ecuadorian Andes (1°51'24.0"S, 78°39'15.6"W). The community is located on a steep topographic gradient facing south to south-east with a maximum elevation of around 3600 m running down to around 2850 m at Cebadas River, part of the Chambo River basin (Fig. 1). Annual precipitation at the highest point in the community was measured to be around 640 mm between 2015-2016 by a private weather station, with an average temperature of 9.0°C. A public weather station (Guaslan - M0133) ran by INAMHI (the National Institute for Meteorology and Hydrology) located at a similar elevation to the lowest part in the community (2850 masl) a couple of km away, indicated an important climate gradient within the landscape, recording a lower average annual precipitation rate of 592 mm, but a higher average annual temperature of 14.2°C. Rain in the parish of Flores mostly falls between January and June with a drier, windier period from July to December (GAD de Flores 2015). The long-term pedogenic processes of the region are dominated by volcanic activity with pyroclastic deposits which gave rise to the formation of relatively uniform and thick layers of hardened volcanic ash upon which lie volcanic (Andisol) soils. The A horizon of the soils in this area is usually stone free and relatively rich in organic matter having developed under cool, moist conditions and natural dense vegetation (either grass páramo at the higher elevations; sub-páramo between 3000-3500 masl or Andean forest below 3000 masl) (De Noni and others 2001; Zehetner and others 2003; Zehetner and Miller 2006). Most of the households of Naubug are located in the middle to upper elevations of the landscape (between 3200-3500 masl). However, in this intensively farmed rural landscape, nearly all remnants of páramo, sub-páramo and Andean forest vegetation types have been removed resulting in erosion and exposure of low organic matter sub-soils composed of hardened volcanic ash, known locally as 'cangahua' (Podwojewski and Germain 2005). In these areas where significant erosion has occurred, soils can be classified as either inceptisols or entisols. Subsistence farming dominates the landscape with only small quantities of crops and livestock being sold at the local market of Cebadas. Potato (*Solanum tuberosum L.*) comprises the most important crop in the community and the largest investment in terms of area and agronomic inputs (eg, manure, fertilizer, pesticides). Potato and cut forages dominate the middle and upper elevations of the landscape, but quinoa (*Chenopodium quinoa*) has become an increasingly popular crop in these zones as well. The lower elevations are mainly dedicated to the production of maize (*Zea mays*) and barley (*Hordeum vulgare L.*). Weather conditions enable nearly year-long production in the upper and middle elevations, and therefore these areas can be cultivated twice a year. Agricultural fields in the lower slopes are up to an 1.5 hr walk from homesteads, are generally considered to have poorer soils, a lower precipitation to evapotranspiration ratio, and are only cultivated once per year.

2.2. Participatory mapping and determination of land-uses

In order to develop a land-use map of the community, a user-consultative 'participatory' mapping process was developed and applied based on the International Fund for Agricultural Development's (IFAD) Review of Good Practices in Participatory Mapping (2009). This process involved three main steps: 1) presentation of the research project to the community in order to raise awareness, inform and encourage participation; 2) identification and mapping of the dominant land-uses via three workshops with key local stakeholders to identify important land-uses on a printed orthophoto (1.8 x 1.5m; 0.3m resolution; taken in 2012) of the community (resulting land-uses and polygons were then digitized using QGIS Desktop 2.4.0); and 3) ground-truthing (via transect walks) and presentations of the map to key stakeholders to verify the location of the polygons and make any necessary adjustments.

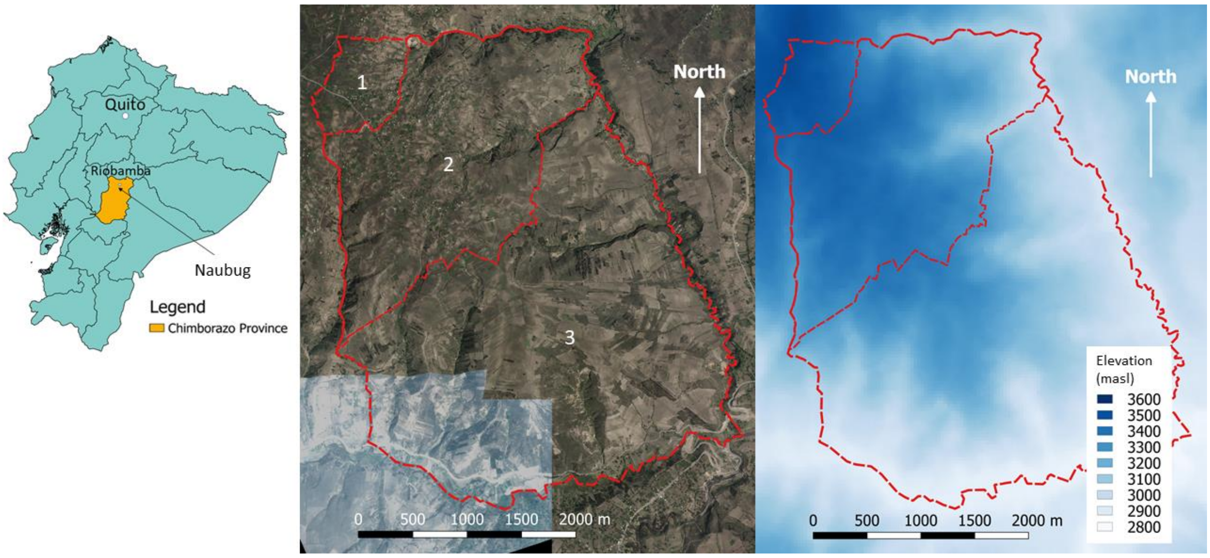

***Figure 1**: **Left:** Map of Ecuador with the province of Chimborazo highlighted and the study site indicated (Community of Naubug, Flores Parish); **Centre:** Outline of Naubug community boundaries with the three agricultural management zones delineated (1. Upper Agricultural Management Zone; 2. Middle Agricultural Zone; 3. Lower Agricultural Management Zone); **Right:** Outline of Naubug community boundaries with the elevation gradient displayed.*

2.3. Sampling Methodology

Randomly generated sampling points within the landscape were stratified by land-use and elevation (agricultural management zone). While agricultural land-use and mixed hedgerows were found throughout the landscape, other land-uses were restricted to either a small range within the upper and top-end of the middle agricultural management zones (in the case native tree hedgerows and grass strips) or the middle and lower agricultural management zones (in the case of abandoned agricultural land and forested land). Sampling occurred at 91 points across the landscape (Table 1). At each point a 10 x 20 m sampling area was delineated for a suite of soil and vegetation measurements. Slope and elevation were also noted at the centre of this area.

2.3.1. Soil Physical and Chemical Properties

At each sampling point three equally-spaced sub-sampling points were located along a 20 m transect running through the centre of each sampling area. For each sub-sample point, a soil monolith (25 x 25 cm and 20 cm deep) was excavated for evaluation of soil macrofauna communities and other soil parameters. Soil from the three monoliths was combined into a composite sample used for characterization of soil chemical fertility. Soils were air-dried and transported to the laboratory of the Ecuadorian National Institute for Agricultural Research (INIAP) for analysis of texture (Bouyoucos 1962), soil organic carbon (SOC; Walkley and Black, 1934), and available P (Olsen method; Olsen and others 1954). Bulk density was assessed by inserting a cylinder (~7 cm dia. x 6 cm long) into the side wall of each soil monolith at two depths, 1-8 cm and at 11-18 cm. The extracted soil was then dried before calculating bulk density.

2.3.2. Biodiversity

Soil macrofauna were assessed by excavation and hand-sorting of all macro-invertebrates (>2mm) from the soil based on methods outlined by Anderson and Ingram (1993). Specimens were collected in 70% ethanol (or 4% formalin for earthworms) and then brought to the laboratory for identification, generally to the order level.

Ground vegetation (vegetation excluding trees and larges bushes) was also evaluated at three points adjacent to the monoliths using a 0.64 m^2 square frame. Each species (or morphospecies) was noted and the area of each was visually estimated within the frame. In agricultural land-uses, the dimensions of the area evaluated was slightly modified to conform with the width of the planting rows, such that ground cover was measured in an area of 1 m x the width between two rows. For both macrofauna and vegetation, diversity was estimated using the Shannon index based on the number of taxonomic groups encountered and their relative abundance (Shannon 1948).

2.2.3. Carbon Stocks

Upon evaluating the cover of all plant species in each 0.64 m^2 frame, vegetation was cut at a 1-2 cm height and weighed in the field. A representative sub-sample of this material was taken to the lab and dried in an oven at 60°C to determine the biomass of ground vegetation on a Mg ha^{-1} basis (excluding shrubs or trees). All agricultural land-use sampling points were measured when the crops were at or nearing physiological maturity.

For land-use other than agriculture (hedgerows, grass strips, forests and abandoned land), vegetation in the four quadrants of the 200 m^2 sampling area were categorized into three types: shrubs, small trees, and large trees. Measurements included the volume (height, width and length) of all the shrubs (Conti and others 2013) and diameter at breast height (1.3 m; DBH) of all small trees (< 10cm DBH) found in 2 of the 4 quadrants of each sampling area. For large trees (>10 cm DBH), DBH was measured in the entire 200 m^2 sampling area (Van Breugel and others 2011). Allometric equations from (Kearney and others 2017a) and from the GlobAllomeTree database (www.globallometree.org) were then used to calculate the biomass. Aboveground biomass components were then summed to determine total aboveground biomass. This was converted into aboveground C stocks by assuming a 50% C content (Giese and others 2003)

Belowground biomass of the vegetation was estimated by assuming a shoot-to-root ratio of 1:0.205 according to Knoke and others (2014) and Mokany et al. (2006). Belowground C stocks were estimated assuming 45% C content in roots (Gayoso and Schlegel 2001). SOC was multiplied by bulk density data to estimate C stored within the surface 20 cm of each sampling area. Total C stocks in above- and belowground biomass as well as in soils was reported on a Mg ha^{-1} basis.

2.3 Statistical Analyses

All analyses were conducted using the average of the sub-samples within each sampling location. To identify interactions between management and environmental factors within the landscape multiple linear regression was applied to a set of predictor and response variables. The main predictor variables tested were elevation (as a continuous variable) and land-use, treated as a categorical predictor variable. Response variables analysed include: clay and sand content, SOC, available P, macrofauna diversity, vegetative diversity and C stocks. The linear regression models were built using a forward step-wise approach, first testing for associations between the response variable and elevation with land-use as an additive variable, and then testing for interactions between elevation and land-use. Predictor variables and interactions with a p-value > 0.15 were removed from the final linear regression models. Post-hoc Tukey's Honest Significant Difference Test were applied to explore differences between land-uses, when significant.

A further linear regression model was built to test the effect of topography (slope) on the relationship between SOC and elevation, thereby assessing the potential influence of erosion processes on soils in this landscape. Furthermore, ANOVA with a Post-hoc Tukey's Honest Significant Difference Test was applied to explore the effects of different agricultural management (between the agricultural management zones) on SOC and available P given their differentiated sensitivity to environmental and management factors (van Apeldoorn and others 2014). All analyses were carried out within the RStudio environment Version 1.1.453 for R (Version 3.5.1) using the packages 'agricolae'; 'emmeans' and 'ggplot2'. Assumptions of homoscedasticity and normality were tested and data transformed as needed using either the log or exponential function.

3 Results

3.1 Participatory land-use mapping

The participatory mapping identified six dominant land-uses located across the landscape (in addition to inaccessible land); these included: agricultural land (in three separate agricultural management zones), abandoned agricultural land, eucalyptus and/or pine forest, and three types of hedgerows (native trees, grass strips and mixed vegetation). The three agricultural management zones varied in elevation and management regime (farming intensity, cropping patterns and inputs, see Table 1 and Fig. 1).

Table 1: *Description of the different land-uses identified in Naubug, Ecuador using a participatory mapping process and characterization according to dominant vegetation and management types. The number of sampling points for each land-use is also indicated. These points were stratified by the elevation with between 10 and 16 sampling points per land-use. See Appendix 1 for photographs of the landscape and examples of the different land-uses.*

Land-use	Description		Surface area by zone# (ha)	Total surface area (ha)	Number of samples
Agricultural land (Ag)	Agricultural fields that have been cultivated within the last two years. Three sub-categories of this land-use were also identified: the upper agricultural management zone, the middle management agricultural zone and the lower agricultural management zone	*Upper Ag Zone:* Intensive year-round cultivation with maximum 1-2 months between harvest and planting. Crop rotation typically characterised by potatoes followed by two cycles of forage crops. OM and fertilizer inputs and pesticide use are usually restricted to the potato crop. Typical OM inputs vary between around 2-7 Mg/ha (fresh weight), although some farmers reported even higher levels of inputs.	-	56.10	10
		Middle Ag Zone: Intensive year-round cultivation with maximum 1-2 months between harvest and planting. Crop rotation typically characterised by potatoes followed by cereals for human consumption and then either a forage crop or another cereal crop for human consumption. OM and fertilizer inputs and pesticide use are usually restricted to the potato crop. Typical OM inputs vary between around 2-7 Mg/ha (fresh weight), although some farmers reported even higher levels of inputs.	-	294.76	16
		Lower Ag Zone: Less intensive cropping cycles with 4-6 months between harvest and planting (one crop per year). The main crops are maize and barley. Little, if any, OM and fertilizer inputs are used.	-	200.56	10
Abandoned agricultural land (Ab)	Agricultural fields that have not been cultivated in the recent past and which the owners no longer intend to cultivate in the foreseeable future (this is usually a result of either emigration or declining yields). This land-use is present in lower and middle agricultural management zones.		UAZ: 0.07 MAZ:76.12 LAZ: 195.18	271.37	10

Land-use	Description	Surface area by zone[#] (ha)	Total surface area (ha)	Number of samples
Eucalyptus and/or Pine Forests (For)	Areas of land that have been planted with eucalyptus and/or pine trees for the purpose of either providing a source of fire-wood or for sale as timber. This land-use is present in lower and middle agricultural management zones.	UAZ: 0.00 MAZ: 11.41 LAZ:22.83	34.24	10
Native tree hedgerows (TH)	Hedgerows that have been planted by farmers surrounding fields composed of local native trees such as Yagual (Polylepis incana and Polylepis reticulata), Andean Alder (*Alnus acuminata*), Lime (*Tilia*), Kishuar (*Buddleia incana*), Andean lupin (*Lupinus mutabilis*). This land-use is present in middle and upper agricultural management zones.	UAZ: 0.24 MAZ: 0.47 LAZ: 0.00	0.71	10
Grass strips (GS)	Hedgerows that have been planted comprising primarily of bulbous canary-grass (*Phalaris tuberosa*). This land-use is present in middle and upper agricultural management zones.	UAZ: 0.49 MAZ: 0.99 LAZ: 0.00	1.48	10
Mixed hedgerows (MH)	Hedgerows comprising of a variety of different types of vegetation: trees, bushes and grasses. This land-use is present in all of the agricultural management zones.	UAZ: 2.38 MAZ: 4.77 LAZ: 7.15	14.30	15
Inaccessible land	Land that is inaccessible, usually comprising of very steep canyons. No sampling was conducted in these areas due to its inaccessibility.	-	349.19	Not applicable

[#]UAZ = Upper agricultural management zone, MAZ = Middle agricultural management zone; LAZ = Lower agricultural management zone

3.2 Soil variability

3.2.1 Soil texture and soil chemical properties

The regression model for soil sand and clay content displayed significant effects of elevation in that clay content increased by 2.5 percentage points per 100 m increase in elevation (Fig. 2), while the soil sand content decreased by 3.2 percentage points for every 100 m increase in elevation (Table 2, Supplemental Table 1(Appendix 2)).

SOC increased exponentially with elevation (Fig. 3a, Table 2). Land-use also had a significant influence on SOC. However, a significant interaction between elevation and land-use suggested that the response of SOC to elevation differed significantly with land-use with agricultural land-use displaying the strongest effect (SOC increasing 1.5 times per 100 m increase in elevation) and forest the weakest effect (increasing just 1.05 times per 100 m increase in elevation) (Fig. 3a, Table 2, Supplemental Table 2 (Appendix 2)). While hedgerows tended to have higher SOC overall (Supplemental Table 2 (Appendix 2)), the strength of effect of elevation on SOC under agricultural land-use meant that at the lowest elevations it displayed the lowest SOC levels (minimum 0.21%), while in the upper elevations of the landscape it surpassed the other land-uses exhibiting the highest levels (maximum 4.70%) (Fig 3a, Supplemental Table 2 (Appendix 2)). Significant interactions between elevation and slope on SOC were also evident, with the effect of elevation decreasing at sites with steeper slopes (Fig. 4).

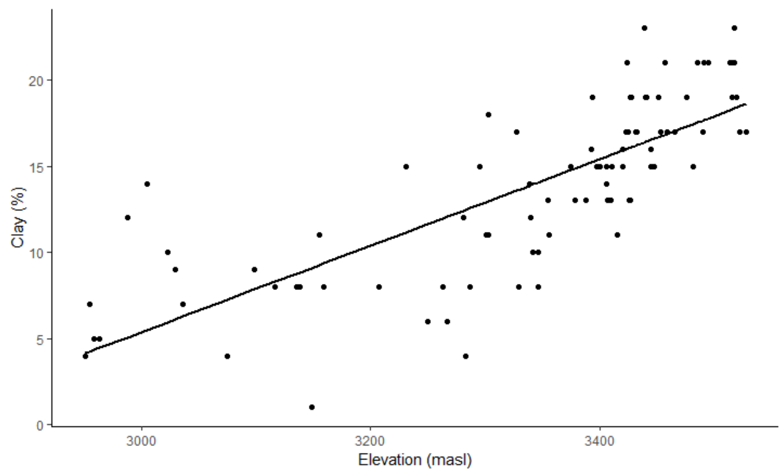

Figure 2: *Relationship between elevation (masl) and clay content (%) within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador.*

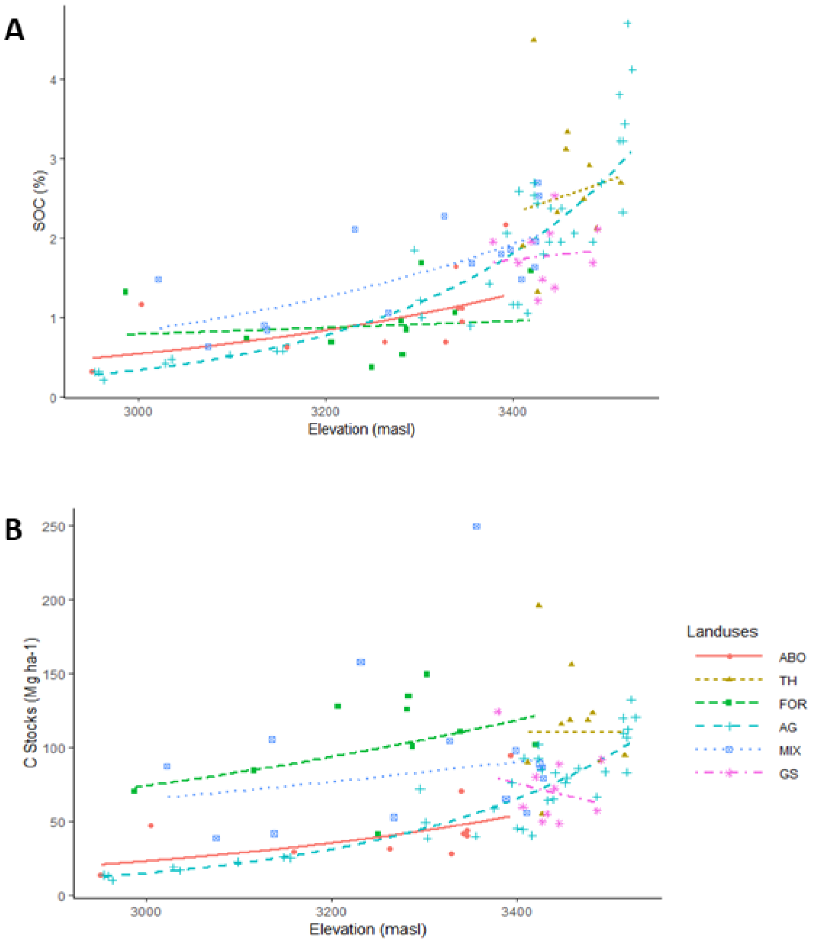

Figure 3: A) *Relationship between elevation (masl) and soil organic carbon (%) of the six different land-uses identified using a participatory mapping process* ***B)*** *Relationship between elevation (masl) and C stocks (MG ha-1) of the six different land-uses within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. The land-uses identified include: ABO, abandoned land; TH, tree hedgerows; FOR, Eucalyptus and/or pine forest; AG, agricultural land; MH, mixed hedgerows; GS, grass strips.*

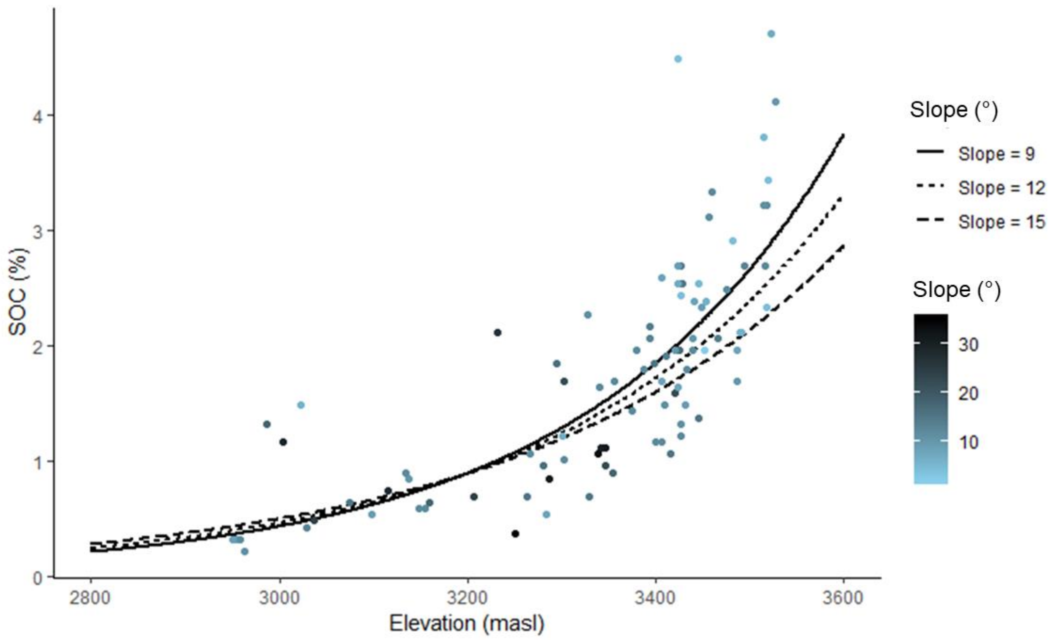

Figure 4: *The relationship between elevation (masl) and soil organic carbon (SOC; %) at different slope gradients (9°, 12° and 15°) within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. The fitted linear regression lines of the three slope gradients are indicated by different line-types (unbroken line = 9°; short dashed line = 12°; long dashed line = 15°). Slope displayed a significant interaction with the association between SOC and elevation (P = < 0.004).*

The model for available P displayed significant effects and interactions for elevation and land-use. Abandoned land, forest and tree hedgerows land-uses decreased in available P with elevation while agricultural, grass strips and mixed hedgerows land-uses increased with increasing elevation (Table 2). The three types of hedgerows displayed higher levels of available P compared to the other land-uses. It is noteworthy that agricultural land exhibited the joint lowest measure for available P (4.20 mg kg-1), but also one of the highest measurements (96.00 mg kg^{-1}) suggesting large variability (Table 2, Supplemental Table 2 (Appendix 2)).

When exploring the effect of the different management strategies of the agricultural zones on soil chemical properties, comparisons with ANOVA suggested that SOC levels increased with agricultural management zone (elevation), while available P showed no significant difference between the upper and the middle agricultural management zones, but significantly lower levels in the lower agricultural management zone (Fig. 5).

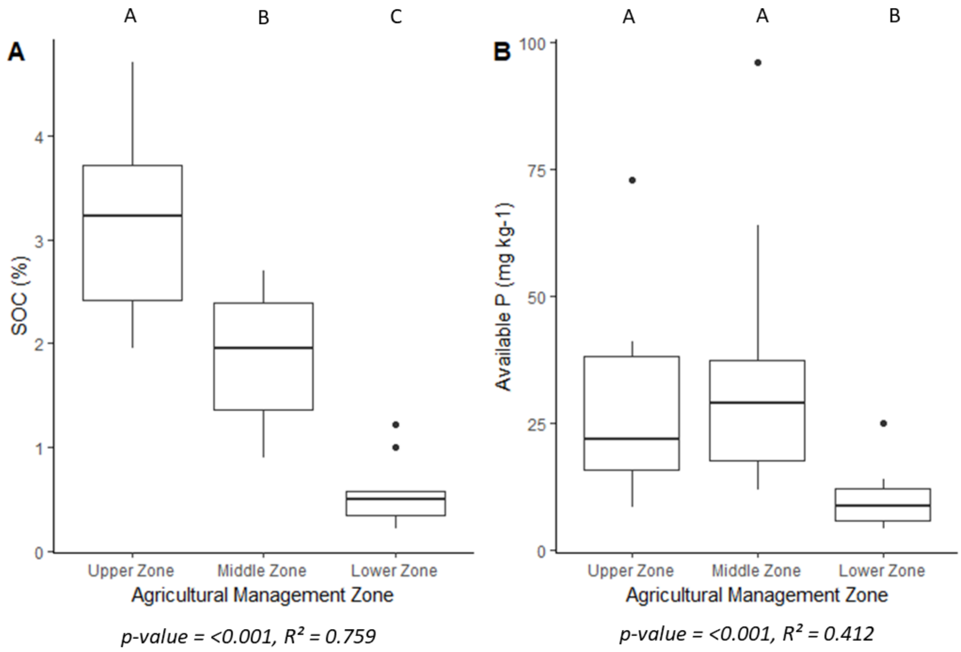

Figure 5: *Boxplots displaying interquartile ranges of (**A**) SOC (%); and (**B**) available P (mg kg-1) levels by agricultural management zone within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. Points located outside the "whiskers" of the boxplots are considered outliers (> 1.5 interquartile range). Post-hoc Tukey's Honest Significant Difference Test results are presented above each box at the top of the plots, with management zones having different letters significantly different at the $P < 0.05$ level. P-values and R^2 values are presented underneath the plots.*

3.2.2 Biodiversity and carbon stocks

Vegetative diversity only displayed a significant relationship with land-use. Mixed hedgerows displayed significantly more diversity (measured on the Shannon Index) of ground vegetation (1.8) than forested (1.3), agricultural (1.0) and grass-strips (1.0) land-uses (Fig. 6a, Table 2, Appendix 2). According to the linear regression models developed for macrofauna diversity, when adjusting for elevation, the highest levels were found in mixed hedgerows (1.9) and the lowest found under forest land-uses (1.1) (Fig. 6b, Table 2).

Total C stocks varied significantly with elevation, increasing exponentially (Fig. 3b, Table 2). Total C stocks also displayed significant differences between land-uses, exhibiting highest levels in land-use practices with perennial components, such as eucalyptus/pine forests, mixed hedgerows and tree hedgerows. A significant interaction between elevation and land-use was also observed for C stocks, such that agricultural land-use displayed a stronger effect of elevation (C stocks increasing by 1.45 times per 100 m increase in elevation) than other land-uses (Fig. 3b, Table 2, Supplemental Table 2 (Appendix 2)).

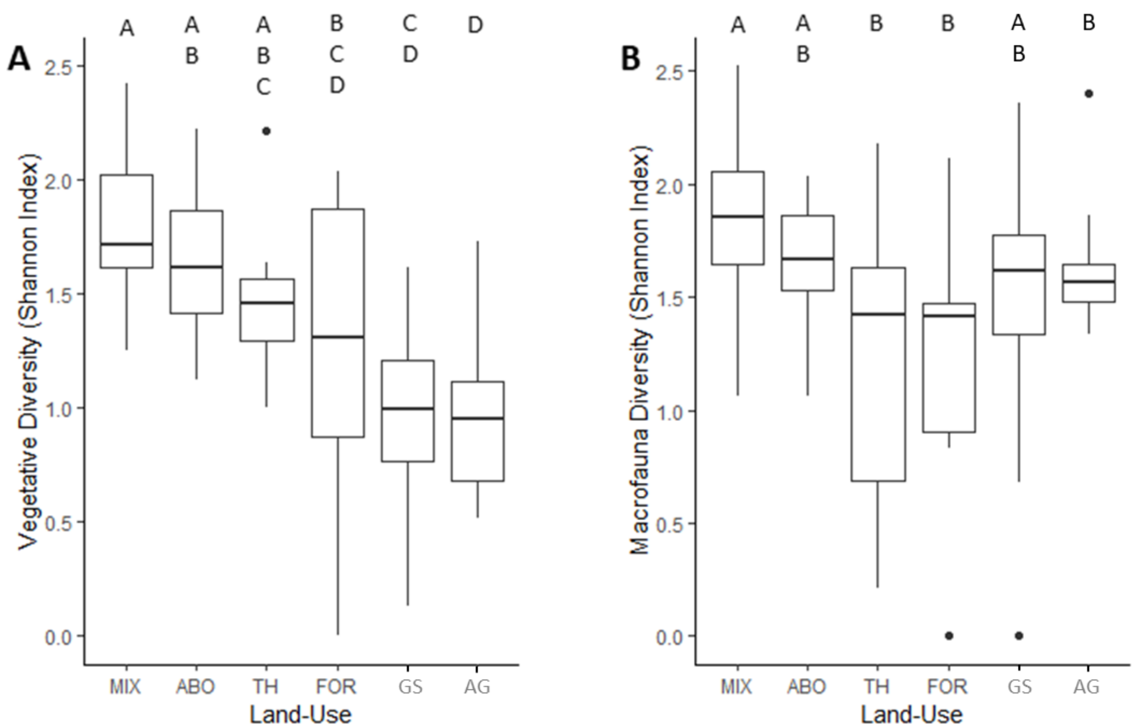

Figure 6: *Boxplots displaying interquartile ranges of (**Plot A**) vegetative diversity (Shannon Index); and (**Plot B**) macrofauna diversity (Shannon Index) levels by agricultural management zone within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. Points located outside the "whiskers" of the boxplots are considered outliers (> 1.5 interquartile range). Post-hoc Tukey's Honest Significant Difference Test results are presented above each box at the top of the plots, with management zones having different letters significantly different at the P < 0.05 level. The land-use acronyms are: MIX, mixed hedgerows; ABO, abandoned land; TH, tree hedgerows; FOR, Eucalyptus and/or pine forest; GS, grass strips; AG, agricultural land.*

Table 2: *Summary of the multiple linear regression analyses applied to the biophysical response variables within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. More detailed summary of the data analyses can be found in the supplementary tables in Appendix 2.*

Response Variable	Predictor Variable	P-value	Interaction p-value	R^2
Clay	Elevation	***<0.001***	-	0.60
	Land-Use	0.322		
Sand	Elevation	***<0.001***	-	0.44
	Land-Use	0.585		
SOC	Elevation	***<0.001***	***<0.001***	0.75
	Land-Use	***0.019***		
Available P	Elevation	***<0.001***	***0.010***	0.54
	Land-Use	***<0.001***		
Macrofauna Diversity	Elevation	0.095	-	0.13
	Land-Use	***0.007***		
Vegetative Diversity	Elevation	0.305	-	0.38
	Land-Use	***<0.001***		

Response Variable	Predictor Variable	P-value	Interaction p-value	R^2
C Stocks	Elevation	***<0.001***	***<0.001***	0.70
	Land-Use	***<0.001***		

4. Discussion

4.1. Environmental drivers of agroecosystem patterns

Our findings highlight the complexity of rural Andean landscapes and provide strong evidence that both environmental and human factors contribute to the emergence of distinct biophysical patterns. Pedogenic factors such as climate and geomorphology are clearly responsible for landscape-scale processes that contribute to biophysical patterns, which subsequently influence, and are influenced by, farm management and land-use. This finding supports our hypothesis and provides further evidence for the position adopted by Ellis and Ramankutty (2008), that most landscape heterogeneity is caused by natural gradients within landscapes and that this heterogeneity is further 'enhanced' by human activities.

In this study, important patterns in the landscape were observed for soil chemical properties, such that SOC displayed an exponential, positive association with elevation (Figs. 3a, Table 2). This finding corroborates past research (eg, Badía and others 2016; Chatterjee and Jenerette, 2015) that reported significant effects of elevation on soil properties. Part of the explanation for the SOC gradient observed in the landscape is linked to the parallel pattern in soil texture which saw soil clay content also increase with increasing elevation (Fig. 2). Clayey soils are known to better stabilize SOM than sandy soils, which has important implications for nutrient management and availability, and subsequent impacts on productivity (Chivenge and others 2007).

Given the large elevation range, climatic conditions (ie, temperature and precipitation) are also an important pedogenic factor on the development of soils across the studied landscape. Such gradients in temperature (an annual average of 9°C in the upper agricultural management zone vs. 14°C in the lower zone) are also likely to contribute to greater SOC accrual in the upper parts of the landscape due to slower organic matter decomposition in cooler climates (Lavoie and Bradley, 2003; Zehetner and Miller, 2006), thus creating a synergistic (exponential) driver with the soil textural properties.

Furthermore, the influence of topography on SOC is also evident, such that the effect of elevation on SOC decreased with increasing slope (Fig. 4). This suggests that erosion processes may be significant in the landscape. As found by two studies in the Ecuadorian Andes, erosion rates average around 25 Mg ha^{-1} yr^{-1} in the study region (Molina and others 2008; Henry and others 2013).

Total C stocks also increased with elevation (Fig. 3b, Table 2) suggesting an important role for the climatic gradients with regard to this agroecosystem function. While aboveground biomass variation accounts for some of this relationship, it is likely that the increase in SOC with increasing elevation also played an important role as a reservoir of C. Takimoto et al. (2008) found that in non-forested areas, such as croplands and abandoned land, soil C accounts for up to 95% of C stocks, while in forested parkland this figure was still between 38-55%.

4.2. Farm management, land-use and environment interactions

Given the strong environmental gradients across this landscape, our findings highlight the need for context specific management to address the relative benefits and limitations of different fields. Delineation of the landscape into three agricultural management zones (broadly along elevation lines) by farmers during the community mapping process provided clear evidence that this is already occurring. For example, the relatively fertile, organic matter rich top soils of the upper and middle agricultural management zones differ in terms of cultivation focus, with a greater proportion of the upper zone crop rotations dedicated to forage crops compared to the middle zone (Table 1). As reported by farmers in the participatory community mapping, the temperature gradient within the landscape is likely an important determinant of this, as lower average temperatures in the upper elevations leads to slower crop development and this may be balanced by a greater focus on forage crops in this zone, which take comparatively less time to reach the point of harvest. On the other hand, the lower fertility status of the soils, greater distance from homesteads, and lower precipitation in the lower agricultural management zone likely explains why farmers use this area less intensively than the upper and middle zones, planting a maximum of one crop per year. It also may explain why farmers are less willing to invest resources (eg, manure inputs) into the lower agricultural management zone than in the other two zones (Table 1). This analysis reflects the the work of Mayer (2002) who described how farming households in the Andes tended to manage land distinctly based on local knowledge with regard to environmental variation in mountain ecosystems.

Differential management of the fields in the three agricultural management zones also appears to feedback into the biophysical patterns of the landscape by reinforcing the existing soil fertility gradient. For example, when comparing both SOC and available P levels under agricultural land-uses between the agricultural management zones, we observed that while SOC increased with the agricultural management zone (elevation), available P displayed no significant difference between the upper and middle agricultural management zones, but occurred at significantly lower levels in the lower agricultural management zone (Fig. 5). Whereas soil type may be an important factor in the development of this pattern, an additional cause, as reported during the community mapping process, may be that farmers typically save organic matter and nutrient inputs for their most productive agricultural fields, and those that are close to their homestead, largely in the upper and middle management zones (Table 1, Fig. 1). The reduced investment in soil fertility in the lower agricultural management zone may be an important farm-agroecosystem feedback loop where reduced productivity further reduces the incentives for farmers to invest in soil fertility inputs, further reducing productivity.

Another noteworthy pattern that may suggest cross-scale interactions is that while the available P levels closely reflect the asymmetric organic matter input flows in the landscape such that the upper and middle management zones display similar levels of available P, but the lower zone significantly lower levels, SOC levels do not follow the same pattern. Instead, SOC patterns under agricultural management see even greater accumulation of SOC in the upper agricultural management zone even when compared to the middle zone and other land-uses assessed (Figs. 3a and 5). This pattern could be the result of the combined effect of the climatic conditions for greater SOC accumulation at higher elevations coupled with agricultural organic inputs. This reflects the findings of (Tittonell and others 2007; van Apeldoorn and others 2014) who reported that available P levels were more sensitive to management influences, while SOC levels were more sensitive to environmental variables. These observations support our hypothesis that important feedbacks exist between environmental variables, farm management,and agroecosystem patterns leading to the co-evolution of biophysical and farming patterns in rural landscapes (Van Apeldoorn and others 2013).

When examining the effect of land-use more broadly, it is not surprising that vegetative parameters (vegetative diversity and C stocks) displayed significantly different values between land-uses (Figs. 3b and 6a, Table 2), given that land-uses are inherently associated with distinct management of crops and trees. However, significant differences were also observed for key soil properties and macrofauna diversity (Table 2). Mixed hedgerows were especially associated with improved levels of different agroecosystem components (Figs. 3 and 6), confirming previous studies investigating the benefits of hedgerows/agroforestry for C sequestration (Albrecht and Kandji 2003; Palma and others 2007; Takimoto and others 2008), vegetative diversity (Deckers and others 2004; Kearney and others 2017b; Smukler and others 2010) and macrofauna diversity (Pauli and others 2011; Rousseau and others 2013).

Eucalyptus/Pine forests performed poorly compared to mixed hedgerows for SOC, vegetative diversity and macrofauna diversity (Figs. 3a and 6). These patches of forest are often planted on already degraded land, as farmers will understandably choose to convert their least productive fields to forest rather than their more productive fields. Nevertheless, the fact that most of these patches of forest are still performing poorly after 20 or more years since establishment, indicates that their potential to restore degraded land may be limited and that attention is needed to explore how best to encourage alternative mixed forestry for purposes of biomass production as suggested by de Valença and others (2017) and Hall et al. (2012), rather than the planting of monoculture pine or eucalyptus patches of forest.

As hypothesised, the notable differences observed between land-uses suggest that land-use choices are contributing to greater spatial heterogeneity (Hall and others 2012). This observation reflects the findings of other studies, even those conducted in drastically different biophysical contexts. For example, Duvall (2011) similarly concluded that land-uses in the Western African Savanna created a complex mosaic on top of the 'natural' biophysical patterns of the landscape.

Understanding this complexity is important from a practical level, as it can inform more context specific and effective intervention strategies to enhance the sustainability of landscapes and the livelihoods of those who manage it. By better understanding the inherent biophysical heterogeneity of landscapes and key 'natural' drivers, decision-makers may be able to develop more nuanced and efficient approaches to increasing both the productivity and overall sustainability of the landscape (Rushemuka and others 2014).

5. Conclusion

Our findings provide evidence that both environmental and human factors contribute to the emergence of distinct agroecosystem patterns and that such interactions also drive the emergence of distinct farm management zones in the rural landscape. Pedogenic influences such as climate, soil textural gradients and geomorphology are clearly responsible for landscape-scale processes that contribute to biophysical patterns along elevational niches, which has given rise the development of context specific management by the local farmers. Asymmetric organic matter inputs within the landscape coupled with environmental interactions appear to have accentuated the underlying biophysical attributes, creating important socio-ecological feedbacks as exemplified in SOC and available P patterns under agricultural land-use. In addition, land-uses were observed to significantly influence soil and agroecosystem properties across the landscape (eg, SOC, available P, macrofauna diversity, vegetative diversity, total C storage). These findings support our original hypotheses that 'natural' landscape level processes drive biophysical patterns in landscapes, which then influence, and in turn, are influenced by soil management and land-use decisions. The resulting feedback leads to the co-evolution of the agroecosystem patterns and farm management of the landscape and contribute to greater spatial heterogeneity. Improved understanding of such socio-ecological interactions in these landscapes can provide more nuanced entry points for improving resource use and conservation strategies, in particular when developed through thoughtful engagement between farmers and local development agencies. For example, by better understanding the inherent environmental and biophysical heterogeneity of this landscape, farmers and other stakeholders may be able to co-develop more nuanced land management practices that target specific areas of the landscape for agricultural intensification and other parts for land conservation while taking into account current management practices within the three management zones.

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Chapter 5: Live barriers and associated organic amendments mitigate land degradation and improve crop productivity in hillside agricultural systems of the Ecuadorian Andes

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Abstract

Land degradation caused by erosion and nutrient depletion in the Andes poses serious existential threats to small-scale farming households. The objective of this investigation was therefore to work with a resource-constrained community to explore locally-developed options for improved agricultural management to address these challenges. Experimental plots were installed to assess water erosion control by hedgerows and the effect of organic amendments harvested from the hedgerows on soil productivity, soil moisture and soil fertility over the course of two years and three crop cycles (two of barley, one of rye). The experiment was conducted in two sites within the community differentiated by elevation (one at 3600 masl and the other at 3100 masl) and associated biophysical contexts. At each site four treatments were established, comparing a control treatment vs. three types of hedgerows: 1) Andean alder (*Alnus acuminate)*, 2) canary grass (*Phalaris tuberosa*) strips, and 3) mixed canary grass and Andean alder. Results demonstrated that hedgerows comprised of canary grass, and canary grass and Andean alder significantly reduced water erosion (50-70% reduction) and increased biomass production and grain yield ($p<0.05$) through the incorporation of organic amendments harvested from the hedgerows. We conclude that while hedgerows are unlikely to produce sufficient quantities of organic resources to satisfy all nutrient input requirements, their potential as a technique to decrease erosion and supplement existing organic matter inputs indicates that they should be strongly considered as an option for improved agricultural management within this and similar resource constrained, socio-ecological contexts.

1. Introduction

Land degradation caused by erosion, soil organic matter (SOM) depletion and negative nutrient balances represents a pervasive long-term threat to small-scale farming households in the Andes (Fonte et al., 2012; Vanek et al., 2016; Vanek & Drinkwater, 2013). The steep slopes of these mountainous agroecosystems mean that the landscapes are inherently susceptible to erosion. For example, a study in the southern Ecuadorian Andes found sediment loss in rural landscapes to range from 0.26 and 151 Mg ha^{-1} $year^{-1}$ with an overall average soil loss of 22 Mg ha^{-1} $year^{-1}$ (Molina et al., 2008). Another study in a watershed located close to the site considered here, found similar erosion losses, averaging 27 Mg ha^{-1} $year^{-1}$, with figures in some sites as high as 150 Mg ha^{-1} $year^{-1}$ (Henry et al., 2013).

Soil degradation, however, not only involves the loss of important soil nutrients, but also the loss of soil biological activity and associated structure, which play a critical role in soil water capture and retention, soil erosion, nutrient recycling, root penetration and the overall productivity of agricultural lands (Bronick & Lal, 2005; Lal, 2001). While the loss of soil fertility can be partly compensated for through the incorporation of more fertilizers, the rehabilitation of overall soil health and productivity is a much slower process (Fonte et al., 2012).

In response to the challenges posed by erosion, farmers in the Andes have long employed soil conservation structures such as terraces, both bench terraces, which are constructed by farmers, and slow-forming terraces, which develop overtime as soil accumulates behind vegetative barriers such as grasses, shrubs and trees (Dercon et al., 2003). While bench terraces are becoming less common nowadays due to their higher labour requirements for maintenance, slow-forming terraces are still frequently used by farmers in the Ecuadorian highlands (Dercon et al., 2003). While slow-forming terraces have been shown to be effective (e.g., Kagabo et al., 2013; Sánchez-Bernal et al., 2013; Tesfaye et al., 2018), these techniques can also accentuate spatial variability in soil fertility, where the fertile topsoils from the upper part of the field accumulate at the lower part of the field leaving strong field-level fertility gradients (Dercon et al., 2006).

In addition to the inherent erosion processes of these mountainous landscapes, land degradation in the rural Andes is also being driven by negative SOM and nutrient balances, where small-scale farmers are unable to replace the degraded SOM and exported nutrients in the harvest of crops (Bahr et al., 2014; De Koning et al., 1997; Vanek & Drinkwater, 2013). Not only are the nutrient balances of the macronutrients nitrogen (N), phosphorus (P) and potassium (K) often observed to be negative in these farming systems, but SOM has also been observed to decrease as a result of agricultural management (due to accelerated degradation of SOM as a result of increased aeration of soils through ploughing). In a study undertaken in the Southern Ecuadorian Andes, SOM levels under annual agricultural land-use were observed to be 15% lower than those of nearby forest sites, which was interpreted as an unsustainable management of the land (Bahr et al., 2014). SOM plays a critical role in maintaining soil health, supporting biological activity and diversity (Moore et al., 2004) and regulating soil processes linked to agroecosystem functions such as nutrient cycling, plant growth, soil aggregation (structure), and water storage (Barrios, 2007; Bronick & Lal, 2005; Lavelle et al., 2006).

A major reason for the pervasive trend of negative nutrient balances within the rural Andes is that the smallholder farmers generally have limited access to agricultural inputs, due to both a low financial resource base to invest in agricultural inputs and their remoteness from population centres (Fonte et al., 2012). While overall inputs are low, there appears to be great variability in the spatial allocation of the available nutrient and organic matter inputs. For example, farmers commonly allocate fewer agricultural inputs to fields that are further from their homestead or that are perceived to be less fertile (Caulfield et al., in prep; Vanek & Drinkwater, 2013). The fact that near fields can often receive high quantities of inputs relative to outer fields suggests that the negative nutrient balances (in the outer fields) are not simply a result of constrained resources, but likely result from labour and logistical limitations as well. This could indicate that alternative, in situ mechanisms for addressing the negative nutrient balances of distant fields are required (Caulfield et al., in prep; Fonte et al., 2012).

One of the criticisms levelled at physical soil conservation structures, such as terraces, has been that they provide poor immediate economic returns given their focus on soil conservation and therefore often are not easily adopted by farmers (Erenstein, 2003; Posthumus & De Graaff, 2005). Organic amendments, green manures and mulches on the other hand, given the right conditions, appear to show some important potential both in terms of improving soil conservation and agricultural productivity (Babalola et al., 2007; Félix et al., 2018). Moreover, such techniques may be applied in situ, providing important sources for nutrient and organic matter inputs in areas that may be less accessible to farmers such as distant fields.

Some promising findings in this regard have been observed with vetiver grass (Vetiveria nigritana). In two similar studies, one undertaken in the central highlands of Kenya, the other in Southern Nigeria, mulching with vetiver grass was shown to both increase yields and decrease run-off (Babalola et al., 2007; Okeyo et al., 2014). Another recent study in Burkina Faso investigated the harvesting of natural resources in situ (ramial wood from Piliostigma reticulatum shrubs) as soil amendments (Félix et al., 2018). They found that while the ramial wood chips did not contain sufficient nutrients to replace those lost from crop production, SOC increased significantly and biomass and grain yields were higher in the high ramial wood treatments compared to the control with no organic inputs. Finally, it is worth noting that leaf litter from N-fixing Alder trees (Alnus rubra Bong.),which are common in many parts of the high Andes, can provide significant amounts of N to the soil and to support crop growth (Swanston & Myrold, 1997; Visscher, 2018).

The objective of this investigation was to work with an indigenous community in the Ecuadorian Andes to explore locally-developed options for improved agricultural management to address the twin challenges of erosion and nutrient depletion in rain-fed small-scale farming systems. As part of an introductory workshop with the community, farmers identified 'live' hedgerows as a promising technique for controlling water erosion and producing supplemental organic amendments to improve soil fertility management. Based on consultation with community members, subsequent laboratory analyses of vegetative material present in the community, and according to the decision-tree developed by Palm et al. (2001), the species identified for inclusion in the hedgerows were Andean alder (Alnus acuminata) and canary grass (Phalaris tuberosa) (Figure 1).

Specifically, we studied the influence of hedgerow barriers and associated organic matter inputs on soil water erosion, topsoil moisture content, soil organic carbon and nutrient stocks, as well as on crop production in two different locations within the same landscape. We hypothesised that the hedgerows would significantly reduce water erosion in different biophysical contexts within the same community. Moreover, we postulated that incorporating organic amendments from these hedgerow species into the soil would have beneficial impacts on both soil quality and crop productivity, a pre-requisite for farmers to adopt these soil conservation techniques more widely.

Figure 1: *Photos of hedgerows used to control erosion. Left) Andean alder (Alnus acuminata) trees interspersed with canary grass (Phalaris tuberosa) hedgerow; Right) Canary grass (Phalaris tuberosa) strip.*

2. Materials and methods

2.1. Study site description

The research took place in from July 2015 to July 2017 in the rural indigenous community of Naubug, Flores Parish, Chimborazo Province, Ecuador (1°51'24.0"S, 78°39'15.6"W), with around 640 inhabitants (120 families). Annual precipitation is ca. 400-500 mm, with most rain falling between November and May (wet season) and a drier, windier period from June to October (dry season). Average annual temperatures reach 12-16°C. The community is characterised by steep topography (slopes are typically between 10-25°) with elevation ranging from 2850 to 3600 masl (Gobierno Autónomo Descentralizado Parroquial Rural de Flores, 2015). The long-term pedogenic processes of the region have been dominated by volcanic activity with pyroclastic deposits giving rise to the formation of volcanic (Andosol) soils rich in organic matter at the higher elevations (De Noni et al., 2001; Zehetner & Miller, 2006). At lower elevations and in areas that have experienced high erosion the sub-soils are exposed revealing thick layers of compacted volcanic ash known locally as “cangahua”. The soils of these areas are roughly classified as entisols or inceptisols.

As a result of these soil patterns and the climate gradients associated with the elevation range, local farmers have delineated the landscape into three agricultural “management zones”, broadly defined along elevation lines – the Upper, Middle and Lower Zones. The lower zone has sandier soils with a low nutrient content, coupled with a climate that is characterised by a lower precipitation:evapotranspiration ratio. The upper and middle zones, have soils higher in clay and nutrients content and a cooler, more moist climate (Caulfield et al., submitted).

The main sources of income in Naubug include the sale of very modest amounts of agricultural products to local markets, monthly government subsidies, and remittances from temporary and permanent migrant family members. Limited financial resources mean access to agricultural inputs and markets are also heavily restricted. Land is privately owned and most farmers own between 12-

18 fields dispersed throughout the landscape amounting to between 2-3 ha of land managed by each farming family. There is no access to irrigation water.

Table 1: *Moisture content and chemical composition of the organic amendments applied to the experimental plots (phenols, lignin C, N, P, K Ca and Mg presented as % of dry matter).*

Organic amendment	Property (%)								
	Water	Phenols	Lignin	C	N	P	K	Ca	Mg
Canary grass	74.95	1.04	6.58	51.10	4.23	0.25	3.18	0.34	0.32
Andean alder leaves	59.17	3.65	11.67	48.98	3.17	0.2	1.18	0.86	0.36

2.2. Experimental plots

A workshop was held with community members to identify existing and alternative improved agricultural techniques that have the potential to decrease land degradation and also 'aggrade' (improve) soils (Figure 1). Dual-use hedgerows were identified as having potential to reduce water erosion and provide sources of soil organic amendments to supplement the small amounts of organic resources currently available to community members. Three types of hedgerows were selected to meet these objectives: 1) grass strips of canary grass (Phalaris tuberosa) 2) 'native' tree hedgerows of Andean alder (Alnus acuminata), and 3) mixed hedgerows of both Andean alder and canary grass. A control with no live barrier or organic inputs was also included in the experimental design. Sub-samples of these organic resources were assessed for nutrient content and quality (Table 1) at the laboratory of the Ecuadorian National Institute for Agricultural Research (INIAP).

Twenty-four experimental plots (8 x 3 m2 each), oriented vertically and placed side-by-side along the contour were then installed in two fields in the rural landscape, 12 in a field in the upper zone at around 3600 masl and with a slope of around 20°; and 12 in a field in the lower zone at around 3100 masl and with a slope of around 13°. In each of the zones the four treatments (three hedgerow treatments and the control) were assigned randomly to replicate blocks. The tops and the sides of each experimental plot were fenced off using corrugated zinc-metal sheets inserted vertically into the soil to a depth of 45 cm and supported by wooden stakes. At the bottom of each plot an erosion trench was dug and lined with thick plastic sheet into which the run-off and sediment would collect. The hedgerows were established at the bottom of the plots, located within the experimental plot area, just up-hill from the erosion trenches with six A. acuminata saplings (1 cm diameter) planted in the pure Alder hedgerows and three saplings in the mixed hedgerows. Canary grass tussocks (30 cm in height) were planted adjacent to one another with a width of around 20-30 cm eight months before beginning the first crop cycle and data measurements (Figure 2). Canary grass was cut every three months to a height of 20-30 cm. To measure erosion, the run-off and sediment was emptied from the sediment capture trenches after each significant precipitation event using a plastic jug. The run-off was filtered twice through cotton cloth. The remaining sediment was then dried in an oven at 60°C until no weight change was observed and the weight recorded. Measurements were taken from July 2015 until July 2017.

To understand the effects of the organic amendments harvested from hedgerows, 40 kg of fresh grass and/or alder leave residues (equivalent of around 16.5 Mg ha-1 fresh weight, harvested from nearby the plots) were applied to the soils in each plot and incorporated two weeks before the planting of each crop with equal weight of seed. The organic amendments incorporated into the soils reflected the hedgerows of the experimental plots such that the experimental plots with Andean alder received 40 kg of Andean Alder leaves, the grass strips received 40 kg of canary grass amendments, and the mixed hedgerows treatment received 20 kg each of canary grass and Andean Alder leaves. The control treatment received no inputs.

At harvest, the total fresh crop biomass of each plot was weighed and recorded. A sub-sample of 100 tillers was then taken, weighed and dried in an oven at 60°C until no change in weight was recorded. The sub-sample was then separated into component parts (grain and stalk) and re-weighed. The first experimental crop cycle was planted with barley (Hordeum vulgare) in October 2015 and harvested in March 2016 (subsequently referred to as Barley 2016); the second crop cycle was planted with rye (Secale cereale) in September 2016 and harvested in January 2017 (subsequently referred to as Rye 2016); and the last crop cycle was planted with barley in February 2017 and harvested in July 2017 (subsequently referred to as Barley 2017). In the lower zone this last crop failed and therefore no data was collected for Barley 2017 in the lower zone.

To measure the effect of the organic amendments on soil moisture we used a soil moisture probe with a SM300 sensor (https://en.eijkelkamp.com/products/field-measurement-equipment/soil-moisture-measuring-system-with-sm300-sensor.html). Measurements were taken every other week from July 2015 to July 2017at three different points in each plot, 1.5 m in from the side and 2, 4 and 6 m down from the top of the experimental plot. An average of each of these measurements per plot and per season (wet: December-May; and dry: June-November) was used for data analysis.

To assess overall impacts of the organic amendments on the chemical composition of the soils, composite soils samples were taken from each experimental plot at the beginning of the study and following the harvest of the last crop cycle. The composite samples were taken by combining 20 samples (0-20 cm) to create a sub-sample of around 2 kg. All soil samples were air-dried and transported to the laboratory of the Ecuadorian National Institute for Agricultural Research (INIAP) for analysis of soil organic carbon (SOC; Walkley & Black, 1934), total N (Kjeldahl, 1883), as well as available P (Olsen method; Olsen et al., 1954), and exchangeable K, Ca and Mg (modified Olsen method, pH 8.5). The net change in soil chemical properties were then calculated for each plot by subtracting the pre-experiment soil results from the post-experiment soil chemical composition results.

Figure 2: *Photo showing experimental plots and sediment capture ditches located in the lower agricultural management zone. Near: Andean alder hedgerow treatment; Left: canary grass strip treatment.*

2.3. Statistical Analysis

One-way ANOVA was applied with block effects to compare erosion between the four experimental treatments for each location of the plots (upper zone and lower zone) and for each year measured (2015/2016 and 2016/2017) separately. A post-hoc Tukey's Honest Significant Difference Test was applied to test which treatments were significantly different at the $p < 0.05$ level. A log transformation was applied to the erosion data in order to adhere to the assumptions of homoscedasticity and normality. ANOVA tests with block effects and post-hoc Tukey's Honest Significant Difference Test ($p < 0.05$) were also applied to test for differences in biomass production and grain yield between the four experimental conditions for each location of the plots (upper zone and lower zone) and for each crop cycle (Barley 2016, Rye 2016 and Barley 2017). The same statistical tests were also applied to soil moisture measurements between the four experimental treatments for each location of the plots (upper zone and lower zone) and for each season (wet and dry); and for the net changes in soil chemical properties (SOC, total N, available P, exchangeable K, Ma and Ca) before beginning the experimental trials and after the last harvest. All analyses were carried out within the RStudio environment Version 0.99.902 for R.

3. Results

3.1. Erosion

Erosion was significantly lower in the canary grass treatment compared to the control treatment for the lower zone in 2015/2016 and in both locations in 2016/2017, i.e., during the second year of measurements. While the results were not significant in upper zone in 2015/2016, the control displayed a trend of greater sediment loss than the hedgerow treatments, with the exception of the pure alder hedgerows in the upper zone which had similar levels to the control treatment in 2015/2016 (Figure 3).

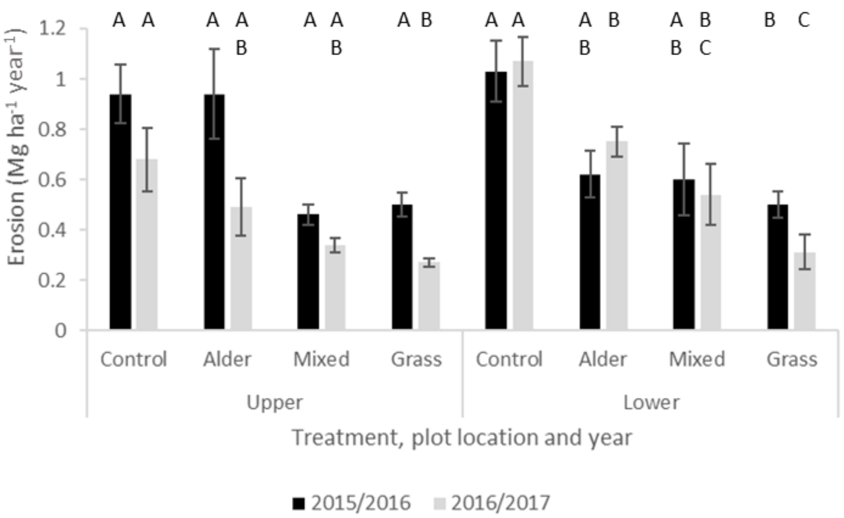

Figure 3: *Total soil erosion by year and treatment (control, Andean alder, mixed canary grass and Andean alder and canary grass hedgerows); and location in the landscape (Upper Agricultural Management Zone and Lower Agricultural Management Zone). Error bars indicate standard error of the mean; letters above bars indicate results from post-hoc Tukey's Honest Significant Difference Test, such that treatments with different letters in the same location and during the same year have significantly different means.*

3.2. Biomass production and yield

The canary grass treatment displayed significantly greater biomass production compared to the control treatment in the lower zone for all crop cycles except Rye 2016. Moreover, it is noteworthy that, while not always significant, the canary grass treatment consistently exhibited the highest biomass production under all three crop cycles and in both management zones, with the exception of Rye 2016 in the lower zone, when mixed canary grass and Andean alder amendments treatment displayed slightly more biomass production than the canary grass treatment. The mixed treatment also displayed significantly greater biomass production than the control in the lower zone for both barley crop cycles (Barley 2016 and 2017). The Andean alder treatment did not display improved productivity compared to the control, exhibiting lower biomass production under all crop cycles and zones except for Barley 2017 in the lower zone, when biomass production under control conditions was particularly low compared to all other conditions (Figure 4A).

Under Barley 2016 and 2017 in the lower zone, the grass amendments treatment exhibited significantly higher grain yield compared to the control treatment. While the canary grass and canary grass and Andean alder amendments treatments did not display significantly higher grain yield compared to the control condition in all instances, it is noteworthy that both treatments displayed consistently more grain yield than the control treatment across crop cycle and location. The pure

Andean alder treatment displayed no significant difference in grain production relative to the control for any of the crop cycles (Figure 4B).

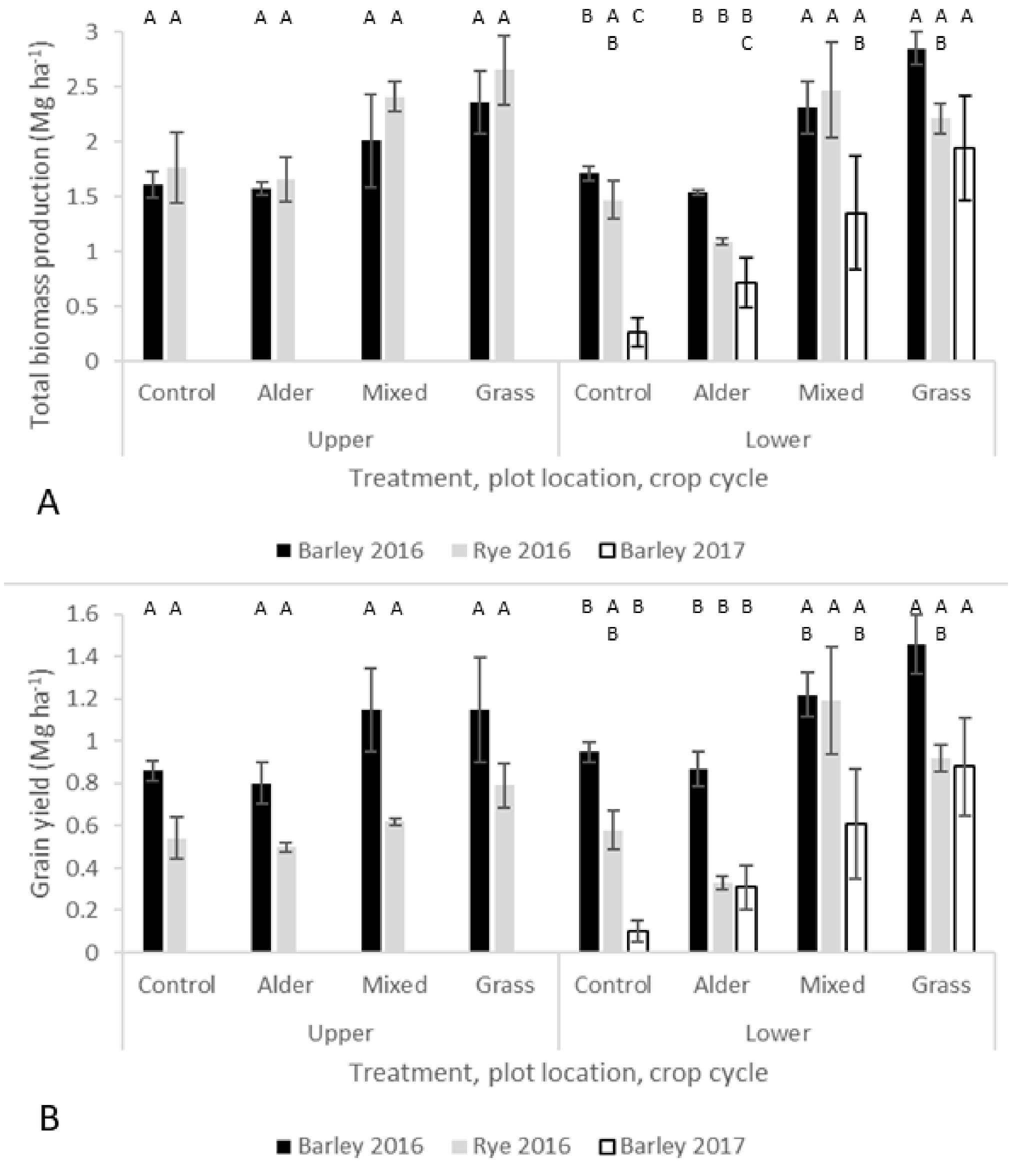

Figure 4: *Production of total dry biomass (A) and grain (B) by crop cycle per treatment (control, Andean alder, mixed canary Grass and Andean alder and canary grass amendments) and location in the landscape (Upper and Lower Agricultural Management Zone). Error bars indicate standard error; letters above bars indicate results from post-hoc Tukey's Honest Significant Difference Test, such that treatments with different letters in the same location and during the same year have significantly different means.*

3.3. Soil moisture

Soil moisture content under the control was significantly lower than for the treatments receiving amendments (hedgerows) in the upper and the lower management zone plots and during the wet and dry seasons. The treatment which consistently exhibited greatest soil moisture content was pure canary grass. In general, soil moisture tended to be higher in the upper zone than in the lower zone (Figure 5).

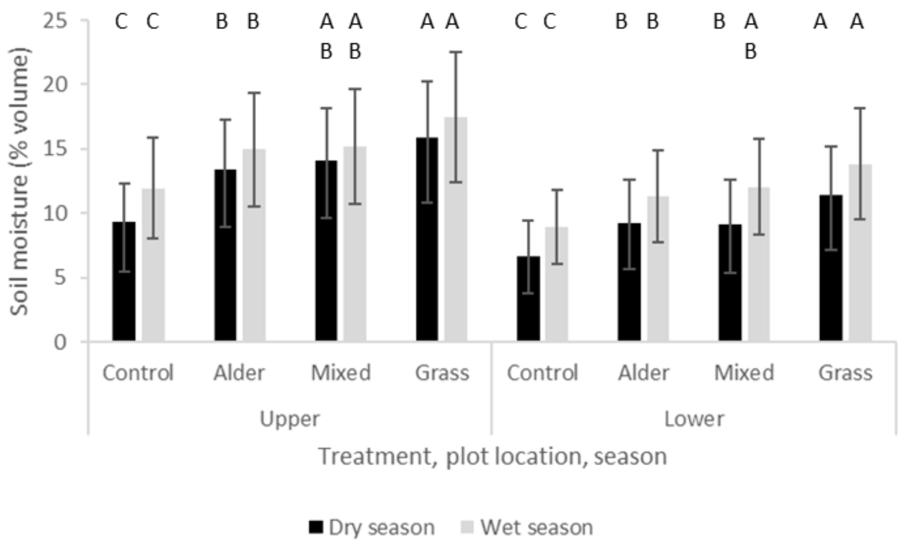

Figure 5: *Soil moisture content by season (dry and wet) per treatment (control, Andean alder, mixed canary grass and Andean alder, and canary grass amendments) and location in the landscape (Upper and Lower Agricultural Management Zone). Error bars indicate standard error of the mean; letters above bars indicate results from post-hoc Tukey's Honest Significant Difference Test, such that treatments with different letters in the same location and during the same year have significantly different means.*

3.4. Net changes in soil chemical fertility

Soil chemical analyses of the experimental plots taken before the first crop cycle (Barley 2016) and after the last crop cycle (Barley 2017) (Table 2) revealed significant increases in exchangeable K with grass and mixed amendment treatments in both management zones relative to the control. The Andean alder treatment also displayed significant increases in exchangeable K compared to the control in the lower agricultural management zone. While not significant, the other main soil chemical property with relatively large net changes was SOC, with a general trend of increase observed for all experimental treatments compared to the control treatment. In particular, the canary grass amendments treatments displayed the highest SOC net increases in both the upper and lower zones (Table 2).

Table 2: *Soil chemical analyses of the experimental plots taken before the first crop cycle (Barley 2016) and after the last crop cycle (Barley 2017). Mean and mean net changes to soil chemical properties[†] are presented by treatment (control, Andean alder, mixed canary grass and Andean alder, and canary grass) and location in the landscape (Upper and Lower Agricultural Management Zones). Post-hoc Tukey's Honest Significant Difference Test results are presented to the right of the mean net changes to soil chemical figures, with different letters significantly different at the p < 0.05 level. Standard errors are presented in parentheses.*

Zone	Treatment	SOC (%)			Total N (%)			Available P (mg kg-1)			Exchangeable K (cmol kg-1)			Exchangeable Ca (cmol kg-1)			Exchangeable Mg (cmol kg-1)		
		Pre	Post	Net Change	Pre	Post	Net Change	Pre	Post	Net Change	Pre	Post	Net Change	Pre	Post	Net Change	Pre	Post	Net Change
Upper	Control	4.23	4.40	0.18a (0.02)	0.32	0.37	0.05a (0.02)	12.33	18.00	5.67a (0.88)	0.02	0.09	***0.07b (0.02)***	18.60	21.10	2.50a (2.17)	4.33	4.07	-0.27a (0.09)
	Alder	4.12	4.48	0.35a (0.13)	0.30	0.38	0.08a (0.01)	13.00	19.67	6.67a (2.03)	0.04	0.26	***0.22b (0.02)***	18.13	22.60	4.47a (0.03)	4.57	4.10	-0.47a (0.18)
	Mixed	4.26	4.69	0.42a (0.14)	0.31	0.40	0.09a (0.01)	13.67	18.00	4.33a (0.34)	0.04	0.42	***0.37a (0.07)***	18.63	22.37	3.73a (0.54)	4.43	3.97	-0.47a (0.13)
	Grass	4.07	4.56	0.49a (0.02)	0.31	0.35	0.04a (0.01)	12.33	19.00	6.67a (0.87)	0.02	0.45	***0.43a (0.03)***	18.37	22.23	3.87a (0.64)	4.50	4.00	-0.50a (0.06)
Lower	Control	1.07	1.36	0.28a (0.10)	0.15	0.16	0.01a (0.02)	11.37	15.33	3.97a (1.71)	0.20	0.25	***0.05c (0.01)***	14.90	15.57	0.67a (0.58)	5.20	4.67	-0.53a (0.03)
	Alder	1.18	1.50	0.32a (0.06)	0.13	0.15	0.02a (0.04)	13.00	16.67	3.67a (0.88)	0.27	0.46	***0.19b (0.04)***	15.13	15.77	0.63a (0.84)	5.30	4.97	-0.33a (0.03)
	Mixed	1.04	1.34	0.30a (0.05)	0.13	0.15	0.02a (0.01)	12.67	17.67	5.00a (1.00)	0.29	0.61	***0.32ab (0.03)***	14.33	15.73	1.40a (0.91)	5.00	4.57	-0.43a (0.17)
	Grass	1.09	1.55	0.46a (0.09)	0.12	0.18	0.06a (0.02)	13.00	17.33	4.33a (1.77)	0.26	0.66	***0.39a (0.05)***	15.23	14.53	-0.70a (0.76)	5.03	4.50	-0.53a (0.03)

[†]Net changes are calculated based on the soil chemical component measurement before starting the experimental treatments and after the last experimental treatment was conducted (Barley 2017)

4. Discussion

4.1. Canary grass hedgerows help control (low levels of) erosion on agricultural fields

The hedgerows comprised of canary grass or canary grass combined with Andean alder displayed significant potential to decrease soil water erosion (Figure 3). Canary grass strips reduced soil loss by about 50% in 2015/2016 and more than 60% in 2016/2017 in the upper agricultural management zone compared to the control. In the lower agricultural management zone the effects were similar with grass strips exhibiting around 50% and 70% less soil loss compared to the control in 2015/2016 and 2016/2017, respectively. Our results corroborate past research demonstrating that grass strips in can be highly effective in controlling erosion (e.g., Donjadee et al., 2010; Tesfaye et al., 2018; Wu et al., 2010; Xiao et al., 2012).

Perhaps more surprisingly, our results exhibited considerably less erosion than observed in other studies from the region. For example, Henry et al. (2013) using the 137Cs technique for erosion measurement at landscape level found average erosion rates of 27 Mg ha-1 year-1, while Molina et al. (2008) using direct measurements of accumulated sediment at 'checkdams' at the catchment level found similarly high erosion rates of 22 Mg ha-1 year-1. Erosion found in this study barely reached levels above 1 Mg ha-1 year-1 in the control condition, which is similar to the estimated global average rate of soil formation (Pimentel, 2006).

Part of the reason why the levels of erosion observed in this study may have been so low compared to the studies referenced above is that the current study assessed erosion at the plot level rather than at the landscape or catchment scales where greater slope lengths can contribute substantially to the erosive energy of overland flow (Kearney et al., 2017b) and also focuses on agricultural land uses, as opposed to other land-uses also present in rural landscapes or catchments. In studies differentiating the effect of different land-uses on erosion it is appears that surface run-off on agricultural land is often low to minimal compared to other land-uses, since high infiltration rates are often associated with cultivated soils (Harden, 2001, 1996; Molina et al., 2007). In a study in the

Ecuadorian Andes using rainfall simulators, the compacted surfaces of paths and roads generated much greater runoff volumes, initiated greater runoff at lower rainfall intensities, and produced runoff sooner during a rain event compared to cultivated areas (Harden, 2001). Similarly, Molina et al. (2007), also working in the Ecuadorian Andes, found degraded and abandoned land to generate surface runoff within a few minutes after the start of the rainfall event, while surface runoff on arable land was rare.

This leads us to conclude that while hedgerows such as the mixed hedgerows and grass strips in this study were effective in reducing water erosion, overall low levels of water erosion in agricultural fields seem not to be a critical challenge for farmers in this particular context. Notwithstanding this conclusion, this is not to suggest that their utility is not important for other types of erosion processes. Erosion induced by animal-powered tillage has been shown to be particularly important in the region of study with soil loss figures in the Southern Ecuadorian Andes reported to be between 30-186 Mg ha-1 year-1 (Dercon et al., 2007). While in our experiment, the effect of hedgerows on animal-powered tillage was not assessed, another study in Ecuador found that the presence of grass strips was very effective in the development of slow-forming terraces, that decrease tillage erosion, however, not without causing important within field spatial variability in fertility (Dercon et al., 2003). Additional research would be necessary to further assess whether the hedgerows used in our study also provided such potential for decreasing erosion from tillage practices.

Moreover, it should be emphasised that while agricultural fields may not produce significant amounts of water erosion in this context, other parts of the landscape clearly do given findings from other landscape and catchment level erosion studies in the region (Henry et al., 2013; Molina et al., 2008). As such we would argue that the use of mixed hedgerows and grass strips under agricultural land-uses could potentially play an important role in addressing this issue if employed more strategically, for example, by considering the overall landscape mosaic and inter-connections between land-uses. However, given that these hedgerows have only been assessed under conditions with relatively low erosion rates, further research would be necessary to be sure they are also effective adjacent to other land-uses that may incur higher rates of erosion. Furthermore, the length of the slope is well recognised as an important factor in soil water erosion (Liu et al., 2000; Renard et al., 1991), as such it would also be necessary to assess the efficacy of the hedgerows used in this experiment under different slope lengths. It may be the case that longer slopes may require broader hedgerows and grass strips.

4.2. Canary grass organic amendments improve soil fertility and productivity

As hypothesised, our results indicate that canary grass has clear potential to increase soil productivity in terms of both overall biomass and grain yield when incorporated into the soil before planting (Figures 3A and 3B). This is an important finding in this socio-ecological context as it suggests that resource-constrained farmers may be able to supplement limited organic agricultural inputs with amendments from canary grass strips to improve their productivity. The results reflect previous studies with vetiver grass in Africa, which was also shown to increase yields when used as a mulch (Babalola et al., 2007; Okeyo et al., 2014).

In contrast, alder-based organic amendments alone did not appear to significantly improve soil productivity in the timeframe of this study. This is surprising given that the scarce research that has been undertaken with regard to the use of alder leaf material as organic amendments, does suggest that it has the potential to increase soil nutrient levels and a range of other soil properties (de Valença et al., 2017; Swanston & Myrold, 1997). Moreover, the laboratory analysis of the chemical composition of the leaf material indicated high quality (i.e., low C:N) and seemingly suitable levels of lignin (< 15%) and phenols (< 4%) (Table 1), according to Palm et al. (2001). It is noteworthy however, that phenols were measured at the high end (3.65%) of the acceptable levels for direct incorporation with annual crops. In cases with levels of phenols higher than 4% the decision-support tool of Palm et al. (2001) suggests mixing the organic resources with fertilizers or high-quality materials. Indeed, when the Andean alder leaves were mixed with canary grass, biomass production and grain yield were often not significantly different to the canary grass treatment (Figures 3A and 3B), although it cannot be discounted that this effect was simply a result of the canary grass amendments included in the mixed amendments treatment. More research is needed to better understand this effect, the minimal quantities of organic amendments necessary to observe significant improvements in soil productivity as well as any potential trade-offs with loss of productive land due to the use of hedgerows on agricultural land.

While it is likely that improvements in soil productivity observed under the mixed and canary grass organic amendment treatments are at least partly due to the additional nutrients these inputs provide, it is also possible that they are due to improved water availability for crops. In both the dry and the wet seasons, average soil moisture levels were significantly higher in all three treatments receiving organic amendments compared to the control (Figure 5). In mountainous rain-fed agricultural systems, which are expected to experience more erratic precipitation patterns in the coming years (Kohler et al., 2014), application of such amendments may help resource-constrained farmers build resilience to climate change.

Given the critical relationship between soil water storage, soil aggregation and SOC (Bronick & Lal, 2005) the increased levels of soil moisture in the experimental conditions are likely a result of the increased levels of SOC incorporated through the organic amendments. While not significant, SOC levels tended to increase in all treatments compared to the control, in particular for the canary grass alone treatment (Table 2). This indication of an increase in SOC following the incorporation of in situ sourced organic amendments reflects the findings of Félix et al. (2018) who found that while the ramial woody amendments that they incorporated did not provide sufficient nutrients to balance the nutrient outflows, they did lead to higher yields and levels of SOC than the control condition.

Noteworthy in these current results however, is the fact that in all treatments, in both locations, SOC and all soil macro-nutrients appeared to increase throughout the experiment with the exception of Mg. While the increases observed in the experimental treatments may be explained by the organic matter inputs incorporated over the course of the three crop cycles, it is less evident why this may be the case for the control treatment as one would expect a decrease. One possible contributing factor to this finding may be that the crop residue left in the fields after harvest may have improved the nutrient balance in the experimental plots with the lowest biomass production (control treatment). Another possible factor that cannot be excluded is that the laboratory analyses of the soils consistently over-measured the soil chemical properties post-experiment in September 2017, or under-measured them pre-experiment in September 2015. This potential methodological bias is not unusual in successive soil analyses and often a range of 20% variability between samples from the same field within the season or subsequent samplings may be expected due to the inherent heterogeneity of farmer-managed soils (Tittonell et al., 2013).

It is important to highlight that hedgerows and grass strips may not produce sufficient quantities of organic amendments to satisfy all carbon and nutrient input requirements (Félix et al., 2018). Indeed, it is unlikely that the quantities of the OM inputs used in this experiment (16.5 Mg ha-1 fresh weight) would be feasibly produced by hedgerows grown around an agricultural field, with a recent study suggesting that a different species of canary grass produced between 4.5 and 9.5 Mg ha-1 year-1 dry matter (or around 30 Mg ha-1 year-1 fresh weight) (Pocienė et al., 2013). Instead, the promising results found in this study for amendments harvested from hedgerows should be placed within the context of identifying farming practices that have the potential to increase overall access to carbon and nutrient resources as mechanisms to supplement rather than replace current input patterns. This potential is particularly useful in mountainous landscapes where the development of soil conservation practices such as slow-forming terraces can lead to important soil fertility gradients at the field level (Dercon et al., 2003). An increased access to organic amendments means that less fertile parts of the field may be targeted with additional inputs, while still being able to provide lower level inputs to the other areas. Moreover, the potential to harvest the amendments in situ may be able to address some commonly observed landscape scale fertility gradients, where far-fields receive fewer inputs than fields located closer to homesteads (Fonte et al., 2012; Vanek & Drinkwater, 2013).

Finally, while our results indicate that out of the three experimental conditions, canary grass strips performed the best both in terms of erosion control and for improving soil productivity, on other metrics it is likely that the other hedgerows would perform better. For example, mixed hedgerows and other agroforestry techniques with important ligneous components have been shown to be particularly valuable for C sequestration (Albrecht & Kandji, 2003; Palma et al., 2007; Takimoto et al., 2008), vegetative richness and diversity (Deckers et al., 2004; Kearney et al., 2017a; Smukler et al., 2010) and macrofauna abundance and diversity (Pauli et al., 2011; Rousseau et al., 2013). When factoring in these ecosystem components, it would appear that mixed hedgerows with canary grass and Andean alder may be optimal, providing the potential for erosion control, sources of organic amendments, C sequestration and improved biodiversity.

5. Conclusion

Our results demonstrate that hedgerows comprised of canary grass, and canary grass and Andean alder have the potential to provide important benefits for small-scale farmers by minimising land degradation due to water erosion and by aggrading soils through the incorporation of organic amendments harvested from these hedgerows. The erosion control potential of canary grass strips decreased water erosion in the plots by between 50-70%. However, we also found that overall annual erosion in agricultural fields was rather low suggesting that water erosion control may not be the greatest driver of degradation for agricultural land-uses in this landscape. Nevertheless, we argue that erosion control structures such as those tested in this study may be effective for other types of erosion, such as tillage erosion, or adjacent to other land-use types that may incur greater erosion rates although more research is necessary to assess these possibilities.

Canary grass and mixed canary grass and Andean alder leaf amendments increased both biomass production and grain yield in this study. Canary grass appears to be a particularly high-quality organic amendment being able to boost soil productivity by itself. Andean alder leaf amendments on the other hand, appear to be less effective, needing to be incorporated with higher-quality organic material or composted. It is likely that the agricultural production benefits were a result of the nutrient inputs from the organic amendments as well as their ability to improve soil moisture levels by increasing SOC levels.

In conclusion, while hedgerows may not be able to produce sufficient quantities of organic resources to satisfy all nutrient input requirements, their potential to supplement existing inputs in a resource constrained socio-economic context mean that they should be strongly considered as an option for improved agricultural management. Not only can these extra resources enable farmers to target additional inputs to low fertile areas within fields, but the potential to harvest the amendments in situ is an additional benefit to address commonly observed landscape scale soil fertility gradients where distant fields receive fewer inputs than fields located closer to homesteads.

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Chapter 6: General discussion

1. Introduction

In this synthesising chapter I outline how the different strands of empirical research presented in the previous four chapters provide an enhanced understanding of some of the relationships between land and farm management, agroecosystems and broader socio-ecological variables; shed a new and more intricate perspective on how farm and land management and agroecosystems patterns have co-evolved within this particular socio-ecological context in the Ecuadorian Andes, as well as providing a concrete case-study as to how the socio-ecological systems (SES) and complex adaptive systems (CAS) frameworks can be used to inform more contextualised and effective natural resource management and intervention strategies. In recognition of the inter-disciplinary approach integral to the study of socio-ecological systems, I employed a diverse range of methodologies from both social and biophysical science backgrounds at different scales of analysis. By adopting this broad approach, I have gained critical insight into the socio-ecological drivers, interactions and effects that have led to the co-evolution of the current socio-ecological context of the main study sites.

It is important to highlight that the work was conducted as part of a broader process of co-learning with a group of farmer "researchers", professors and students from a local university and key policy makers and intervention agents. The group, in particular the group of farmer researchers, were deeply involved in the study, from planning, to data collection and analysis. The work culminated in the co-development of a "Landscape Level Natural Resource Management Plan" which aimed to identify and outline more nuanced and contextualised natural resource management and intervention strategies for the community.

Following the DEED approach (Descheemaeker et al., 2016; Giller et al., 2011), the preceding chapters of this thesis have focused mainly on the first three steps of the DEED cycle (Describe; Explain; Explore) whose analysis, conclusions and implications will be subsequently discussed and synthesised here under the framework of CAS. I will then go on to present and discuss the final step in the DEED cycle (Design) outlining how key concepts from the SES and CAS frameworks facilitated the co-development of a contextualised landscape level natural resource management plan.

2. Panarchy and the co-evolution of system regimes and asymmetric landscape patterns

In line with the SES and CAS frameworks, we found evidence that both land management and landscape agroecosystem patterns are driven by a panarchy, or network, of complex adaptive cycles connected by a nested hierarchy (Gunderson and Holling, 2002; Ostrom, 2004). As will be outlined below, specifically we found evidence that supports the hypotheses outlined in the Introduction of this thesis that multiple interacting socio-ecological factors, at different scales, influence the development of farm management and agroecosystem patterns; feedback loops exist across scales such that farm management and agroecosystem patterns co-evolve; and system regimes can be found at different scales of analysis.

2.1. Land management co-evolves through multi-level socio-ecological interactions

In Chapter 2, through the use of Structural Equation Modelling, we found that temporary out-migrations were indirectly related to the use of industrialized farming techniques (use of mechanized tillage and agro-chemical use) via their positive correlation with household financial resources and subsequent farm-level decisions to increase the proportion of potato cultivation, a cash-crop in the area. Fundamentally, the research highlighted the importance of intermediary (or multi-scale) socio-economic and cultural factors on farm management. The opportunities presented by temporary rural out-migrations (greater financial resources) coupled with the local market demand for potatoes influenced cropping and investment decisions and thereby farm management. This finding adds support to the conclusions of Tittonell (2014) who argued that alternative farm or livelihood strategies are determined and constrained by local agro-ecological potential, demography, market connectivity and local institutions.

Chapter 3 provided further insight into the influence of socio-economic and cultural factors on farm and land management. In this study, despite the close proximity of the three communities considered, farm management differed significantly in terms of field inputs of organic matter. Specifically, it was argued that farmers in the community of Tzimbuto consistently incorporated more OM inputs than the other two communities as a result of improved structural opportunities (access to irrigation water, stronger links with local and regional markets and better transport links with the provincial capital) enabling farmers there to invest more in agricultural production due to the potential greater return on (agricultural) investment.

In Chapter 4, we observed how asymmetric landscape agroecosystem patterns can influence social processes. By means of participatory community land-use mapping, local farmers identified three agricultural management zones in the community of Naubug broadly delineated by elevation. The farmers reported that the upper and middle agricultural management zones differed in terms of cultivation focus (proportion of forage crops) due to differences in temperature as a result of the topographic gradient. On the other hand, the lower fertility status of the soils, greater distance from homesteads, and lower precipitation rate in the lower agricultural management zone were the reasons given by farmers for using this area less intensively and investing fewer resources than the upper and middle zones.

In addition to its effects on farm management, asymmetric landscape agroecosystem patterns may also be influencing farming family land-use. As the zone with the lowest fertility status and greatest potential for water stress, it is not a coincidence that the lower agricultural management zone is also the area of the landscape with the highest proportion of forest and abandoned agricultural land (Chapter 4). These findings reflect the work of Mayer (2002), in underlining the importance of asymmetric agroecosystem patterns in the development of farming systems along elevational niches, especially in mountainous areas where climatic gradients can be particularly strong.

The result of the interactions described above is the co-evolution of system regimes related to farm management at multiple scales. In Chapter 3, we observed that farm management differed significantly between communities with regard to agricultural inputs, while in Chapter 2 we observed different farm management between farming families with temporary out-migration and those without temporary out-migration. Finally, in Chapter 4 we also observed significant differences in farm management within farm, through the development of three distinct agricultural management zones. In each case, differences in farm management at different scales of analysis co-evolved as a result of different socio-ecological interactions.

2.2. Asymmetric landscape agroecosystem patterns co-evolve through multi-level socio-ecological interactions

The evidence outlined in Chapter 4 provides insight into how elevation-induced climate and soil textural gradients have led to asymmetric agroecosystem patterns. The research revealed that soil organic carbon (SOC) and carbon stocks increased exponentially with elevation. It was argued that this was a result of the pedogenic processes that encouraged soil organic matter (SOM) accumulation in cooler climatic conditions and in soils with greater levels of clay (Chivenge et al., 2007; Zehetner and Miller, 2006) (Figure 1A). This important agroecosystem pattern was moderated by slope gradient, whereby the effect of elevation decreased in areas of the landscape with higher slope gradients, indicating significant erosion processes and the influence of geomorphology. Given the importance of SOM in providing energy resources for soil food webs, it is not surprising that soil biological activity (macrofauna richness) also increased with elevation in the same landscape (unpublished data).

This analysis underlines the importance of how multiple environmental gradients work together to generate asymmetric agroecosystem patterns. The elevation and soil textural gradients have a structuring effect on soil chemical composition (SOC), which in turn has a structuring effect on soil biological activity. In other words, systematic variation is a driver of ecosystem patterns (Cumming et al., 2008). These landscape level processes and patterns reinforce the idea that soils should be studied as dynamic entities within a landscape (Pennock and Veldkamp, 2006). A good example of such an approach was carried out in a agricultural landscape in Montours, France, where the authors aimed to explain the effect of a hedgerow network on soil organization and redistribution (Follain et al., 2006). In the study they found that hedgerows modified landscape-level soil distribution as well as landforms by enhancing deposition in the uphill position and soil erosion downhill of hedgerows (Follain et al., 2006).

In addition to moulding the emergent agroecosystem patterns of the landscape, the environmental context of the landscape also seemed to be influencing the biophysical responses to the OM inputs incorporated into the landscape by farmers. This was especially evident in the measurements of SOC under agricultural land-use in Chapter 4. While the levels of available P reflected the OM inputs reported by farmers in the participatory land-use mapping, where OM inputs were equally high in the upper and middle agricultural management zones, but minimal in the lower agricultural management zone, SOC levels continued to increase from the lower to middle and from middle to the upper agricultural management zones. Indeed, compared to other land-uses the increase in SOC with elevation under agricultural land-use was strongest, in so much that it displayed the lowest levels in the lower elevations of the landscape, but the highest in the upper elevations. It was argued that this was a consequence of greater accumulation of SOC from the agricultural OM inputs in the upper agricultural management zone compared to the middle zone due to the environmental context (cooler climate, higher clay levels) (Figure 1B). This conclusion is important as it suggests that multiple cross-scale processes drive such landscape patterns.

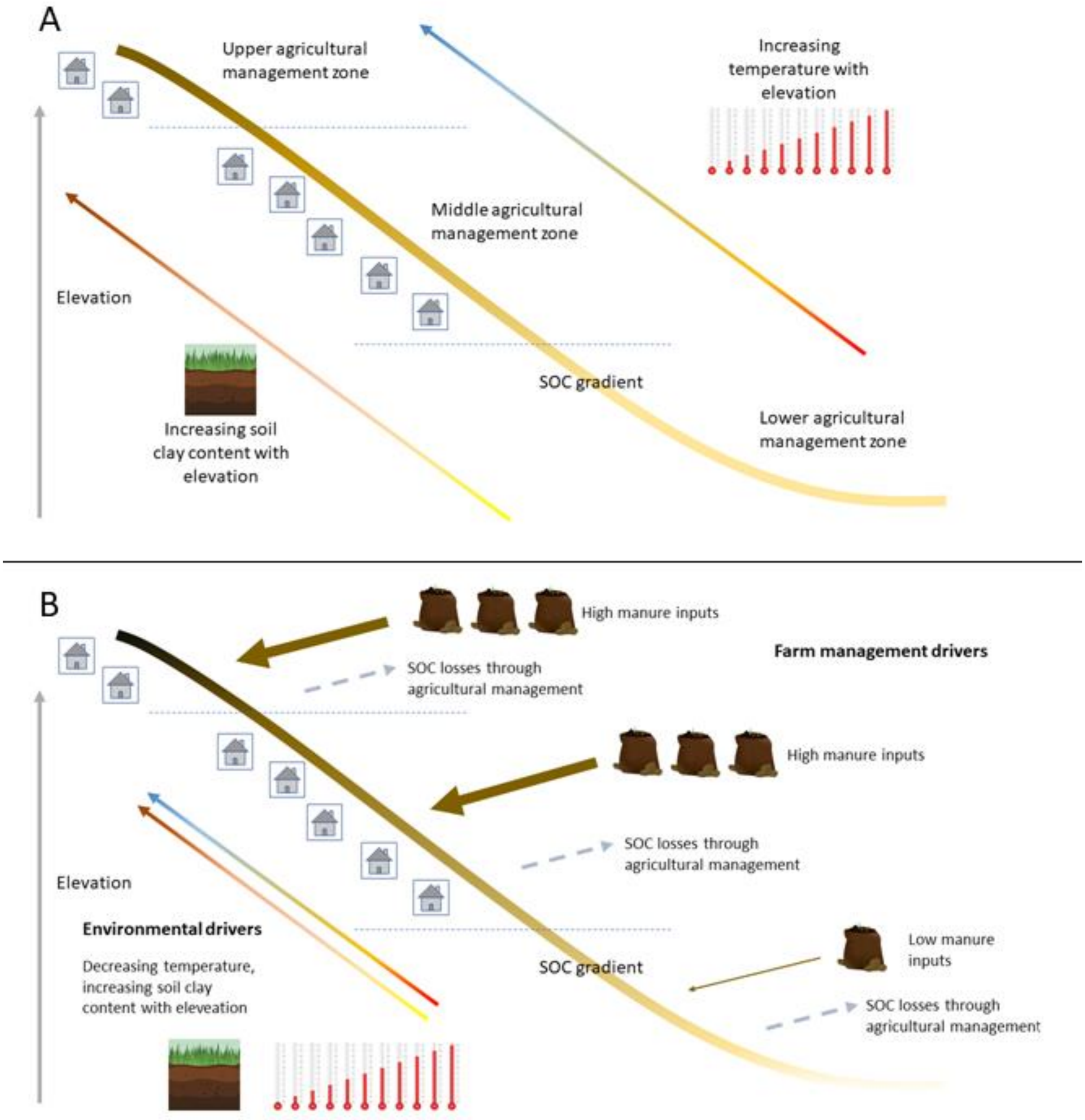

Figure 1: A) *Conceptualisation of environmental drivers for asymmetric SOC landscape patterns, where both temperature and soil clay content gradients combine to drive greater SOC levels in the upper parts of the landscape than the lower parts.* ***B)*** *Conceptualisation of socio-ecological drivers of SOC patterns in the landscape, where both the social and ecological factors combine to drive even higher SOC levels in upper agricultural management zone, and even lower SOC levels in the lower agricultural management zone. SOC gradient is visualised as a gradient of colour from yellow (low) to brown to black (high).*

These emergent agroecosystem patterns of the landscape were further shaped by land management. Chapters 3 and 4 both provided evidence for effects of distance from homestead on soil chemical composition, similar to those commonly reported in African contexts (e.g., Tittonell et al., 2010; Zingore et al., 2007). Farmers tend to concentrate nutrient inputs to fields close to the homestead leading to significant decreases in soil macronutrient fertility the further a farmer's field is located from their homestead. This effect appears to be rather robust being observed in the three rural communities considered in this study, even in the community with the highest organic matter inputs overall (Chapter 3).

Indeed, in Chapter 3 the research shed light on another important positive feedback loop. It was observed that farmers' perception of fertility was positively associated with organic matter inputs. The more fertile the field was perceived to be, the more OM inputs the farmer incorporated into the field. It is easy to imagine how such a feedback loop could lead to both virtuous and vicious cycles, whereby fertile fields on a farm would become increasingly more fertile, but where less fertile fields would become increasingly less fertile (Figure 2). Indeed, the consequences of this may have been observed in Chapter 4 where the agricultural soils in the lower agricultural management zone of the landscape were severely nutrient and carbon deficient (Figure 1B). This conclusion suggests that feedbacks between the social and ecological systems display an important element of self-organisation (Green and Sadedin, 2005) (Figure 2).

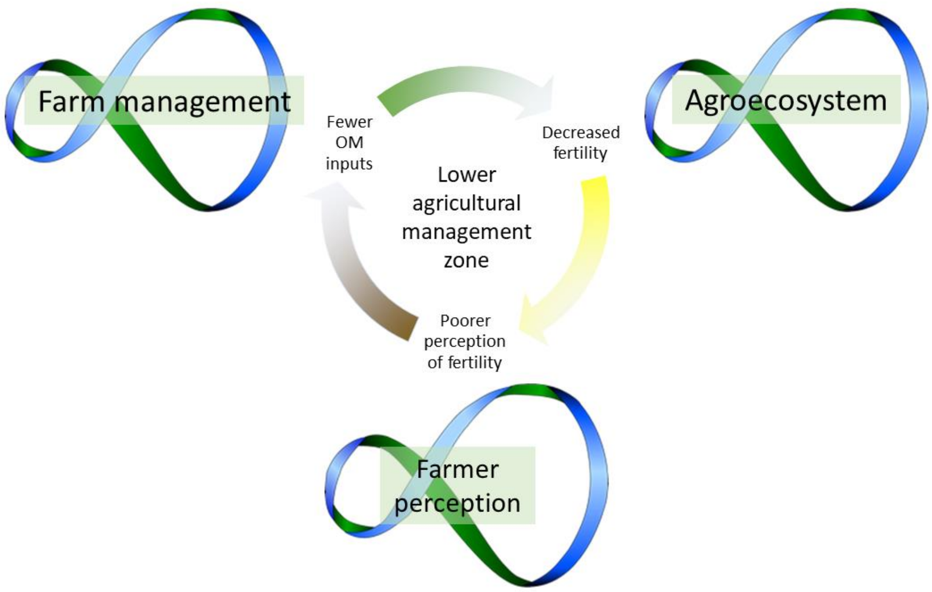

Figure 2: *An example of self-organisation within a panarchy of nested hierarchies, whereby feedback loops between adaptive systems lead to the current farm management and soil fertility status of the lower agricultural management zone in the community of Naubug, Chimborazo Province, Ecuador.*

In Chapter 3 it was also argued that this 'perception of fertility' feedback loop was further influenced by the environmental context. In the communities of Naubug and Tzimbuto, farmers' perception of field fertility was correlated with SOC, total N and available P. However, this was not the case in Basquitay, where farmers' perception of fertility correlated only with total N and available P. These differences were argued to be a result of the fact that the soils in Basquitay tended to have comparatively high SOC levels. These high baseline levels of SOC provide a conducive environment for plant growth, therefore it becomes a less important variable to differentiate soil fertility. The overall environmental context in this case can therefore be said to have an important influence over farmers' perception of fertility and therefore also on OM inputs levels and ultimately the agroecosystem patterns of the landscape. In Figure 2 this would add an additional adaptive system to the Figure, which would have cross scale linkages with 'farmer perception', as well as farm management and agroecosystems as demonstrated above.

Non-agricultural land-uses under the management and ownership of farming families also have important roles in influencing the agroecosystem patterns of the landscape. In Chapter 4 we observed that the different land-uses displayed significant differences in terms of soil chemical properties, biodiversity and carbon stocks and that these land-uses were distributed differently throughout the landscape. Mixed hedgerows, for example, were especially associated with improved levels of different agroecosystem components compared to all other land-uses in Naubug, while eucalyptus/pine forests performed poorly compared to mixed hedgerows for SOC, vegetative diversity and macrofauna diversity. Given that the land-uses are distributed across the landscape asymmetrically (i.e., greater proportion of forest and abandoned land in the lower agricultural management zone), these associations between land-use and agroecosystem components and their spatial distribution are likely contributing to greater spatial asymmetry in the agroecosystem landscape patterns (Hall et al., 2012).

2.3. Better explaining inconsistent scientific findings using the complex adaptive systems framework

The conceptualisation of land and farm management and asymmetric landscape agroecosystem patterns as emergent properties that have co-evolved from a complex adaptive system may seem theoretical or even trivial. However, critically the application of the framework has proven vital in this research in shedding light on the reasons why, in many instances, scientific research into farm management and agroecosystems patterns have reached inconsistent findings. For example, similar to the results presented in Chapter 2, in a study undertaken in the south of Ecuador, Gray (2009) found that out-migrations were associated with agricultural intensification and the increased use of agro-chemicals. However, in another study, this time in China, the opposite was found (Qin, 2010). Another example, is that of the effect of distance from homestead on soil fertility presented in Chapter 3, which appears to be a relatively common finding being observed in the three communities considered in this research and in many other reports in the literature (e.g., Vanek and Drinkwater, 2013; Zingore et al., 2007b). Nevertheless, even for such a seemingly robust pattern as this, others have found opposite patterns (eg, Haileslassie et al., 2007; Masvaya et al., 2010).

By framing the understanding of farm management, and agroecosystem patterns within a panarchy of complex adaptive cycles that include other socio-ecological adaptive cycles (Figure 3), such inconsistencies are in fact expected, given that variables are considered to be non-deterministic and responses context specific. In this regard the SES and CAS frameworks can better account for the different findings reported in the literature than the early formulations of theoretical frameworks addressing land-use change and the consequences of rural population mobility, for example, which can be considered overly deterministic (e.g., the Household Lifecyle Theory (Thorner et al., 1986); the Forest Transition Theory (Mather, 1992); New Economics of Labour Migration (Stark and Bloom, 1985)).

Taking the examples above once again, the inconsistent findings with regard to the effects of out-migration can be better understood once the nested hierarchies, or 'context', is taken into account. In the two case studies from Ecuador, additional financial resources generated through out-migration were invested in the intensification of agriculture through the cultivation of cash crops (potato in one case, maize in the other), thus providing livelihood strategies that enabled farming families with out-migration to 'stay put' in their communities (Mata-Codesal, 2018; Stockdale and Haartsen, 2018). In the case study from China however, income from rural out-migrations was sufficient enough that it lowered the dependency on agriculture for the livelihoods of the rural households while enabling them to remain in their communities, creating a tendency toward a deintensification of their agricultural activities (Qin, 2010). In other words, the broader socio-ecological context (e.g., the potential income generated from temporary out-migration and the market demand for local agricultural products) affected how rural households responded the opportunities presented by out-migration (intensification or deintensification).

With regard to the inconsistent findings in terms of decreasing fertility with increasing distance from homestead, for the landscape studied by Vanek and Drinkwater (2013), it is likely that the fertility gradient observed was at least partly a result of the decreased agricultural inputs due to the inaccessibility of far-fields in the mountainous Andean terrain. As discussed above, the fertility gradient observed in Chapter 3 appears to have co-evolved out of multiple interactions and feedbacks between farm management, agroecosystem patterns and the environmental context. In the case study from Zimbabwe (Masvaya et al., 2010), where the opposite pattern was found, the authors argued that this pattern was a result of the fact that the population density was relatively low in the district where the research took place, enabling farm expansion to fields further away from the homestead. As these newly acquired fields were located on land that was previously forest, their fertility status had declined less than fields closer to the homestead (Masvaya et al., 2010). In another study in the Central Ethiopian Highlands, the reason given for the contrasting fertility gradient was that the far-fields were used to cultivate the most important cash crops and therefore received the most agricultural inputs (Haileslassie et al., 2007). In these examples, again by better understanding the interactions and feedbacks with the broader context (field accessibility, land-use change, agricultural expansion, market demands for particular agricultural products, and field suitability for crop cultivation) we are now able to explain how different fertility gradients may arise in different contexts. Asymmetric patterns, whether social (farm management) or ecological (agroecosystems), are a consequence of the cross scale interactions and feedbacks between the biophysical and socio-economic and cultural domains and trajectories unique to each individual context (Caldas et al., 2007; de Sherbinin et al., 2008; Tittonell, 2014).

3. Horses for courses: context dependent farming techniques

Hedgerows were identified by farmers as techniques to potentially conserve and aggrade soils for improved productivity. As outlined in Chapter 5, such techniques do provide the potential to mitigate soil water erosion and to act as sources of organic matter that can be used as amendments to improve soil quality and productivity. However, the effect on biomass accumulation and agricultural production was only significantly different to the control treatment in the lower agricultural management zone. This reflects the broader findings of the research outlined above suggesting that context, in this case the environmental context, is critical.

The lower agricultural management zone of the landscape differed significantly from the upper zone in terms of SOC content (lower); macro-nutrients (lower) as well as temperature (higher) and precipitation (lower). This means that specific to this area of the landscape there was a greater need for nutrient and organic inputs to help increase soil nutrients and water retention capacity. Conversely, the opposite conditions in the upper elevations of the landscape meant that such inputs were potentially less critical as the inherent soil fertility was already relatively high suggesting the need for better soil conservation rather than soil aggradation in this area of the landscape.

The fact that these techniques for harvesting organic amendments *in situ* appears to work best in distant fields in this context may be especially important in that it is these fields that receive much fewer inputs compared to the fields found in the upper or middle agricultural management zones. As discussed in Chapter 3 and above, these patterns of resource flows have probably co-evolved as a result of different interactions and feedbacks between different factors including inaccessibility of distant fields, agroecosystem patterns and environmental gradients, and not simply as a result of constrained access to agricultural inputs. In cases where distant field inaccessibility may be an important factor associated with decreasing agricultural inputs, such *in situ* techniques may prove to be particularly well suited to the socio-ecological setting.

However, in view of the discussions above, it would be foolhardy to promote such techniques as panacea solutions to asymmetric resource flow patterns in the Andes or elsewhere. Indeed, as highlighted in Chapter 2, rural out-migrations are an important trend in the region that has significant consequences for household labour availability providing important restrictions for farming techniques that require greater labour inputs. Instead it is important to place them within the broader socio-ecological context of each unique setting, presented as a single option among many for improved landscape and natural resource management. As the SES and CAS frameworks help us understand, solving sustainability challenges requires the co-development of contextualised options using a multi-tiered diagnostic approach (Ostrom and Cox, 2010; Sayer et al., 2013).

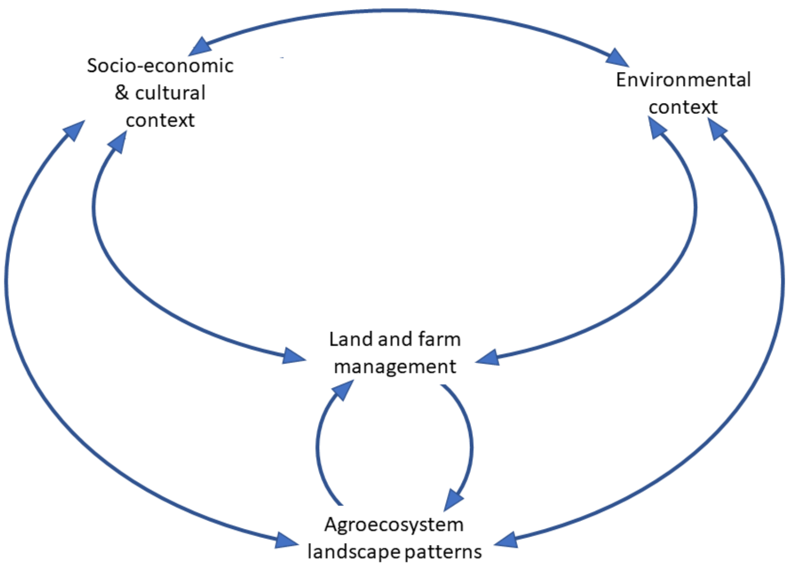

Figure 3: *Conceptualisation of the co-evolution of land and farm management and agroecosystem patterns within a panarchy of socio-ecological adaptive cycles.*

4. Learning together: piecing together complexity for improved natural resource management

The overarching 'developmental' objective of this thesis was to facilitate a co-learning, 'co-evolutionary' process with local stakeholders using the SES and CAS frameworks to explore more sustainable pathways towards improved landscape level natural resource management. As Rammel et al. (2007) articulated so well:

"*a central idea of a co-evolutionary approach must be to enhance a shared contextual understanding about natural resource management systems in such a way, that researchers provide the stakeholders involved in the decision-making process with 'integrative information' about the system in question, but letting them their own way to reach compromise solutions*". (Rammel et al., 2007, p. 16).

To achieve this goal, farmers and local stakeholders played an integral role in the design, data collection and analysis of the research. In addition, the evidence provided by the empirical research outlined in the previous chapters was synthesised in order to develop a series of three workshops with the ultimate objective of co-developing a landscape level natural resource management plan for the community of Naubug. The first workshop aimed to develop possible land-use change scenarios based on current land-use, past socio-economic and cultural trends and current challenges and opportunities, reflecting the *Narrative* methodology proposed by Cumming (2011). The second workshop was based around a role play game that was developed using the data and insights collected in Chapters 2, 3, 4 and 5 to explore and design more sustainable and productive farming systems taking inspiration from the FarmDESIGN model and conceptual framework (Groot et al., 2010, 2007). The third workshop focused on bringing together the results of the research and the previous workshops in order for the local stakeholders to design options for improved landscape level natural resource management based on key concepts from the SES and CAS frameworks. The results of the landscape management plan are summarised in Table 1.

Table 1: *Summary of the main findings of the co-developed draft landscape level natural resource management plan*

Agricultural management zone	Landscape level natural resource management plan summary
Upper	As part of the Landscape Management Plan local stakeholders argued that the upper agricultural management zone should be targeted for soil conservation measures. While it was recognised that the soils already received considerable organic matter inputs that have contributed to conserving their agroecosystem functions, other techniques could also be trialled such as zero or minimum tillage and the use of multi-purpose hedgerows. Stakeholders further argued that it is likely that climate change is going to prove to be an important dynamic in the landscape in the future. Indeed, it has been suggested that the freezing point may rise several hundred meters over the next century in the Andean Cordillera and that this phenomenon may affect tropical mountain ecosystems more than those at higher latitudes (Kohler et al., 2014). While this may increase the productivity potential in this upper part of the landscape, it is also important to highlight that climate change is also likely to bring more erratic precipitation patterns, increased risk of hail damage, and greater evapotranspiration rates (Kohler et al., 2014). Moreover, it will affect the environmental context that is contributing to the accumulation of SOC in the upper elevations suggesting even greater need for soil conservation measures to ensure the current benefits gained from higher SOC levels in this part of the landscape are not lost.

Agricultural management zone	Landscape level natural resource management plan summary
Middle	The middle zone was perceived by stakeholders as the most important for agricultural production, but one that also faces important sustainability challenges. Stakeholders recommended that the zone is best suited to explore alternative techniques for sustainable intensification (improved cropping patterns, increased and more targeted fertilizer inputs, associative cropping, use of multi-purpose hedgerows, rain-water harvesting among others). However, to achieve these changes in management and production it was recognised that fundamental changes to the broader socio-economic context must occur in parallel that facilitate access to resources (land, agricultural inputs, water) and markets (road network, transportation, market demand).
Lower	Generally speaking local stakeholders tended to be rather pessimistic with regard to the lower agricultural management zone, if a planned irrigation system were not installed in the future. Recommendations to improve agricultural productivity were suggested especially for farming techniques to increase soil carbon and nutrient levels. However, fundamentally, questions were raised as to whether farming in this area of the landscape would be sustainable without radical changes to the current farming systems such as a re-orientation toward orchard cultivation or silvo-pastoral systems. In the absence of such changes it was expected that farming would be abandoned in the zone leaving either abandoned agricultural land or eucalyptus or pine forest.

5. Reflections on the application of the complex adaptive systems framework for the co-development of a natural resource management plan

In the co-development of the landscape level natural resource management plan developed for the community of Naubug, we were able to examine how key concepts from the SES and CAS frameworks facilitated more contextualised and nuanced management options and intervention strategies. Based on qualitative assessments of the data and statistical analyses from the empirical research and group discussions, participants in the workshops were asked the normative question as to whether the current system regimes in the three agricultural management zones (the upper, middle and lower) were desirable or not taking into account productivity and agroecosystem health, as well as assessing their vulnerability (Adger, 2006), and what could/should be done either to ensure their resilience or to instigate transformation (Cumming and Collier, 2005). The final step was to evaluate the proposed regime changes (building resilience or instigating transformation) within the broader socio-ecological context, gauging the adaptive capacity of the regimes (Fabricius and Cundill, 2010).

5.1. System regime: desirability and vulnerability

With regard to the upper agricultural management zone, farmers and local stakeholders argued that the current system regime was somewhat desirable given that both agricultural productivity and the agroecosystem 'health' were acceptable for the landscape. However, importantly it was also argued that while the zone may become slightly more productive in the future as a result of climate change due to increasing temperatures, such changes would also increase its vulnerability to land degradation as the cooler temperatures at this elevation currently contribute to the higher levels of SOC.

The middle agricultural management zone was perceived by farmers and local stakeholders as currently the most important for agricultural production and thus desirable as a system regime.

However, it was also highlighted that this system regime faces more immediate threats and is therefore even more vulnerable than the upper zone.

Finally, farmers and local stakeholders were rather negative regarding the desirability of the current system regime of the lower agricultural management zone, both with regard to its agricultural productivity and its agroecosystem health. Moreover, farmers and local stakeholders argued that the current system regime was very vulnerable and that agricultural production would likely be abandoned in the zone in the near future either leaving abandoned agricultural land or pine and eucalyptus forest in its place (a regime-shifting process that already seems to be occurring).

5.2. Opportunities for building resilience or instigating regime shifts: a question of Panarchy

Having evaluated the desirability and vulnerability of the current system regimes (agricultural management zones), farmers and local stakeholders identified and assessed opportunities for either building resilience or instigating regime-shifting transformation. At this stage it was also important to gauge the system regimes' adaptive capacity. From an agricultural development perspective this assessment was farming family-focused, and raised fundamental questions as to whether the broader socio-economic and cultural structural constraints could be adapted to empower farmers to make the changes that they had envisaged.

With specific regard to the upper agricultural management zone, farmers and local stakeholders argued that in order to build resilience farmers should focus on the exploration and development of knowledge with regard to soil conservation measures that will enable them to take advantage of any potential increase in temperature at that elevation. In particular, techniques such as multi-purpose hedgerows and minimum tillage were discussed as means to protect and conserve the current 'health' of the soils in the management zone. It was also recognised that this process of resilience-building would be helped by strategic interventions that aimed to co-develop knowledge regarding potential soil conservation techniques and their efficacy.

As the most important zone for farmers in the community from an agricultural production perspective, as well as more immediate signs of vulnerability than the upper zone, farmers and local stakeholders agreed that it was important and indeed urgent to build the resilience of the middle agricultural management zone. In particular, alternative techniques for sustainable intensification were discussed with the dual goal of both increasing production and better conserving the agroecosystems. Improved cropping patterns, more targeted fertilizer inputs, associative cropping, the use of multi-purpose hedgerows and rain-water harvesting were techniques mentioned that could achieve such a goal. Similarly to the upper agricultural management zone however, to increase the adaptive capacity of the middle agricultural zone through these techniques, strategic interventions should be aimed to co-develop and share knowledge for such sustainable intensification techniques.

More fundamentally however, farmers and local stakeholders perceived critical structural constraints (i.e., constraints found at different scales within the panarchy of nested hierarchies) to achieving their envisaged pathway toward more sustainable intensification in the middle management zone. Fundamentally, two key components of the broader socio-economic and cultural context were identified by farmers and stakeholders that required change to enable farmers to invest in further sustainable agricultural intensification: improved market access (in all respects – logistics, market information, demand etc.); and improved access to financial, social and natural resources (in the forms of micro credits, cooperative organizations, land and irrigation water). Farmers and local stakeholders argued that in the absence of such changes to the overall system that would increase its resilience, farmers were unlikely to be able to continue farming in the coming decades leading to regime-shifts such as permanent land abandonment.

In contrast to the upper and middle agricultural management zones, the lower agricultural management zone was identified by farmers and local stakeholders as 'undesirable', and indeed vulnerable to a regime shift where agricultural land is either abandoned or replaced with pine and eucalyptus forest. Alternate system regimes were envisaged by participants at the workshops where the zone would be connected to an irrigation canal to boost productivity, or where farmers would shift to alternative agricultural production methods such as orchards or silvo-pastoral systems. However, it was also recognised that such 'preferred' regime shifts would require large amounts of investment that are currently beyond the means of the farming-families of the community at this point in time. Given the results presented in Chapter 4 that suggest land-use change to abandoned agricultural land and/or eucalyptus and pine forest in this landscape may not be the optimal strategy to restore (agro)ecosystem functioning, it is clear that an important discussion between all stakeholders is urgently necessary with regard to the future of the lower agricultural management zone, in order seize any opportunities that may exist to improve its future trajectory.

5.3. Reflections

The application of the SES and CAS frameworks in the co-development of the landscape level natural resource management plan proved to be particularly beneficial in providing a nuanced, multi-scale insight into the challenges and opportunities faced by farming-families in the community of Naubug. Firstly, the better understanding of the interactions and feedbacks between the agroecosystem patterns of the landscape and farm management created a more profound appreciation of the system regimes in the upper, middle and lower agricultural management zones. This enabled participants at the workshop to more easily assess the vulnerability of the system regimes as well as their desirability. In turn, such an assessment coupled with a better understanding of the socio-ecological interactions made it easier to identify zone-specific agricultural options for improved farm management to increase resilience and adaptive capacity through soil conservation and sustainable agricultural intensification measures. These zone-, or context-, specific agricultural options to improve the natural resource management of the landscape are particularly important in helping reduce risks faced by farmers (Descheemaeker et al., 2016; Scopel et al., 2013), especially in rural mountainous landscapes where elevation-induced climate gradients create many different environmental niches (Mayer, 2002).

Beyond these context-specific options however, by framing the co-learning process within the SES and CAS frameworks and a panarchy of nested hierarchies with multi-scale socio-ecological interactions and feedbacks, it became clearer to all workshop participants that interventions at the field or farm level will not suffice, as many different constraining factors exist at multiple scales. This was particularly evident when workshop participants argued that even if farmers were to adopt all of the context-specific options for improved agricultural management, it would still be unlikely that farming would continue in the community in the coming decades unless market access was improved along with access to financial, social and natural resources. Thus in tandem to a bottom-up process of development, work is also required at policy and market level to empower farmers to enhance resilience and adaptive capacity, or to make regime shifts to more sustainable pathways (Descheemaeker et al., 2016; Tittonell, 2014).

6. Conclusions

The empirical research outlined in this thesis strongly underlines the utility of framing land and farm management, and agroecosystem research within the SES and CAS frameworks in order to better understand the nuances of how farm management and asymmetric agroecosystem patterns co-evolve. Specifically, we have observed how different system regimes with regard to farm management have co-evolved at different scales (between community, within community and within farm) as a result of interactions and feedbacks between variables in both the social and ecological domains connected by a nested hierarchy. Moreover, we have seen how both the broader socio-ecological context, and land and farm management have led to asymmetric agroecosystem patterns suggesting processes of systemic differentiation with important feedback loops to farm management.

Fundamentally, the research reminds us that, by ignoring these multi-scale interactions and feedbacks we risk creating misconceptions, where single deterministic variables are often argued to lead to universal pathways. Instead the SES and CAS frameworks encourage us to practice scientific research beyond silos in a multi-disciplinary, multi-scale fashion in order to develop a more nuanced and contextualised understanding of drivers, responses and emergent patterns. In so doing, the frameworks enable us to understand why, for example, out-migration may lead to agricultural intensification in one instance but not in another, or why fields may become less fertile the further away from the homestead they are located in one landscape but not in another.

These conclusions are not merely theoretical, but also have important practical implications. As outlined above, the use of key concepts from the SES and CAS frameworks, such as system regimes, vulnerability, resilience, transformation and adaptive capacity, facilitate the co-development of more targeted options for improved landscape level natural resource management. More critically, it underlines the idea that development strategies must be co-developed using bottom-up approaches, reflecting the local socio-ecological context. Moreover, in recognising the multi-scale influences or constraints inherent in CAS, the frameworks also highlight the importance of acting at other scales (e.g., policy and market level) to empower farmers to enhance resilience and adaptive capacity, or to make regime shifts to more sustainable pathways.

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Appendicies

Chapter 3

Supplemental Table 1: *Mixed model regression results (p-values) and means of field SOC by perception of fertility in the communities of Basquitay, Naubug and Tzimbuto, Chimborazo Province, Ecuador. Different letters to the right of the means (a, b) signify significant differences at the p <0.05 level.*

Community	**p-value**	**SOC (%)**			
		Very good	**Good**	**Average**	**Poor**
Basquitay	0.893	4.10a	3.73a	4.10a	3.90a
Naubug	***<0.001***	***2.47a***	***1.65a***	***1.46a***	***0.69b***
Tzimbuto	***<0.001***	***1.37a***	***0.95a***	***1.03a***	***0.51b***

Chapter 4

Appendix 1: Supplementary images of the study site and land-uses

Photo 1: *Panoramic view from the upper agricultural management zone of the study area, Naubug Community, Flores Parish*

Photo 2: *Agricultural land-use in the lower agricultural management zone of the study area, Naubug Community, Flores Parish*

Photo 3: *Abandoned agricultural land, Naubug Community, Flores Parish*

Photo 4: *Eucalyptus forest patch, Naubug Community, Flores Parish*

Photo 5: *Tree hedgerow, Naubug Community, Flores Parish*

Photo 6: *Grass strip, Naubug Community, Flores Parish*

Appendix 2: Supplementary results tables

Supplemental Table 1: *Linear regression results for soil texture by elevation; and minimum, maximum and mean values for soil texture within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador.*

Soil texture	Min	Mean	Max	Expected increase (per 100m increase in elevation)
Clay (%)	1	13.89	23	2.50
Sand (%)	30	41.35	75	-3.22

Supplemental Table 2: *Rates of change in soil chemical properties and C stocks by elevation separated by land-use; and minimum, maximum and mean values for soil chemical properties and C stocks within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador.*

Variable	Land-use	Min	Mean	Max	Rate of increase with elevation (per 100 m)
SOC† (%)	Abandoned land	0.32	1.05	2.17	1.24
	Agricultural land	0.21	1.88	4.70	1.53
	Forest	0.37	0.98	1.69	1.05
	Grass strips	1.22	1.81	2.54	1.07
	Mixed hedgerows	0.63	1.66	2.70	1.24
	Tree hedgerows	1.32	2.67	4.49	1.17
Available P† (mg kg^{-1})	Abandoned land	4.20	11.20	20.00	-1.09
	Agricultural land	4.20	25.90	96.00	1.29
	Forest	10.00	14.90	25.00	-1.09
	Grass strips	26.00	74.90	187.00	2.31
	Mixed hedgerows	9.70	39.58	98.00	1.48
	Tree hedgerows	14.00	48.60	90.00	-1.36
C Stocks† (Mg ha^{-1})	Abandoned land	13.33	43.92	94.25	1.24
	Agricultural land	9.77	65.71	132.50	1.45
	Forest	41.10	104.61	149.40	1.12
	Grass strips	48.54	72.70	124.11	-1.20
	Mixed hedgerows	38.43	93.16	250.00	1.09
	Tree hedgerows	54.77	115.78	196.10	1.0

†Log transformations have been applied to the variable data to adhere to the assumptions of normality and homoscedasticity

Supplemental Table 3: *Means and minimum and maximum values for macrofauna and vegetative diversity within a rural landscape (Community of Naubug) in the Parish of Flores, Chimborazo Province, Ecuador. Letters to the right of mean refer to post-hoc mean separation analysis adjusted for the effect of elevation using Tukey's HSD at the 5% significance level*

Variable	Land-use	Min	Mean	Max
Macrofauna diversity†	Abandoned land	1.06	1.64ab	2.04
	Agricultural land	0.00	1.50b	2.36
	Forest	0.00	1.14b	2.11
	Grass strips	1.33	1.64ab	2.40
	Mixed hedgerows	1.06	1.86a	2.52
	Tree hedgerows	0.21	1.26b	2.17
Vegetative diversity	Abandoned land	1.13	1.67ab	2.22
	Agricultural land	0.13	0.99d	1.62
	Forest	0.00	1.27bdc	2.04
	Grass strips	0.52	1.01cd	1.73
	Mixed hedgerows	1.25	1.84a	2.59
	Tree hedgerows	1.00	1.47abc	2.22

†Exponential transformation has been applied to the variable data to adhere to the assumptions of normality and homoscedasticity

Summary

The agroecosystems of the Ecuadorian Andes are threatened by severe land degradation processes and the risks associated with climate change. These agroecosystems are not only critical to the livelihoods of the farming families that live in them, but also for broader society through their role in watershed protection, carbon storage and the conservation of regional biodiversity. The land degradation processes are driven by the inherent susceptibility of these mountainous terrains to erosion, coupled with inappropriate farm and land management. Negative nutrient and soil organic matter (SOM) balances are widespread in the region, decreasing soil productivity, soil biological activity and diversity, soil aggregation, and water storage capabilities. Instead of targeted strategies for land restoration, abandoned agricultural land is often either left fallow or converted to eucalyptus of pine patches of forest.

The mountainous nature of these Andean rural landscapes creates an additional level of complexity in the relationships between management and agroecosystems in these contexts. The elevation-induced climate gradients drive many different environmental niches moulding agroecosystem patterns and shaping farm and land management practices, often resulting in feedback loops and non-linear responses to landscape gradients. Understanding such complex socio-ecological relationships between farm and land management practices and landscape agroecosystem dynamics is paramount to the development of more successful developmental and natural resource conservation management and intervention strategies.

Based on a framework of Complex Adaptive Systems (CAS) for the purposes of understanding critical environmental challenges within a social context the recently emerging Socio-Ecological Systems (SES) framework represents great promise in better understanding these inter-relationships and therefore providing greater insight for the development of more contextualised management and interventions strategies. The PhD project was therefore designed to contribute to the understanding of some of the main relationships between land and farm management, agroecosystems and socio-

ecological variables, shed a new light on how farm and land management and agroecosystems patterns have co-evolved within this particular socio-ecological context in the Ecuadorian Andes, and to provide an empirical case-study as to how the SES and CAS frameworks could be used to inform more contextualised natural resource management.

In line with the SES framework, the research applied a diverse range of methodologies from different disciplines. Furthermore, the PhD project was conducted as part of a broader process of co-learning and co-evolution with a group of farmer 'researchers' as well as professors and students from a local university and key policy makers and intervention agents who became intricately involved in this action-research, from planning to data collection and analysis. The work of this group culminated in the co-development of a "Landscape Level Natural Resource Management Plan" that outlined pathways for a more contextualised natural resource management and intervention strategies in the main community of study.

In Chapter 2, I assessed how an important regional socio-demographic trend, rural-out migrations, influenced farm management. Based on linear regression analyses of data from household surveys and semi-structured interviews with farming families from a rural indigenous Kichwa community, I developed a Structural Equation Model (SEM) to elucidate the direct and indirect effects between temporary out-migrations and the use of agro-chemicals and mechanized tillage (industrialized farming intensification techniques). The model indicated that temporary out-migrations were indirectly related to the use of industrialized farming intensification techniques through their effects on household financial resources and subsequent farm-level decisions to increase the proportion of potato cash crops. The statistical modelling was complemented by a role-play game to provide a more qualitative appreciation of the potential adaptations (regime shifts) farmers would make should their broader socio-economic circumstances (access to labour and financial resources) change. The overall findings highlighted the importance of intermediary (or multi-scale) socio-economic and cultural factors on farm management in that such a relationship between out-migration and agricultural intensification arose as a result of the opportunities presented by temporary rural out-migrations (greater financial resources) coupled with the local market demand for potatoes, a cash-crop in the area. It was argued that the relationship between rural out-migration and agricultural intensification is thus context-specific, and as found in other reports in the literature, reverse patterns are expected to be found where out-migrations may lead to other farm management responses (e.g., deintensification) due to different contexts.

The objective of Chapter 3 was to document and better understand asymmetric allocation patterns of OM inputs by farmers and their consequences on agroecosystem patterns at different scales of analysis (between community, between farm and within farm). The study was carried out in three indigenous Kichwa communities located in close proximity to one another. Field level variables ('distance from homestead' and 'perception of fertility') were found to be significantly associated with asymmetric OM allocation patterns and were also significantly associated with soil fertility gradients within farms. At the between community scale, overall OM allocation patterns differed significantly, and were also associated with significant differences in soil fertility, with the highest levels of available P and exchangeable K found in the community with the highest OM inputs. The results of this study demonstrated that important differences in OM allocation patterns may be encountered at different scales of analysis, both within farms and among neighbouring communities, and also suggested that the associated fertility gradients are mediated by the broader socio-ecological context.

In Chapter 4, in a rural landscape in the Ecuadorian Andean province of Chimborazo, I identified the main biophysical patterns in soil quality, biodiversity and C stocks that emerged from 'natural' landscape pedogenic processes, resulting from elevation-induced climate gradients, erosion and soil textural patterns. I also assessed farm management and land-use effects on and their interactions with these biophysical patterns. The findings revealed that the climate and soil textural gradients of the landscape led to an exponential increase in SOC with elevation, moderated by slope gradient, indicating significant erosion processes. It was also found that farmers adapted their farm management (cropping patterns and agricultural inputs) according to the observed environmental patterns creating three distinct management 'zones'. Differentiated agricultural management and land-uses in these zones were observed to significantly influence soil and agroecosystem properties. For example, available P was found to be significantly higher in the upper and middle agricultural management zones where agricultural inputs were higher compared to the lower agricultural management zone, while mixed hedgerows displayed significantly higher Shannon Index scores for vegetation and macrofauna compared to other agricultural land-uses. The results provided important insights into how the agroecosystem patterns and farm management of the landscape co-evolved from environment, management and land-use interactions.

The objective of Chapter 5 was to explore locally-developed options for improved agricultural management to address the challenges posed by land degradation caused by soil water erosion and nutrient depletion. Experimental plots were installed in two different sites in a rural landscape in Chimborazo Province to assess water erosion control by hedgerows and the effect of organic amendments harvested from the hedgerows on soil productivity, soil moisture and soil chemical properties over the course of two years and three crop cycles (two of barley, one of rye). The results demonstrated that hedgerows comprised of canary grass, and canary grass and Andean alder had reduced water erosion (between 50-70% less erosion) across sites and increased biomass production and grain yield significantly through the incorporation of organic amendments harvested from these hedgerows at one of the sites. The fact that the effect of the incorporation of soil organic amendments on biomass and grain production was only significantly different to the control treatment at one of the sites suggested that the biophysical context may be an important factor in the efficacy of this technique. We concluded that while hedgerows are unlikely to produce sufficient quantities of organic resources to satisfy all nutrient input requirements, their potential as a technique to decrease erosion and supplement existing organic matter inputs in a resource constrained socio-economic context means they should be strongly considered as an option for improved agricultural management.

Finally, in Chapter 6, I described a case-study as to how the CAS and SES frameworks could be used to co-develop a natural resource management plan for the main study site. In a series of three workshops, farmers and local stakeholders explored the co-developed knowledge outlined in Chapters 2-5 of this thesis and designed pathways for more sustainable natural resource management at the landscape level. Specifically, in the third and last workshop, participants used the concepts of vulnerability, resilience, adaptive capacity and transformation from the CAS and SES frameworks to assess the current system regimes (agricultural management zones) located in the landscape. Through this assessment they were able to evaluate the desirability of the system regimes, develop more contextualised options or pathways for improved agricultural and land management, as well as to identify the main constraints to achieving these pathways found within the broader socio-ecological context.

I concluded the thesis by arguing that the use of the CAS and SES frameworks in the research provided a profound insight into how farm and land management and agroecosystem patterns in the Ecuadorian Andes co-evolve from multiple socio-ecological interactions and feedbacks. Moreover, I contended that by ignoring these multi-scale interactions, we risk creating mis-conceptions where single deterministic variables are thought to lead to universal pathways, a premise that is clearly mistaken given the existence of multiple examples in the scientific literature where the same individual variable does not result in the same socio-ecological pattern. The SES and CAS frameworks are therefore robust scientific theories in this respect, being able to explain the occurrence of these inconsistent findings. Finally, I also argued that the SES and CAS frameworks facilitate the co-development of more contextualised options for improved natural resource management as well as identifying the main constraints within the broader socio-ecological context to adopting these more sustainable pathways.

Acknowledgements

PhD theses are often characterised as long arduous journeys. Reflecting on my PhD journey while looking out over my favourite rural landscape in a remote hamlet in the South-West of France, I can agree that the journey has been long, nearly five-years. It has also been tough, at times. But the sentiment that most stands out in my mind is that of a wonderful, exciting adventure that has taken me places I only ever dreamed of a decade ago. In fact, not only am I sad that this journey is ending, I am apprehensive of leaving it behind. It's provided me with purpose and challenge, while comforting me with flexibility and independence.

> *"The sea snail slithered all over the rock, and gazed at the sea and the ships in the dock, as she gazed, she sniffed and sighed 'the sea is deep and the world is wide! How I long to sail!' said the tiny snail."*

When I look back and reflect upon the origins of my PhD journey, I often think back to when I was living in Brussels, reading to my daughter (Jemma) and son (Ilias) the beautiful story of the 'Snail and the Whale' by Julia Donaldson and Axel Scheffler (2003). I would get emotional recounting how the naive and fragile snail lived out its dream of travelling the world on the tail of the whale, secretly wishing I too could go on such an adventure. After a chance viewing of a jobs page, the dream became a reality when Evelien (my wife) was offered a job in Ecuador. We seized the chance despite all my inner fears screaming out at me that it was crazy to do so.

> *"These are the other snails in the flock, who all stuck tight to the smooth black rock and said to the snail with the itchy foot, 'Be quiet! Don't wiggle! Sit still! Stay put!'."*

After three years into our adventures in Ecuador, having kept myself busy looking after the kids, travelling, when we could, to explore the stunningly biodiverse country, studying for an MSc, playing squash, and doing a number of small consultancy jobs, I eventually and unwittingly stumbled upon this greatest of opportunities, my PhD project. The stars aligned in the craziest of ways. An old work

contact from my days as a lobbyist for the food and drink sector in Brussels had given me the contact details of an academic from Wageningen who helped found the local Ecuadorian NGO, Fundación EkoRural. His name was Steve Sherwood and he was to become one of my co-promotors. Steve, you truly were the key to unlocking all of these adventures that I've had during my PhD. I cannot thank you enough. Whenever I have asked, you have always been there to help. Your work on improving more sustainable and responsible consumption through grassroots movements is exemplary. You're one of the few (unfortunately myself excluded) who "walks the talk".

> *"This is the whale who came one night, when the tide was high and the stars were bright, a humpback whale, immensely long, who sang to the snail a wonderful song of shimmering ice and coral caves, and shooting stars and enormous waves."*

Steve put me in contact with Ross Mary Borja and Pedro Oyarzun, the co-founders and two motors behind Fundación EkoRural, the NGO with whom I conducted the research for my PhD. I will always remember our philosophical discussions at the beginning. You must have thought, as indeed you pointed out a number of times, how naive and hood-winked I was by the powers of the of the multi-national food industry. Despite this, you still trusted me enough to give me the opportunity to develop my PhD project with you. Hopefully, I was able to pay back some of that trust. Thank you!

Through Ross and Pedro, I got to know Claire Nicklin and the McKnight Foundation who funded my research. Clearly without McKnight's generous support I would not have been able to do the PhD, I am thus eternally grateful to them. The Collaborative Crop Research Programme (CCRP) of the McKnight Foundation in the Andes is much more than simple financing however. It is a huge family of diverse scientists that have the common goal of creating more sustainable pathways for rural communities in the Andes. Through them I also received the invaluable support of Carlos Barahona and Sam Dumble from Statistics for Sustainable Development, who provided me with much needed unfussy advice on statistics. Despite, seeming to always catch a virus before each of our annual community of practice meetings, I valued them enormously. The amount I have learned from fellow

CCRP participants is immeasurable and too numerous to recount here. Claire, you have an insatiable energy that continues to drive forward the quality of the CCRP in the Andes. Thank you for giving me access to all these priceless opportunities that I have experienced.

> *"And this is the tail of the humpback whale. He held it out of the starlit sea and said to the snail 'come sail with me'. This is the sea, so wild and free. That carried the whale and the snail on his tail to towering icebergs and far-off lands."*

And now the story turns to my PhD committee. I met Pablo Tittonell, my promotor, when he came to participate in a mini-conference on soils in Peru organised under the auspices of one of the projects run by the McKnight Foundation. While we haven't been able to spend much time together in person since then, given my status as an external PhD student and your move to Argentina, you always managed to weigh in at the right time, with the right words and advice to push me forward and improve the quality of my work. Thank you. Your work on socio-ecological systems and the potential of agroecology is an inspiration to me and many, many others. As the world faces the greatest existential threats in human history, from climate change to global biodiversity loss, to growing social inequity and a population crisis, the world needs global communicators like you to continue to step up to challenge the status quo and plough more sustainable pathways.

Jeroen Groot, deserves special recognition for his support during my PhD. Your disarmingly calm and deeply considerate approach as a co-promotor have pulled me through my most challenging times as a PhD student. Your contributions to my draft thesis chapters were clear and concise, but most importantly you often challenged fundamental questions posed by my drafts significantly improving their quality. Furthermore, as an external student I have often found it challenging to navigate the seemingly casual administration processes of Wageningen. You have always been my anchor at the Farming Systems Ecology Group. Thank you for all you have done.

Steve Fonte and Steve Vanek complete the remaining members of my PhD Committee. Steve F. has been the rock upon which I have clung throughout my PhD journey. Steve, you have always been

there for me with encouraging words, sound advice and a kind, listening ear. I truly appreciate all the selfless time and effort you have invested in me. I have learned so many fundamental tools and approaches to being a successful scientist from you. Your eye-for-detail is second to none and your approach is rigorous and tireless. You often made me feel like you could push water up hill! I hope one day that I may be able to re-pay your kindness. You've become a good friend. I also want to thank you Steve V. especially for the time at the beginning of the PhD journey as I tried to develop a coherent methodology and theoretical approach to my research. Without your input, I wouldn't have been able to develop my research proposal successfully. I learned so much from you.

> *"These are the waves that arched and crashed, that foamed and frolicked and sprayed and splashed the tiny snail on the tail of the whale. These are the caves beneath the waves, where colourful fish with feathery fins and sharks with hideous toothy grins swam past the whale and the snail on his tail."*

I am indebted forever to the faming families with whom I worked (and played) in Naubug, Basquitay and Tzimbuto during our research project. The kindness with which you welcomed me into your families and communities is humbling. You overlooked my foibles as a crazy white middle-aged man as if they weren't there. The joy of working the fields with you will live with me (and my children, who both enjoyed time harvesting different crops with you) to eternity. My adopted name, 'José Mono', and the stories about the 'Chupa Cabra' still make me smile as I write these words. As the leader of the farmers' research group in Naubug I would especially like to thank you Julio Guambo. You worked tirelessly to help us achieve our goals. Silvia Guambo, as my field assistant I relied on you for everything. Your flexibility, intellect and organisation always shone through. Thank you.

The local team of Fundación EkoRural in Riobamba and Salcedo were also essential elements to the success of the field research. Sonia, Elena, Francisco and Guadalupe I miss you guys. It was always a pleasure to drive down from Quito to Riobamba knowing that I would be met by your beaming smiles. We spent hours in cars together driving back and forth from the three communities. I enjoyed those times immensely – reflecting on things that had happened that day, discussing politics, working out pragmatic solutions to problems we faced in the field research, organising work and simply passing time together. Thank you for all your support.

As a PhD student, I had the pleasure of working with Judith Bouniol who conducted her Master's thesis research presented in Chapter 2. Judith you were a breath of fresh air. You worked determinedly during the few months you were in Ecuador, managing to become fluent in Spanish in an enviable amount of time and building very close relationships in the community in which you were based. The research data you developed as part of your Master's thesis proved to be very insightful and led to the collaboration with the wonderfully collegial and insightful Aad Kessler from the Soil Physics and Land Management Group, as well as the first published peer-reviewed manuscript of this thesis. I can't thank you enough. I do so hope that our paths will cross again soon.

The professors (Franklin Arcos and Xavier Mera) and bachelors students (Mayra, Maritza, and Cristina) from the Escuela Politécnica de Chimborazo (ESPOCH) also deserve special recognition for their contributions to this co-learning process. Franklin and Xavier thank you for the time you spent participating in the community workshops and in the organisation of the seminar we held at your university during the visit of Jeroen. It was a true pleasure to chat with you about agro-ecological research in the Andes and learn about your research. A fellow PhD colleague from Wageningen I should thank is Birthe Paul, who has been particularly helpful in sharing knowledge as we navigate our way through the PhD thesis submission and defence administration.

I am sure there are many more people that I have forgotten to thank who I remain indebted to for their contributions to my PhD. If you are one of them, I beg your forgiveness, as time is now getting short before needing to submit the thesis for final printing. I do however, still need to thank my mum and dad. You have been the bedrock of support throughout my life. Even when I told you of our decision to leave Europe for Ecuador all those years ago, yanking your grandchildren away from your daily lives, you were selfless in your advice and support. I still remember how happy it made me feel when you told me that dad was “proud of our decision” mum.

Finally, I must thank you Evelien, Jemma and Ilias for your unfaltering support. Jemma and Ilias, you have grown so much since our unceremonious arrival in Quito. Indeed, you’ve gone on to experience new adventures in Jerusalem, Palestine and Israel. Making new friends, experiencing new ways of life. However hard it has been, you both approach times of upheaval with the same positive, constructive attitude. Finding the silver in the lining of the clouds. I am proud of what you have become. Evita, words escape me now... You have given me everything. You have worked relentlessly over the past decade and however challenging things became you always had time for me and the kids. You have a steely determination and a selfless, caring heart, attributes rarely coupled in the world today. You deserve all the success and all the love in the world. Thank you for allowing me to crawl on to your tail. I await with the same apprehension and excitement our new adventures in Morocco.

> *“And she gazed at the sky, the sea, the land, the waves and the caves and the golden sand. She gazed and gazed, amazed by it all. And she said to the whale, ‘I feel so small’.”*

Quotes from: Donaldson, J., Scheffler, A., 2003. The snail and the whale. Macmillan Children’s Books.

About the author

Mark E. Caulfield was born in Oxford, UK and grew up with his parents and two brothers in the small Regency town of Leamington Spa in the Midlands. After completing his secondary education in the UK, studying science and language A-levels he spent a year at Barcelona University successfully completing a year-long course on Hispanic Studies. The year after he enrolled in a four-year BA in Psychology at the University of Exeter, UK, with an Erasmus year spent in Valencia, Spain. During his time studying for the BA he developed a keen interest in politics and European integration. After his BA at Exeter he enrolled in an MA in European Studies (social and political sciences) graduating in 2001. Over the next decade he worked in Brussels on EU and international public affairs and public policy issues related to the environment, agriculture and trade for the American Chamber of Commerce to the EU and for the food company Kellogg. Wanting to develop a closer and more technical appreciation of the public policies he had been working on, when his wife was offered a job in Ecuador in 2011, he happily moved along with his family and began a new chapter in his life which included studying for an online MSc in Environmental Management from the School of Oriental and African Studies, University of London, UK, graduating in 2013. In tandem with studying for the MSc he worked on a number of consultancy projects related to environmental and rural development issues for local and international NGOs, international organizations and private companies. He also conducted a number of environmental and social impact assessments, audits and monitoring programmes as well developing environmental and community relations management plans for natural resource and infrastructure projects in Ecuador and abroad. In September 2014, with the generous funding of the McKnight Foundation's Collaborative Crop Research Programme, he enrolled as an external PhD student at the Farming Systems Ecology group of Wageningen University & Research. Given his breadth of disciplinary backgrounds and life experiences, his over-riding objective for the PhD was to initiate a process of multi-disciplinary, multi-scale co-learning with a group of farmer 'researchers' and local stakeholders in the Ecuadorian Andes to explore options for more sustainable natural resource management.

Publication list of Mark Caulfield

Peer reviewed journal articles

Caulfield, M., Bouniol, J., Fonte, S.J., Kessler, A., 2019. How rural out-migrations drive changes to farm and land management: A case study from the rural Andes. Land Use Policy 81, 594–603. https://doi.org/10.1016/j.landusepol.2018.11.030

Submitted

Caulfield, M., Fonte, S., Vanek, S.; Sherwood, S.; Dumble, S.; Borja, R.; Oyarzun, P.; Tittonell, P., Groot, J.. Between community and within farm asymmetric organic matter allocation patterns drive soil fertility gradients in a rural Andean landscape. Land Degradation and Development

Caulfield, M.; Fonte, S., Groot, J.; Vanek, S.; Sherwood, S.; Dumble, S.; Borja, R.; Oyarzun, P.; Tittonell, P. Environment, management and land-use interactions drive soil and agroecosystem patterns in a rural Andean landscape. Ecosphere.

Caulfield, M.; Groot, J.; Fonte, S.; Sherwood, S.; Dumble, S.; Borja, R.; Oyarzun, P.; Tittonell, P. Live barriers and associated organic amendments mitigate land degradation and improve crop productivity in hillside agricultural systems of the Ecuadorian Andes. Land Degradation and Development.

Conference/Symposium Proceedings

Caulfield, M.; Fonte, S., Groot, J.; Vanek, S.; Sherwood, S.; P.; Tittonell, P. 2015. Exploring dominant land-uses and their associated soil-based agroecosystems in a heterogeneous agricultural landscape in the Ecuadorian Andes. Wagenigen Soils Conference

Caulfield, M.; Fonte, S., Groot, J.; Sherwood, S.; P.; Tittonell, P. 2017. Environment-management interactions drive soil-based agro-ecosystem characteristics in a rural Andean landscape. Wagenigen Soils Conference

PE&RC Training and Education Statement

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)
- Exploring endogenous, contextualized pathways to a more sustainable and resilient agricultural landscape in the Ecuadorian Andes (2015)

Writing of project proposal (4.5 ECTS)
- Writing of PhD project proposal: exploring endogenous, contextualized pathways to a more sustainable and resilient agricultural landscape in the Ecuadorian Andes (2015)

Post-graduate courses (3.8 ECTS)
- Farming systems and rural livelihoods; WUR (2018)

Laboratory training and working visits (3.3 ECTS)
- Modelling: assessing potential of application of LUCIA model to PhD project; University of Hohenheim, Germany (2014)
- Soil sampling; Escuela Superior Politecnica de Chimborazo, Ecuador (2014-2018)

Invited review of (unpublished) journal manuscript (2 ECTS)
- The Journal of Peasant Studies: different farming styles behind the homogenous soy production in southern Brazil (2014)
- Environmental Health Review: do Bolivian farmers, trained on Integrated pest management, disseminate their knowledge with a potential to prevent occupational pesticide poisonings? (2015)

Deficiency, refresh, brush-up courses (6 ECTS)
- Statistics in applied climatology; University of Reading (2014)
- Statistics made simple; University of Reading (2015)

Competence strengthening / skills courses (1.5 ECTS)
- Career perspectives; PE&RC (2018)
- Presentation skills; Kellogg Company (2009)
- Leadership training; Kellogg Company (2010
- Time management; Kellogg Company (2011)
- Media training; Kellogg Company (2011)

Discussion groups / local seminars / other scientific meetings (5.4 ECTS)
- Mirada desde el suelo; oral presentation; Lima, Peru (2014)
- Regional meeting of McKnight projects; oral presentation (2016)
- Regional meeting of McKnight projects; oral presentation (2017)
- Regional meeting of McKnight projects; oral presentation (2019)

International symposia, workshops and conferences (4.4 ECTS)
- Wageningen soils conference; poster presentation (2015)
- Wageningen soils conference; oral presentation (2017)

Supervision of MSc students (6 ECTS)
- Improving cropping patterns to increase soil fertility for different farm types in three different communities in Chimborazo, Ecuador
- Migrations and land management in the Ecuadorian Andes: how do farmers adapt their practices to reduced labour and increased income?

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