UNIVERSITY OF SOUTHERN QUEENSLAND

EVOLUTION, ADOPTION AND ECONOMIC EVALUATION OF AN AGROFORESTRY-BASED FARMING SYSTEM WITH AND WITHOUT CARBON VALUES: THE CASE OF NEPAL

A Dissertation Submitted by

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Abstract

Modern agriculture, although high yielding, has several negative consequences such as land fertility loss through erosion and nutrient depletion and water source contamination. Most importantly it has deteriorated the global climate through emissions of greenhouse gases (GHGs): methane, nitrous oxide and carbon dioxide into the atmosphere. The modern agriculture has accelerated land degradation. The other human-induced phenomenon taking place around the globe is deforestation, which is mostly caused by agricultural expansion in order to feed the growing population. Nepal, as one of the least developed countries (LDC) with a fragile ecosystem, is not free of these global problems. Agroforestry, although not a panacea to deforestation and land degradation, has come to the forefront as a sustainable land-use strategy to mitigate these problems as agroforestry has the potential of enhancing soil quality and reducing emissions. However, the adoption of the agroforestry-based farming system is not widespread. Therefore, the aim of this research was to perform an integrated evaluation of such promising land use in Nepal, which covers adoption potential of agroforestry-based farming system at landscape as well as farm level, its financial return over other land uses such as agriculture and an integrated evaluation of GHG mitigation potential of it.

For this case study, out of 2000 households, a sample of 200 was randomly selected, using a random table. The study was carried out in nine VDCs of Dhanusha district, Nepal. Household survey, focus group discussion and inventory of agroforestry tree species were the three methods used to collect the required data. Considering the rotation period of horticultural trees, a 30-year time horizon was used for this study as one agroforestry cycle. Data on demography, adoption, cost and benefits and GHG emissions sources were collected from household survey questionnaires. The costs and benefits of farming systems were converted into monetary terms and discounted to produce net present values. One focus group discussion was conducted with agroforestry farmers to trace the history of agroforestry-based farming system development and to explore the major drivers behind this development. Diameter at breast height (DBH) and height were measured on five agroforestry tree species i.e. *Eucalyptus camaldulensis, Dalbergia sissoo, Gmelina arborea, Melia azedarach* and *Anthocephalus chinensis* and three horticultural tree species i.e. *Mangifera indica, Artocarpus heterophyllus* and *Litchi chinensis* to develop a tree growth model so as to estimate the carbon sequestration potential of agroforestry-based farming systems.

The study revealed that out of eight variables the farm size (*t=3.512*) was the most determining factor with regards to adoption of agroforestry. The results of a regression model for the household data showed that the model explained approximately 75% variation, out of which about 60% variation was explained by this variable alone. The other seven variables significantly influencing adoption were 'availability of irrigation water' (*t=6.271*), 'education level of household heads' (*t=3.582*), 'number of agricultural labour force' (*t=5.494*), 'frequency of visits' (*t=3.146*), 'expenditure on farm inputs' (*t=2.753*), 'household's experience in agroforestry' (*t=2.589*) and 'distance of home to government forest'(*t=2.676*). The benefit-cost analysis showed that all three indicators of financial analysis, NPV (Net present value), B-C (Benefit-cost ratio) ratio and return-to-labor, were higher in agroforestry systems than in subsistence agriculture, reflecting that integrating trees

on farms is financially more attractive. Although financially attractive, the finding suggests that the current harvest cycles of agroforestry tree species were below the optimum level which has stopped them from getting the actual benefits from tree planting and also minimised the carbon sequestration potential of the system.

Inclusion of carbon showed that it contributed by less than 0.5% to the total NPV. Therefore, the income from carbon could not be an incentive to motivate small farmers towards agroforestry intervention. However, considering emission reduction as a carbon benefit from agroforestry, a considerable amount of income could be generated from carbon sale and that could be a motivating factor for small holders to adopt agroforestry. The finding suggested that integrating trees could reduce GHG emissions by 40% to 64% in a hectare basis depending on tree density on the farm in a 30-year period compared to subsistence-based agriculture. However, given the land constraints the chance of small farmers moving to agroforestry-based farming system is heavily constrained. A mechanism for joint farming practice such as cooperative farming, i.e. integrating small farms together to form a larger one, could be a viable policy intervention to encourage small holders towards adopting the environmentally and economically viable land use system such as agroforestry-based farming system.

Certification of Dissertation

I certify that the ideas, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. It is also certified that the work is original and has not been previously submitted for any other award except where otherwise acknowledged.

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Abbreviations

AF	Agroforestry
AFLMP	Agroforestry-based Land Management Practice
AFOLU	Agriculture, Forestry and Other Land Uses
AI	Adoption Index
BA	Basal Area
C	Carbon
CBA	Cost Benefit Analysis
CDI	Crop Diversity Index
CDM	Clean Development Mechanism
CF	Conversion Factor
CH_4	Methane
CI	Cropping Intensity
cm	Centimetre
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CSP	Carbon Sequestration Potential
D	Density
DAP	Di-ammonium Phosphate
DBH	Diameter at Breast Height
DDC	District Development Committee
DI	Diversity Index
FAO	Food and Agriculture Organization
FGD	Focus Group Discussion
FYM	Farmyard Manure
g	Gram
GHG	Greenhouse Gas
GWP	Global Warming Potential
H	Height
ha	Hectare
HH	Household
HI	Harvest Index
HIS	Highly Integrated Agroforestry-based Farming System
HYV	High Yielding Variety
ICRAF	World Agroforestry Centre
IDRC	International Development Research Centre
IF	Improved Fallow
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
LDI	Livestock Diversity Index
LIS	Less Integrated Agroforestry-based Farming System
LPG	Liquefied Petroleum Gas
MAI	Mean Annual Increment
MIS	Medium Integrated Agroforestry-based Farming System
MoP	Muriate of Potash
MV	Modern Variety
N	Nitrogen

N_2O	Nitrous Oxide
NAF	Nepal Agroforestry Foundation
NR	Negative relationship
NPV	Net Present Value
PES	Payments for Ecosystem Services
Pg	Petagram
RCBD	Randomized Complete Block Design
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SAS	Subsistence based Agricultural System
SFDP	Sagarnath Forestry Development Project
SOC	Soil Organic Carbon
TAP	Tri-ammonium Phosphate
tC	Ton Carbon
TFP	Total Factor Productivity
TPFDA	Terai Private Forest Development Association
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
VAT	Value Added Tax
VDC	Village Development Committee

Glossary of Nepalese words

Bhari	A load that an adult male/female carries on his/her back. An average Bhari is 30 kg.
Gahat/Rahari	Type of pulse crops.
Katha	Unit of farm area measurement. 30 Kathas make a hectare.
Koro	Small-size timber produced from a eucalypt tree that is used as beams for house construction.
Terai	Plain area.

List of Publications during the PhD Study Period

1. List of Journal Papers during PhD

Dhakal, A, Cockfield, G & Maraseni, TN 2012, 'Factors Affecting Adoption of Agroforestry-based Land Management Practice: A Case of Dhanusha District Nepal', *Agricultural systems* (*Under review).*

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Webb, EL & Dhakal, A 2011, 'Patterns and Drivers of Fuelwood Collection and Tree Planting in a Middle Hill Watershed of Nepal', Biomass and Bioenergy, vol. 35 no. 1, pp. 121-132.

2. List of Conference Papers during PhD

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Dhakal, A, Cockfield, G & Maraseni, TN 2012, 'Agroforestry-based Farming Systems, *Madhesi* Community and Climate Change Mitigation: A Case of Dhanusha District, Nepal, *paper presented to the International Conference on Climate Change Mitigation with Indigenous Peoples and Local Communities: Practices, Lessons Learned and Prospects*, Cairns, Australia, 26-28 March 2012.

Dhakal, A, Cockfield, G & Maraseni, TN 2011, 'Agroforestry-based Farming System, Farm Characteristics and Climate Change: A Study of Dhanusha District, Nepal', *Proceedings of Third International Conference on Addressing Climate Change for Sustainable Development through Up-Scaling Renewable Energy Technologies (RETRUD-011),* Kathmandu, Nepal, 12-15 October 2011,pp. 1-8.

Chapter 1

Introduction

1.1. Background

Integrating trees in agricultural land, labelled as agroforestry in the late 1970s, has been practiced for millennia by the people around the globe (King 1987; Regmi & Garforth 2010). The prime goal of such integration was solely related to livelihoods because trees fulfilled some of the peoples' fundamental needs such as fodder, fuelwood, fruits and timber even though trees generate some positive environmental externalities such as soil erosion control, biodiversity conservation and moisture conservation(Alavalapati et al. 2004; Long & Nair 1999; Nair 1985).

In the recent past agroforestry intervention has been considered as a strategy to halt deforestation and land degradation. Deforestation is a global problem facing human kind and it is more severe in the tropical region and many developing countries including Nepal, following the population growth that led to agricultural expansion to feed the growing population (Adesina & Chianu 2002).With time, agroforestry has evolved not just as a livelihood strategy within the farm but also as a global strategy to mitigate and halt the deforestation. Several agroforestry interventions such as alley cropping, improved fallow, live fence and windbreaks have been developed and introduced in the tropics to stop further agricultural expansion and support forest conservation (Jose 2009; Mercer 2004).

Land degradation is another problem facing human kind, particularly in developing countries (Bhatta & Neupane 2011). The main causes of land degradation are the intensive use of fertile land and use of marginal land, not suitable for agriculture, for agricultural production (Paudel & Thapa 2001). The intensive land use demands high use of inputs such as chemical fertilizers and agro-chemicals such as pesticides/insecticides to maintain the farm production and this not only resulted in land quality deterioration at farm level but also had some negative environmental impacts at landscape level such as water source contamination and biodiversity loss (Karkee 2004; Paudel & Thapa 2001). Therefore, current agriculture is not necessarily a sustainable land-use practice even though it provides high yields, because these alone are not a sufficient condition for any farming practice to be sustainable (Karkee 2004). Agroforestry, however, is not a panacea to land degradation but several studies have shown that agroforestry intervention has rehabilitated the degraded land in many developing countries (Maikhuri et al. 1997; Murgueitio et al. 2011; Parrotta et al. 1997). The premise behind the positive role of agroforestry in rehabilitating the degraded land is that agroforestry creates a favourable ecological interaction among the system components that enhances soil microbial activities through addition of organic matter in the soil, regulates the nutrient cycling within the system and controls soil erosion (Kaur et al. 2000; Kurzatkowski et al. 2004; Narain et al. 1997). Agroforestry has also enhanced farm productivity (Current & Scherr 1995; Duguma 2013; Franzel 2005; Neupane & Thapa 2001; Ramírez et al. 2001).

Very recently a new role that agroforestry can play to benefit the global population has been identified and recognized - climate change mitigation (Jose 2009). Because of the tree component that agroforestry integrates within the system, agroforestry is considered as a carbon sink as trees capture atmospheric CO_2 and store as biomass carbon in tree biomass and in the soils (Nair et al. 2009), while agriculture is a source of emissions because of livestock, paddy cultivation and use of farm inputs such as chemical fertilisers, irrigation, fossil fuels and agrochemicals (Johnson et al. 2007; Lokupitiya & Paustian 2006; Maraseni & Cockfield 2011b). This new benefit of agroforestry has created an avenue for farmers in developing countries to get financial incentives from participating in the newly emerged global carbon markets (Nair et al. 2009). Some policy mechanisms such as Clean Development Mechanism (CDM) under the Kyoto Protocol and Agriculture, Forestry and Other Land Use (AFOLU) have recognised agroforestry as a climate change mitigation strategy. However, participating in CDM by smallholder farmers could be highly costly because of high transaction costs of the project (Takimoto et al. 2010). Similarly, under the UNFCCC, the reducing emissions from deforestation and forest degradation (REDD+) policy has also recognised agroforestry as an emission reduction strategy (Thangata & Hildebrand 2012) because deforestation cannot be controlled by just ignoring the agricultural sector.

Given the immense opportunities and benefits that an agroforestry can create and provide at farm level, regional level and even at global level, the adoption and diffusion of such a promising land use has not taken place at rapid pace (Adesina et al. 2000; Amsalu & de Graaff 2007; Bayard et al. 2007; Franzel et al. 2001; Salam et al. 2000). Several agroforestry interventions have failed in the past. Some farmers have abandoned agroforestry after the development agency stopped providing support to them (Kiptot et al. 2007; Pisanelli et al. 2008). Even though agroforestry is an economically viable and environmentally sustainable land-use practice, why farmers are reluctant to adopt this practice is a crucial question to be addressed for the benefit of future generations.

Amidst these opportunities, benefits and issues, there is a need for understanding the evolution of agroforestry-based farming systems, factors responsible for farmers' decisions of agroforestry adoption at farm level and economic feasibility of adopting such systems. Therefore, this study attempts to address these issues using the case of Nepal.

1.2. Statement of problem

The global population is increasing and so is the demand for food. FAO (2009a) predicts that the global population will rise to 9.1 million in 2050 from a current 6.7 million and a 70% increase in farm production is required to feed the growing population. The global cultivated land is getting degraded and marginal land, not suitable for cultivation, is being used for cultivation in developing countries to meet the present need of food of the growing population (Govaerts et al. 2009). Developing countries such as Nepal, which is already a food-deficit country, will further suffer. During the last decade the cereal crop production in Nepal has increased but the per capita food access/year has fallen from 288 kg in 1996 to 250 kg in 2007 even though there has been an increase in cultivated land during this period (FAO 2009a). The globe has witnessed rapid climate change that has resulted in irregular patterns of floods, rainfall, drought which could affect food production in the 21st century, particularly in the developing world (Mertz et al. 2009).

Increased concentration/emissions of greenhouse gases (GHGs) mainly carbon-dioxide (CO_2), methane (CH_4) and nitrous-oxide (N_2O) resulting mainly from the burning of fossil fuels and land-use change, such as deforestation and agricultural expansion (IPCC 2007), has caused this rapid change in climate. Livestock farming and paddy cultivation are also responsible for CH_4 and N_2O emissions into the atmosphere (Gupta et al. 2009; Swamy & Bhattacharya 2006). Further, some agricultural inputs such as chemical fertilisers, irrigation, and agrochemicals are also contributing to GHGs emissions from the agricultural soil (Maraseni & Cockfield 2011a). Agriculture-based farming system is becoming unsustainable. Therefore, in the frame of present and future food crisis, any farming system should not only be high yielding but also sustainable. Available literature suggests that there is no research which is focused on assessing adoption potential of agroforestry to address the above problems of land management, climate change and food crisis. Therefore, this study examines the adoption potential of agroforestry in the particular context of Nepal. Amidst these problems, the following gaps were identified in the literature.

1.2.1. Methodological gap in adoption studies

Defining adoption, the dependent variable, is very crucial because the way adoption is defined determines the relationship between dependent and independent variables. Previous studies on agroforestry adoption and similar land management practice adoption have used the binary choice method, which simply splits population under study into two categories: adopters versus non-adopters (Adesina & Chianu 2002; Amsalu & de Graaff 2007; Brodt et al. 2009; Ojiako et al. 2007; Tiwari et al. 2008; Valdivia & Poulos 2009). According to this method, both the farmers who have adopted multiple farm technologies and who have adopted a single farm technology are considered adopters. This might be the reason why the effect of independent variables on adoption (dependent variable) is mixed and inconsistent in most studies. Therefore, there is no such point that could separate farmers exactly into two categories: adopters and non-adopters. Adoption is a process which means farmers are at different levels or stages of adoption. Developing an adoption index in place of binary choice could capture different levels of adoption. However, developing a valid index is not an easy task (for details see Chapter 2).

1.2.2. System-specific research gaps in carbon estimation

All the previous studies on carbon dynamics in agroforestry systems are from single agroforestry planting/technology such as agroforests (woodlots), alley cropping, windbreaks, live fence, home garden and parkland (Kaonga & Bayliss-Smith 2009; Kumar 2006; Makumba et al. 2007; Murthy et al. 2013; Saha et al. 2010; Takimoto et al. 2008; Takimoto et al. 2009). However, in many parts of the world, such distinct agroforestry is hard to find because farmers integrate many agroforestry technologies within the production system. For example, in the study area (Dhanusha District of Nepal), farmers consider different agroforestry plantings/technologies such as alley cropping, boundary plantation, agroforestry, homestead agroforestry and home garden (fruit orchard) as a part of the whole farming system. Also the carbon sequestration potential of agroforestry system is dependent on climate (tropical or temperate), silvicultural management regimes, and tree species and their growth characteristics. Such a mix of several agroforestry technologies might have higher sequestration potential than that of single technology. Therefore, a holistic research is lacking while estimating carbon sequestration potential of agroforestry system.

Although carbon-dioxide (CO_2) is the single most important GHG, other GHGs, namely nitrous oxide (N_2O) and methane (CH_4) to be emitted from the agroforestry system, could not be ignored because these gases have 298 and 25 times higher global warming potential (GWP) than that of CO_2 because of their unique radiative properties and long residence time in the atmosphere (IPCC 2007). Agriculture (mainly livestock and paddy) is considered to be the major source of CH_4 and N_2O emissions. Since paddy and livestock are the integral part of an agroforestry system in many parts of the world, while evaluating agroforestry as a climate friendly land management practice, these gases should be taken into consideration but the previous studies did not consider this aspect (Andrade et al. 2008; Kaonga & Bayliss-Smith 2009; Makumba et al. 2007; Saha et al. 2010; Sharrow & Ismail 2004; Takimoto et al. 2008). There are several farm activities that are linked with these two gas fluxes, such as use of farm manure, application of chemical fertilizers and use of fossil fuels in harvesting and post harvesting. The dynamics of these gases resulting from these agricultural inputs/activities need to be further investigated to assess the accurate estimate of carbon sequestration potential of agroforestry system. Greenhouse gases are also released during production, packaging, transportation of chemical fertilisers and fossil fuels. These aspects are also ignored in previous agroforestry studies.

1.2.3. Methodological gap in estimating carbon sequestration

There is a gap in the methodological approach that previous scholars have used to study the carbon dynamics under different agroforestry systems. Most study results are based on plot level data following certain experimental designs such as randomized complete block design (RCBD), split plot design, and factorial design (Kaonga & Bayliss-Smith 2009; Maia et al. 2007; Makumba et al. 2007). The major drawback of such designs is they are delicately controlled and far from real farm situations. Such ideal conditions, while important to research, often contrast with the real farm situation and farmers' practices at farm level where farmers are faced with several constraints that they suffer from bringing such ideal conditions into real practice.

Most farmers tend to prefer to continue what they are currently doing unless some unexpected political changes and some natural disasters take place (Adesina & Chianu 2002) as they know the associated risk from long experience with that particular farm practice. Therefore, farm level research is deemed necessary in agroforestry to get a wider adoptability/acceptability of the research findings. Studies have shown that most agroforestry technologies recommended, based on the findings from plot level study, had a low adoptability potential or sometimes resulted in complete rejection by the farmers because farmers are risk-averse and are reluctant to introduce new practices with the perceived additional risk to household food security (Binswanger 1980; Sood & Mitchell 2009) even though these recommended land management technologies might be more environment friendly and more productive.

1.3. Research objectives

The broader objective of this research is to make deeper understanding on economic performances and problems of adoption of agroforestry based farming system and contribute knowledge in literature. Specific objectives of the study are:

- To evaluate the development of the agroforestry-based farming system at landscape level in the study area;
- To assess the factors affecting adoption of the agroforestry-based farming system at farm level;

- To evaluate the economic performance of the agroforestry-based farming system with and without carbon values.

1.4. Research questions

This research has been organized around the following research questions:

a) Regarding development of agroforestry-based farming systems
- What are the major milestones (periods) in farming system developments in the study area?
- What are the major changes in farming systems during each period?
- What are the major drivers of change in the farming system and of development of the agroforestry-based farming system in the study area?
- What are the types of farming systems in the study area?
- How each farming system differs from one another?

b) Regarding adoption of the agroforestry-based farming system
- What are the major factors that affect the agroforestry adoption decision of farmers in the study area?

c) Regarding the system performance
- What are the components of the agroforestry-based farming system in the study area?
- What are the costs and benefits associated with each system component?
- What is the relationship between farm size and farm productivity?
- What is carbon sequestration potential (above- and below-ground) and how it varies with types of farming systems in the study area?
- What is the emission potential and how it varies with types of farming systems in the study area?

1.5. Research hypothesis

It is expected that agroforestry-based farming systems are more profitable than cultivation provided positive ecological interaction among the system components exist. Further, if environmental benefits of an agroforestry system were to be considered in economic analysis, the net present value (NPV) of such a system would be higher than cultivation. In this context, the following hypotheses were developed and tested.

H1: The highly integrated agroforestry-based farming system (HIS) sequesters higher amounts of carbon compared to the medium integrated agroforestry-based farming system (MIS) and less integrated agroforestry-based farming system (LIS)

H2: The HIS agroforestry releases the lower amount of GHGs emissions compared to other three farming systems (MIS, LIS and SAS)

H3: HIS agroforestry generates higher economic return than any other faming systems i.e. MIS, LIS and subsistence-based agriculture (SAS).

H4: The NPVs of all agroforestry-based farming systems (HIS, MIS and LIS) are greater than SAS when GHGs values are included.

1.6. Research rationale

In the present day context of climate change, agriculture including livestock is not a very environmentally friendly land-use practice from GHG emission perspective even though modern agriculture is high yielding with technological advancement in this field. Several activities associated with agriculture and livestock have been a constant source of GHG emissions. Some recommendations have been postulated to mitigate GHG emissions from the agriculture sector. Retention of crop residue in the farm, no tillage or reduced tillage and crop rotation are some management practices of prime importance with regards to GHG mitigation being successfully practiced in developed countries such as USA (Lal 1997; Lal & Kimble 1997). However, these recommendations are not equally applicable in many developing countries. For example, in Nepal where this PhD research was conducted, crop residue is a good source of livestock feed and therefore farmers do not keep residue in the farm after the crop harvest. Similarly, adoption rate of zero or reduced tillage in south Asian countries is very low (Block et al. 2007; Erenstein et al. 2008). An agroforestry-based farming system could be a better option of land management in mitigating GHG emissions from agriculture sector. Therefore, the finding of this research would help promote and design a climate smart agriculture in developing countries.

This study attempts to be more comprehensive than other previous studies in agroforestry. There are some studies that considered only the tangible benefits of agroforestry and other land use such as cultivation. This study analyses different types of land use incorporating all three greenhouse gases from different sources and sinks and tangible benefits in one place. Moreover, it is field-based empirical research which could relatively reflect the real world scenario, as opposed to entirely model-based research.

1.7. Scope and limitations of the study

The major limitation of this research is the use of chronosequence data instead of time series data to develop the growth models of five agroforestry tree species. Also, it was not possible to measure the DBH of trees under age of four and therefore the growth up to that age i.e. four was assumed to be linear. Since farmers do not keep annual records of tree growth and even the government institution has not established permanent research plots in farmers' fields, it is difficult to get the annual growth data (time series data) in developing countries like Nepal. Further, in the study area, it is a common practice that trees are grown in different niches such as homestead, boundary plantation, alley and agroforest (woodlot) and this has a direct effect on the growth and development of the trees. Trees raised in belts such as alley and boundary and around homesteads exhibit higher growth rate than that of agroforest (woodlot) for the same species. However, in this study growth it was assumed to be the same irrespective of the niches. Given the time constraints, samples for tree measurement were taken only from the agroforest (woodlot). Therefore, this might have resulted in slightly lower estimation of biomass of these agroforestry tree species.

Use of allometric equations for estimating biomass carbon is another limitation of the study. Two types of allometric equations are used in this study: species-specific and generalized. In case of *E. camaldulensis*, the regression model used was developed for the study area region and therefore the biomass carbon estimation gave more precise estimation. However, in case of *D. sissoo*, a species-specific model was used; the model was developed for the Indian state close to the study area. Therefore, some error in estimation cannot be rejected. For the rest of the tree species i.e. *G. arborea, M. azedarach* and *A. chinensis* and for three fruit tree species i.e. M. *indica*, *L. chinensis*, and *A. heterophyllus*, generalized models were used. Having no species-specific regression models for the study area for these tree species, these models were used. Using the generalised models in place of specific ones would definitely result into some error in biomass carbon estimation.

Use of default values for estimating GHG from different activities of the farming systems is also a limitation of this study. Except for biomass burning, for all other farm activities, Nepal has no country-specific default values for methane, nitrous oxide and carbon dioxide. Therefore, in most cases the IPCC default values have been used to estimate the GHG emissions from the farming systems. Emissions are location-specific and influenced by several factors. Using IPCC default values is not free of risk. Therefore, findings of this study should be used with caution. Even though this study is more comprehensive and more integrated than the previous studies, this study still does not cover the soil carbon dynamics of agroforestry-based farming systems, which leaves room for further research.

1.8. Organisation of dissertation

This dissertation has been arranged in seven chapters. Following this introductory chapter, chapter two provides a review of past works and pertinent issues related to agroforestry adoption and GHG dynamics in the agroforestry system. The literature review is followed by detailed discussion of research methods and study area in the next chapter.

Chapter four covers the development of agroforestry-based farming systems and major drivers of agroforestry development. Chapter five concentrates on developing the adoption index to study the factors affecting adoption decisions by farmers with regards to agroforestry-based farming system.

Chapter six looks on GHG dynamics, carbon sequestration potential and profitability of four farming systems with and without incorporating carbon values. Finally chapter seven summarises the major findings of the study and provides conclusions, research contribution and recommendations.

1.9. Conclusions

This chapter highlighted the background of this research. Problems and gaps in literature were identified. The major gap in literature was defining adoption as a dependent variable in agroforestry-related studies. The other major gap was in assessing GHGs gas dynamics in agroforestry systems. Available literature was focused on carbon sequestration potential only. The broad objective followed by three specific objectives supported with research questions and hypotheses were set to address the identified research problem. Scope and limitation and rationale of the study were also highlighted.

Chapter 2

A Review of Adoption, Carbon Dynamics and Agroforestry Economics

2.1. Introduction

The aim of this research is to assess the potential of agroforestry intervention in Nepal from both economic and environmental perspectives in the context of changed climate. Therefore, this chapter includes a review of some pertinent issues. In the first section, the concept and different agroforestry practices have been reviewed with an aim of understanding the diversification of agroforestry in Asia and elsewhere and particularly defining agroforestry that is in practice in the study area with respect to the globally accepted definition of agroforestry. The second section reviews theoretical perspectives of technology adoption, factors affecting adoption of agroforestry and some methodological issues related to adoption. The third section reviews the carbon and greenhouse gases' (GHG) dynamics in agroforestry systems and some gaps in literature. The last section reviews the economics of agroforestry particularly focusing on the farm size- productivity relationship- Negative relationship (NR).

2.2. Agroforestry: definition, history and adoption

2.2.1. Defining agroforestry

Defining the term agroforestry is no easy matter. Although the word "agroforestry" dates back only to the 1970s, many agroforestry practices have been utilized for centuries or millennia (King 1987). From its roots, it is known that agroforestry has something to do with agriculture and forestry. In the inaugural issue of the journal Agroforestry Systems, the editorial board asked key agroforestry experts to give their definitions of "agroforestry" (Nair et al. 1985). There is a wide range of concepts used to try to explain what agroforestry really is. Also, very many national and international organizations related to agroforestry, such as the World Agroforestry Centre (ICRAF), the Association for Temperate Agroforestry (AFTA) and the USDA National Agroforestry Centre (NAC), have each provided their own definitions to try to elucidate the concept (Nair 1985).

Efforts to define agroforestry as a form of land management that is applicable to both farm (agriculture) and forest began in the mid-1970s as a result of increasing global concern for the spread of tropical deforestation and ecological degradation in combination with concerns that the basic needs of the world's poor were not being adequately addressed (Nair 1993). In the last two decades a plethora of studies have been conducted in the tropical regions in relation to agroforestry promotion, development, adoption and diffusion because it was thought that tropical forests were under persistent stress resulting from a range of factors such as commercial exploitation and fuelwood demands to shifting cultivation. In 1977 the International Development Research Centre (IDRC), located in Ottawa, Canada, responded to these concerns in conjunction with regional experts from around the globe, and concluded that "the solution to the problems besetting tropical forests arose from population pressure exerted through the need to produce food and fuelwood (Steppler 1987). From this initial research evolved the concept of agroforestry, defined as a sustainable management system for land that increases total production, combines agricultural crops, tree crops and forest plants and animals simultaneously or sequentially, and supplies management practices that are compatible with the cultural patterns of the local population (Bene et al. 1977).

In the late 1970s and early 1980s, as studies began on the diversity and scope of agroforestry practices, the field suffered from an excess of definitions and a general lack of common understanding caused by a scarcity of hard information. These early struggles to define a new area of study were documented in the inaugural issue of Agroforestry Systems (Nair 1985) where a selection of definitions, proposed by various authors, were reviewed in an editorial entitled "What is Agroforestry?." These interpretations were discussed and refined at the International Council for Research in Agroforestry (ICRAF) and the following definition of agroforestry was proposed: Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately used on the same land-management units as agricultural crops and animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components (Lundgren & Raintree 1983).

At the mention of the word agroforestry, many, including some of the most experienced experts, automatically think of the tropics, however, agroforestry may also be a potentially efficient use of land in extra-tropical (sub-tropical and temperate) regions of the world. Alavalapati et al. (2004) and Schoeneberger (2009) documented a number of agroforestry innovations around the globe both in the tropical and temperate zones (Table 2.1). In Nepal's *terai*, the study region (sub-tropical), different types of agroforestry are in practice i.e. alley cropping, agroforest (woodlot), windbreaks (boundary plantation), fruit orchard (home garden) and homestead agroforestry. However, these agroforestry innovations in the study region are part of a whole farming system. This implies that on a single farm, one or any combination of these five types is prevalent making it difficult to define which agroforestry system the farm belongs to, out of 15 different types as documented by (Alavalapati et al. 2004). Therefore, a new term 'agroforestry-based farming system' was coined to denote the farming system under study to avoid confusion. However, a form of agroforestry is very common in rural Nepal. Nepalese farmers protect trees that grow naturally on their farms for their livestock (Regmi and Garforth, 2010). This kind of simple agroforestry is wide-spread but the agroforestry as defined here for this study is not wide-spread in Nepal.

2.2.2. Historical perceptives on agroforestry

Agroforestry has evolved over time from simple and primitive agroforestry innovation such as shifting cultivation, also known as slash and burn and swidden cultivation, to more complex (home gardens) and modern innovations such as alley cropping, live hedge fence, and improved fallow.

Cultivation of trees with agricultural crops dates to the beginning of plant and animal domestication (King 1987; Williams et al. 1997). Since then, a variety of agroforestry systems have been developed, adopted and diffused in Asia, Africa, Europe, and parts of North and South America (Oelbermann et al. 2004). These early agroforestry practices, like modern agroforestry systems, had a strong focus on sustainable crop production and soil conservation. For example, in Middle-Age Europe, degraded forest stands were clear-cut and seeded with crops. The slash was burned and crops were cultivated for varying time periods before new trees were planted again. Integrating apple orchards with sheep pasture or integrating timber or nut trees with cereal crops was also a common agroforestry practice in Europe

(Gordon et al. 1997). In the tropics, farmers adopted vertical forest structures by planting a variety of crops with different growth habits, resulting in high species diversity on a small land area (Kass & Somarriba 1999; Wilken 1976). This system not only provided a diversity of crops to the farmer but also protected the soil from erosion by reducing the impact from raindrops, and litter from trees provided organic material to sustain soil nutrient levels.

Research on agroforestry systems and agroforestry adoption did not begin until the mid-1970s. Since the establishment of ICRAF in 1977, agroforestry has been promoted as a sustainable land-use management system in both tropical and temperate latitudes. Modern experimental work in agroforestry began in the late 1970s including the first experiment on hedgerow intercropping (alley cropping) in Ibadan, Nigeria. Studies on nutrient cycling, using perennial crop combinations in Central America, and studies on the effectiveness of contour hedgerows on erosion control were also addressed (Young 1997).

Agroforestry systems in the tropics often have a different purpose than those of temperate latitudes. In the tropics, in most cases agroforestry land management practices maintain landowner self-sustenance (Huxley 1999), whereas in temperate latitudes the focus is on resource management policies, farming technology, labour costs and real estate values (Williams et al. 1997). However, in both biomes, trees are viewed as an integral part of agroforestry with the potential to restore degraded lands, to maintain soil fertility, and more recently to sequester C for mitigating atmospheric CO_2 emissions.

These early anecdotes on agroforestry merely put forward some practices adopted at a certain point in time in history, globally, but did not trace any evidence of how they evolved and what factors played a role in the development of these practices.

Table 2.1: Major agro-forestry practices in tropical and temperate zones

Agroforestry practice	Brief description
Tropical zone	
Taungya	Agricultural crops grown during the early stages of forest plantation establishment.
Home gardens	Intimate, multi-story combinations of a variety of trees and crops in homestead gardens; livestock may or may not be present.
Improved fallow	Fast-growing, preferably leguminous woody species planted during the fallow phase of shifting cultivation; the woody species improve soil fertility and may yield economic products.
Multipurpose trees	Fruit and other trees randomly or systematically planted in cropland or pasture for the purpose of providing fruit, fuelwood, fodder, and timber, among other services, on farms and rangelands.
Plantation-crop combinations	Integrated multi-story mixtures of tree crops (such as coconut, cacao, coffee, and rubber), shade trees, and herbaceous crops.
Silvopasture	Combining trees with forage and livestock production, such as grazing in existing forests; using trees to create live fences around pasture; or to provide shade and erosion control.
Shelterbelts and windbreaks	Rows of trees around farms and fields planted and managed as part of crop or livestock operations to protect crops, animals, and soil from natural hazards including wind, excessive rain, seawater, or floods.
Alley cropping	Fast-growing, preferably leguminous woody species in single or grouped rows in agricultural fields. Pruning from the woody species are applied as mulch to the agricultural production alleys to increase organic matter and nutrients or are removed from the field for other purposes such as animal fodder.

Agroforestry practice	Brief description
Temperate zone	
Alley cropping	Trees planted in single or grouped rows within agricultural or horticultural fields with crops grown in the wide alleys between the tree rows.
Forest farming	Forested areas used for production or harvest of natural standing specialty crops for medicinal, ornamental, or culinary uses (e.g. ginseng, ferns, shiitake mushrooms).
Riparian buffer strips	Strips of perennial vegetation (tree/shrub/grass) planted between croplands/pastures and water sources such as streams, lakes, wetlands, and ponds to protect water quality.
Silvopasture	Combining tress with forage and livestock production, such as growing trees on ranch lands, grazing in existing forests, providing shade and erosion control or environmental services.
Shelterbelts and windbreaks	Rows of trees around farms and fields planted and managed as part of crop or livestock operations to protect crops, animals, and soil from natural hazards including wind, excessive rain, seawater, or floods.

2.2.3. Adoption of agroforestry: theoretical perspectives

In many parts of the world, agroforestry adoption has proceeded slowly despite apparent benefits. This has promoted significant research focusing on the factors that affect adoption (Pattanayak et al. 2003). However, the theoretical backstopping of agroforestry research on adoption comes from studies of agricultural technologies adoption (Feder & Umali 1993; Mercer 2004) because agroforestry is a kind of agricultural technology even though adoption of agroforestry is considerably more complex than traditional agriculture (Amacher et al. 1993).

Most adoption studies on agricultural innovations tended to be dominated by separate lines of research by sociologists, economists and geographers (Mercer 2004). Economists historically emphasized profitability and investment risks while sociologists concentrated on the social rewards associated with adoption. Geographers highlighted the spatial differences in resource endowments and diffusion, and anthropologists were more concerned with compatibility of innovation with social norms and values (Boahene et al. 1999).

A similar historical path can be observed in agroforestry adoption research. Until the 1990s, adoption research in agroforestry was primarily concerned with physical and biophysical interactions with little or no emphasis on economics or sociology (Adesina & Chianu 2002; Mercer & Miller 1998). Viewing adoption in isolation is problematic because adoption and diffusion of any technology/innovation depends on a combination of social, economic, biophysical, cultural and institutional factors (Adesina & Chianu 2002; Mercer 2004; Rasul & Thapa 2003). Adoption should be viewed from a multidisciplinary perspective because it is a multi-dimensional process dependant on a variety of factors such as perceived profitability, cost of establishment, compatibility with social value systems and biophysical settings and the ability to communicate knowledge and information between and among adopters and potential adopters (Boahene et al. 1999).

Several economic models were postulated by earlier research scientists with regard to the adoption potential of new technology. The most prominent and widely used model is the work of Just and Zilberman (1983) who applied the expected utility framework to technology adoption under uncertainty, commonly known as the expected utility model. The model assumes that adoption decisions by farmers are based on the maximization of expected utility or profit subject to land, credit, labour and other constraints. This implies that any farming innovation that maximises the profit would have a high adoption potential. However, this is not the case in the real world because profitability alone does not guarantee the adoption and diffusion of any technology. For example, fish farming in Nepal's *terai* is a more profitable farm business than cereal crops such as rice and wheat farming (Manandhar et al. 2011). However, it is not as widely adopted as cereal crops because fish farming requires higher investment (land and water supply) at the beginning, which small farmers cannot afford (Manandhar et al. 2011). Affordability and acceptance by famers is more important for any farm technology to be adopted and diffused widely at landscape and regional level.

In a study of farm level profitability of agroforestry, the majority of the 56 agroforestry technologies in the Current et al. (1995) volume were labelled as potentially profitable, based on positive net present values (NPVs) and assuming a 20% discount rate. This sort of research finding solely based on financial returns is, however, crucial for all from donors/policy-makers/researchers to farmers, the ultimate beneficiaries of the technology. Donors/policy makers may need this type of information and analysis to determine how/if the innovations contribute to household welfare and economic development as a basis for research and development allocation decisions. Researchers developing improved farming systems need this information to insure that their experimental systems are appropriate for farmers' needs, abilities and circumstances. This type of information is invaluable to farmers as they attempt to make informed adoption on agroforestry systems that typically require considerable resources, skills and time to implement and manage (Franzel & Scherr 2002).

In addition to the expected financial returns, the relationship between the new technology and total farm enterprise, the existing capital, labour and land constraints and other socio-economic and institutional factors are crucial to the adoptability of the systems (Mercer 2004). Now adoption research has advanced significantly from descriptive and prescriptive research lacking formal theoretical development and rigorous analysis (Allen 1990; Fujisaka 1989; Raintree 1983) to development of advanced regression models that include a range of variables, broadly categorised into five groups by Pattanayak et al. (2003), influencing adoption decisions by farmers. However, these models still fail to depict the real picture of agroforestry adoption given the inherent error in defining the dependant variable i.e. agroforestry adoption. This is discussed under the sub-heading 'agroforestry adoption and methodological gap' in detail.

2.2.4. Reviewing factors affecting agroforestry adoption: an empirical studies review

Knowler and Bradshaw (2007) documented 46 variables influencing farmers' decisions with regard to adoption of conservation agriculture including agroforestry and grouped them into four broad categories: farmer and farm household characteristics, farm biophysical characteristics, farm financial/management characteristics and exogenous factors. Similarly, Pattanayak et al. (2003) documented 21 variables explaining adoption of various types of agroforestry practices that are in use at different geographic locations and grouped them into five broad categories: preferences, resource endowments, market incentives, biophysical factors and risk.

Even though there were some technology-specific variables influencing adoption, the most and highly used variables in both studies were education, age, farm size, tenure and farm income. Since agroforestry is considered a land conservation technology, this review includes studies related to both adoption of conservation agriculture and agroforestry technologies. Since adoption is a continuous process and therefore is uneven from farmer to farmer (Knowler & Bradshaw 2007), certain farmer and household characteristics are associated with the uneven adoption. Negatu and Parikh (1999) and Gould et al. (1989) emphasised awareness/perception/knowledge on the part of farmers of land degradation and land problems as a pre-requisite to adoption.

In most cases, farmer perceptions/awareness of the land problems and towards agroforestry activities was found to positively and significantly correlate with adoption (Ajayi 2007; Batz et al. 1999; Caviglia & Kahn 2001; Gould et al. 1989; Khan et al. 2008; Neupane et al. 2002; Salam et al. 2000; Sidibé 2005; Valdivia & Poulos 2009). However, this is not universally so because Alavalapati et al. (1995) and Thangata and Alavalapati (2003) found no relationship between perception/ awareness and agroforestry adoption decision and even in some cases the relationship was reported to be negatively correlated (Anley et al. 2007; Carlson et al. 1994).

The presence of conservation attitudes among farmers has been assessed in relation to both conservation agriculture and agroforestry adoption, and studies have revealed positive (Alavalapati et al. 1995; Carlson et al. 1994; Valdivia & Poulos 2009; Warriner & Moul 1992) and no relationship (Okoye 1998; Saltiel et al. 1994). The level of education of household head has been assumed to influence adoption decisions. Education was commonly found to be positively correlated with adoption of agricultural and agroforestry innovations(Anley et al. 2007; Sidibé 2005; Warriner & Moul 1992); however, some studies have revealed education to be an son-significant factor (Adesina & Chianu 2002; Caviglia & Kahn 2001; Clay et al. 1998; Nkamleu & Manyong 2005; Ojiako et al. 2007; Thangata & Alavalapati 2003; Tiwari et al. 2008). In some cases, education appeared to be negatively correlated with adoption decision of farmers (Bayard et al. 2007; Neupane et al. 2002; Okoye 1998; Oladele 2012).

The age of the farmers is another variable frequently assessed to see its impact on adoption decisions. It is generally assumed that young farmers are more likely to adopt new technology than old farmers. However, the results are mixed as studies have shown positive (Okoye 1998; Oladele 2012; Shiferaw & Holden 1998; Shively 1997; Warriner & Moul 1992), non-significant (Alavalapati et al. 1995; Ayuk 1997; Caviglia & Kahn 2001; Nkamleu & Manyong 2005; Ojiako et al. 2007; Sidibé 2005; Tiwari et al. 2008) and negative correlations (Anley et al. 2007; Clay et al. 1998; Neupane et al. 2002; Thangata & Alavalapati 2003; Valdivia & Poulos 2009). The farmer’s experience also has been assumed to influence adoption decisions. Studies have shown positive (Adesina & Chianu 2002; Caviglia & Kahn 2001; Clay et al. 1998; Oladele 2012) and no relationship (Nkamleu & Manyong 2005; Ojiako et al. 2007).

In addition to the aforementioned characteristics of farmers, a considerable emphasis has been given to a variety of biophysical characteristics in relation to adoption of agroforestry and agricultural land management technologies. The most common factor used in adoption studies is farm size (or sometimes planted area) (Knowler & Bradshaw 2007; Pattanayak et al. 2003). It is assumed that large farmers are more likely to adopt new technology (Tiwari et al. 2008). However, the role of farm size in adoption decisions is not universal. Some studies have observed positive correlations (Anley et al. 2007; Oladele 2012; Salam et al. 2000; Sidibé 2005) while others have revealed insignificant (Ayuk 1997; Ojiako et al. 2007; Thacher et al. 1996) and even negative correlations (Mercer et al. 2005; Pisanelli et al. 2008). Physical characteristics of the farmland such as steepness and erodible soils also influence the adoption decision (Soule et al. 2000). Studies have shown that farm with erodible soils because of steep slope have a greater tendency to adopt agroforestry and soil conservation practices such as hedge row planting and terracing (Anley et al. 2007;

Valdivia & Poulos 2009), however in some cases these variables have no effects on adoption decision and are insignificant (Clay et al. 1998; Thacher et al. 1996).

Among the many factors that reflect the financial conditions of a farm, land tenure, farm income/profitability and labour sources; have attracted some attention in studies of agroforestry adoption and conservation agriculture (Knowler & Bradshaw 2007; Pattanayak et al. 2003). With respect to land tenure, it is a conventional wisdom that owned land is better maintained by farmers than leased ones. The logic behind this is that agroforestry is a long-term investment and farmers are unwilling to invest in such activities unless they have land tenure security. However, this hypothesis does not always hold true. Some studies supported this hypothesis (Clay et al. 1998; Oladele & Wakatsuki 2009; Thacher et al. 1996), some rejected (Anley et al. 2007; Fuglie 1999) and some found no significant relationship (Adesina & Chianu 2002; Ayuk 1997; Neupane et al. 2002; Nkamleu & Manyong 2005). However, in a review of 23 journal papers by Pattanayak et al. (2003), they found that out of 18 papers that included tenure as an explanatory variable, 12 papers supported that land tenure positively influenced the adoption of different types of agroforestry practice, only one paper showed a negative correlation while 5 papers found no relationship.

With respect to farm income, it is generally expected that the adoption of conservation technology such as agroforestry and conservation agriculture requires sufficient financial resources because agroforestry incurs high initial investment cost (Knowler & Bradshaw 2007). In support of this view, a majority of studies (Alavalapati et al. 1995; Pattanayak et al. 2003; Phiri et al. 2004; Tiwari et al. 2008) that investigated the impact of farm income on adoption revealed a positive correlation. Very few found a negative and no relationship (Caviglia & Kahn 2001; Clay et al. 1998; Okoye 1998; Warriner & Moul 1992). Labour is another variable widely used in adoption studies.

Even though the impact of labour in adoption decision is mixed, a majority of studies found no significant correlation with agroforestry adoption (Knowler & Bradshaw 2007; Pattanayak et al. 2003). Thacher et al. (1996) revealed that family labour had a negative relationship with adoption of a reforestation program, a kind of agroforestry practice. Neupane et al. (2002) reported the similar result in a study carried out in one of mid-hills watersheds of Nepal, while a study by Salam et al. (2000) in Bangladesh found that labour was positively and significantly correlated with adoption of homestead agroforestry. Another study by Nkamleu and Manyong (2005) in Cameroon revealed no significant relationship of adoption of alley cropping, improved fallow and live fencing with family labour.

Some institutional factors such as extension service and membership have been assessed as to whether or not they have influenced adoption decisions by farmers (Pattanayak et al. 2003). It is regularly hypothesized that the provision of extension service and farmers' association with organization such as farmers' groups, cooperatives and NGOs result into adoption of agroforestry practices (Knowler & Bradshaw 2007). However, with respect to extension service, studies have shown positive (Adesina & Chianu 2002; Matata et al. 2008; Nkamleu & Manyong 2005; Ojiako et al. 2007; Thacher et al. 1996; Thangata & Alavalapati 2003) and no relationship (Neupane et al. 2002). With respect to membership, both positive (Caviglia & Kahn 2001; Matata et al. 2008; Nkamleu & Manyong 2005; Ojiako et al.

2007) and non-significant (Ayuk 1997) relationship has been reported. There are some other variables found in the literature used occasionally to assess the adoption decision of farmers such as livestock size, social status, and provision of training, output prices, access to credit and access to information. Studies have shown mixed results: positive, negative and non-significant (Knowler & Bradshaw 2007; Pattanayak et al. 2003).

This review clearly indicates that the empirical records contained many ambiguities and inconsistent results because all the variables discussed in previous paragraphs have shown mixed effects on adoption of agroforestry practices. It can be concluded that there is no strong evidence of universality in the variables influencing the adoption decision. One possible reason for mixed results as urged by Knowler and Bradshaw (2007) could be that as a variable is entered into more analyses the chance that an anomalous result might be obtained increases. Another reason for this inconsistency would be locale of investigation that might influence the result. For example, studies from North America tend to show a more positive significant effect of education on adoption than do studies from other regions (Knowler & Bradshaw 2007; Oladele 2012; Pattanayak et al. 2003).

Several studies from African regions have shown that education had no effects (Adesina & Chianu 2002; Ayuk 1997; Ojiako et al. 2007; Sidibé 2005; Thangata & Alavalapati 2003) on adoption decision of farmers. Similarly, Neupane et al. (2002) in a study carried out in Nepal’s mid-hills region found a significant negative correlation of education with agroforestry adoption decisions. This is because in Nepalese culture educated people are reluctant to involve themselves in agricultural work and out-migrate for job. Another plausible reason for such anomalous results might be the statistical method of the analysis used for the study. For example, with respect to farm size, Knowler and Bradshaw (2007) revealed that the majority of studies that used a Logit or Probit model found it positively correlated with adoption, whereas the majority of studies that tested for the same relation using ordinary least square (OLS) identified no significant causal relation.

This review reveals that a substantial amount of literature on adoption of agroforestry and agricultural land management practices has been published over the past two decades. However, many of the studies are confined to certain geographical areas (Pattanayak et al. 2003), have adopted a piecemeal approach, focused on few factors and thus make it difficult to draw general conclusions. A comprehensive research on adoption covering all potential variables is lacking. Since several variables influencing adoption decision are locale–dependent, area-specific studies are necessary for policy intervention and scaling up the new technology.

2.2.5. Agroforestry adoption and methodological issue

Even though adoption studies have come a long way from the very descriptive and prescriptive study that lacked formal theoretical development and rigorous empirical analysis (Allen 1990) to more advanced study using regression models to assess the adoption factors (Adesina & Chianu 2002; Anley et al. 2007; Matata et al. 2008; Valdivia & Poulos 2009), the methodological issue is still at centre stage of debate in the adoption literature (Ajayi et al. 2003; Kiptot et al. 2007). As highlighted in the previous section, the anomalous results of the adoption studies are attributed to the methodology used in the analysis.

In many of the studies, adoption of agroforestry technologies is viewed as a binary choice problem (Adesina & Chianu 2002; Amsalu & de Graaff 2007; Neupane et al. 2002; Ojiako et al. 2007). Previous studies of farmers' views of agroforestry systems focused almost exclusively on the question of whether farmers adopt technology or not, and was viewed from a single point in time. In other words, researchers regarded a farmer as having 'adopted' a given technology if the individual had or used the technology. Sometimes there is a problem getting a precise definition for the word 'adoption' of agricultural technology (Marra et al. 2003) and especially in the context of agroforestry because agroforestry adoption decisions are more complicated than those for annual crops (Scherr & Müller 1991). This may explain why some of the results of the studies appear ambiguous.

Kiptot et al. (2007) pointed out a classification system of only adopters versus non-adopters is an oversimplification of the temporal process because adoption is a continuous process that varies from farmer to farmer, which implies that farmers are at different stages. There exists variation in adoption level within this 'adopters' group too. Therefore, this binary choice method using Logit, Probit and Tobit-regression models would not be able to capture a real picture of the technology adoption and disadoption. For example, a farmer adopting a single technology such as improved maize and a farmer adopting multiple technologies such as improve maize, improved livestock and some other land improvement technologies, should not be put in the same category. Likewise, a farmer adopting a single agroforestry technology such as alley cropping and a farmer adopting multiple technologies such as alley cropping, agroforest, and home garden, must be grouped separately as the two farmers represent the different level of technology adoption.

A clear-cut delineation is required within adopter farmers based on the adoption stage (phase) to avoid the possible ambiguity in results (Kiptot et al. 2007). Franzel and Scherr (2002) delineated farmers who were in 'testing phase' from 'adoption' phase and grouped farmers into testers/experimenters, adopters and non-adopters. This approach has been used in adoption studies carried out elsewhere in which researchers asked farmers to classify themselves as 'experimenters' or 'adopters' (Adesina et al. 2000). In another study, Pisanelli et al. (2008) distinguished 'experimenter' from 'adopter' farmers according to whether farmers continued to use improved fallows following a period of initial experimentation.

Kiptot et al. (2007) further classified farmers into four groups; non-adopters, adopters, testers/experimenters and pseudo-adopters. This classifying of farmers certainly helps minimize variations within the group and hence gets better results than binary choice models do. However, this delineation also fails to differentiate between single technology adopters and multiple technology adopters as discussed earlier. One plausible way to overcome this problem could be to regard adoption as a continuum where individual farmers are conceptualized to occupy positions along a continuum of adoption path depending on the extent to which they have taken up various components of the technology. Ajayi et al. (2003) proposed that several indicators, such as the size of field, density of agroforestry trees within the field, proportion of farm holding devoted to improved fallows relative to total cropped area, number of years of agroforestry practice and level of management attention given to agroforestry field, may be used to assess a farmer's position within the continuum and develop an adoption index for each farmer.

While developing such adoption index following Ajayi et al. (2003), there exists a problem of how or what value is to be assigned for each indicator, either equal or different, based on the importance that individual farmer places on a particular indicator. One plausible option to avoid such a problem would be listing all components of agroforestry that individual farmers have adopted instead of those indicators proposed by Ajayi et al. (2003) and giving equal value to each component so that personal bias of researchers and farmers can be checked. An adoption index will be more appropriate rather than binomial Logit models (adopters versus non-adopters). This would minimize the definitional problem regarding the exact delineation between 'non-adopters', 'testers' and 'adopters' and 'pseudo-adopters.

2.3. Agroforestry, carbon sequestration and greenhouse gas (GHG) emissions

Agroforestry in general represents a significant opportunity for sequestering C on agricultural lands in that a substantial proportion of the C is sequestered in woody biomass, thus creating a system that sequesters a large amount of C per unit area and for a longer duration than many other conserving practices (Montagnini & Nair 2004; Schoeneberger 2009). A growing interest in the role of different types of land use in reducing atmospheric CO_2 concentration and lowering the emissions rate of this GHG, has led to an increased research on the function of agroforestry systems as carbon sinks. In the following section a comprehensive review of agroforestry in relation to carbon storage and GHG emissions is discussed.

2.3.1. Carbon sequestration potential of agroforestry systems

Carbon sequestration potential of agroforestry systems has attracted attention from both industrialized and developing countries in recent years following the recognition of agroforestry as a GHG mitigation strategy under the Kyoto Protocol (Albrecht & Kandji 2003; Makundi & Sathaye 2004; Sharrow & Ismail 2004; Takimoto et al. 2008). The Clean Development Mechanism (CDM) under the Kyoto protocol has provided opportunity to industrialized countries with a GHG reduction commitment to invest in mitigation projects in developing countries as an alternative to what is generally more costly in their own countries. This has created an avenue for farmers who are the practitioners of agroforestry in developing countries to get economic incentives from C sale to the industrialized countries.

Nair et al. (2009) proposed that agroforestry practices like alley cropping and silvopasture have the greatest potential for conserving and sequestering C because of the close interaction between crops, pasture, trees and soil. Having a direct near-term (decades or centuries) C storage capability both in trees and soils, and also the potential to offset immediate GHG emissions associated with deforestation and shifting cultivation, it is claimed that agroforestry systems could be superior to other land use at the global, regional, watershed, and farm level (Dixon 1995; Sanchez 2000; Schoeneberger 2009). With the view that agroforestry is a potential land use in climate change mitigation in long-term, several studies on agroforestry both in tropical and temperate latitudes have been conducted in the last two decades.

Several studies have investigated the carbon sequestration potential (CSP) of agroforestry systems. Wright et al. (2001) estimated that the goal of assimilating 3.3Pg C year^{-1} would require 670−760 Mha area of improved maize cultivation, whereas this goal can be achieved by adoption of 460 Mha of agroforestry. They even suggested that agroforestry is the only system that could realistically be implemented to mitigate the atmospheric CO_2 through terrestrial C sequestration. Estimation of C stocks all over the world indicated that, with the proper implementation of agroforestry at the global scale,1.1 to 2.2 Pg C can be removed from the atmosphere within 50 years (Albrecht & Kandji 2003).

Sharrow and Ismail (2004) reported C sequestration to be higher in silvopasture systems than in forests and pastures. Silvopastures accumulated approximately 0.74t ha^{-1} year^{-1} more C than forests and 0.52t ha^{-1} year^{-1} more C than pastures in Oregon, USA. They concluded that agroforestry systems had both forest and grassland nutrient cycling patterns and would produce more total annual biomass. In Brazil, Schroth et al. (2002) observed that multi-strata systems had an aboveground biomass of 13.2–42.3t ha^{-1} and a belowground biomass of 4.3–12.9t ha^{-1} compared to those of monoculture at 7.7–56.7t ha^{-1} and 3.2–17.1t ha^{-1}, respectively.

In West African Sahel, Takimoto et al. (2008) found higher amount of SOC (aboveground + belowground) in parkland agroforestry systems (*Faidherbia albida* and *Vitellaria paradoxa* trees as the dominant species), compared to live fence and fodder bank. They observed that the live fence, fodder bank and parkland agroforestry systems could generate 0.59t C ha^{-1}year^{-1}, 0.29t C ha^{-1}year^{-1} and 1.09t C ha^{-1}year^{-1}, respectively. In a study carried out in Canada's temperate region, Peichl et al. (2006) observed that the temperate tree-based intercropping systems can uptake 0.83t C ha^{-1}year^{-1}. The annual carbon uptake by agroforestry wood-lot in India was 6.53t ha^{-1} (Mohan Kumar et al. 1998) while this amount was almost double (12.04t C ha^{-1}) in the case of agroforestry wood-lot in Puerto Rico (Parrotta 1999). The Nair review noted that an agroforestry such as mixed species stands in Puerto Rico had storage potential as high as 15.21t C ha^{-1}year^{-1} while the agroforestry such as fodder bank in west African Sahel had the lowest sequestration potential (0.29t C ha^{-1}year^{-1}) (Nair et al. 2009).

This comprehensive review clearly indicates that carbon sequestration potential varies with agroforestry types and geographic locations like temperate and tropical. There are several other factors associated with type, structure and function of agroforestry that could affect the carbon sequestration potential. The amount of C sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental (soil type, soil characteristics, rainfall, temperature) and socio-economic factors (Albrecht & Kandji 2003; Tian et al. 2005).

Other factors influencing carbon storage in agroforestry systems include age, tree density, tree species and system management (Albrecht & Kandji 2003; Oelbermann et al. 2004). Silvicultural aspects such as stand density and rotation length also influence biomass production (and the perceived CSP) of species. Oelbermann et al. (2004) and Peichl et al. (2006) noted that system management (i.e. conservation tillage), use of groundcovers, fallowing, and tree species utilized also influence the storage of C in agroforestry. Some studies attributed the quantity of carbon accumulated in an ecosystem to several factors; silvicultural management such as pollarding, thinning and pruning (Albrecht & Kandji 2003; Peichl et al. 2006; Scott et al. 2004; Vogt et al. 1995), climate (Rao et al. 1997), and soil conditions such as texture and clay properties and land-use history (Tian et al. 2005).

Overall storage of carbon in the agroforestry system of any geographic location is largely determined by socio-economic, environmental, bio-physical and silvicultural factors. Since these major factors vary greatly from place to place and thus carbon potential of the system, it is, therefore, difficult to make a general conclusion. Estimating carbon in an agroforestry-based on data from the agroforestry practiced elsewhere would definitely result in either overestimation or underestimation, with very little probability of the estimate being ‘close to precision’. Therefore, location-specific agroforestry needs to be studied for more accurate estimation of its sequestration potential.

In the studies cited above, the potential of different agroforestry systems practiced in different parts of the globe has been assessed based on single agroforestry planting such as improved fallow, live fence, alley cropping, intercropping, etc. Carbon fixed within such a single agroforestry planting appeared to be small compared to global emissions (Soto-Pinto et al. 2010). If study is carried out at farm level as in this study, the amount can become significant. In the present context where enormous opportunities of economic incentives exist for the farmers of developing countries through carbon sale mechanisms such as CDM and REDD+ and other mechanisms such as payments for environmental services (PES), and agriculture, forestry and other land use (AFOLU), the potential of agroforestry should be assessed at farm level rather than component level as previously done.

Another important aspect in relation to carbon is undoubtedly the age of the agroforestry cycle. The age of the cycle is determined by the rotation age of the tree component of the agroforestry system (Jose 2009). The rotation of tree component largely determines the sequestration potential of the system as carbon increases in tree biomass with age (Asante et al. 2011). In the previous studies cited above, this aspect has not been considered. They only focused on existing agroforestry cycles and did not consider the possibility of carbon enhancement through change in duration of the harvest cycle.

There are two major concepts in determining the harvest cycle of a tree. One is economic rotation, i.e. the age when a tree attains the highest net present value (NPV) and the other is sustained yield rotation, i.e. the age when a tree attains a maximum Mean Annual Increment (MAI) (Kula & Gunalay 2012). The sustained yield rotation would definitely not be a preference for farmers because they are more interested in profit maximization rather than yield maximization. However, if farmers are paid for environmental services such as carbon sequestration, the potential of agroforestry in terms of carbon sequestration could be enhanced while the farmers’ objective of profit maximization is met. Future research should focus on enhancing dual goals; profit maximization and carbon maximization.

2.3.2. Agroforestry and soil organic carbon (SOC) sequestration

Soil plays a major role in global C sequestration (Lal 2002). Out of the total stock of C in the soil + plant system, soils store significantly higher proportion of C than the vegetation. The global soil C pool is 2300 Pg, which is 3 times the size of atmospheric C (770 Pg) and 3.8 times the size of biotic pools (610 Pg) (Lal 2001). However, the idea of soil C sequestration did not get adequate recognition due to inadequate understanding of the role of soil in global C cycle and the processes involved (Lal 2002).

The SOC varies with the land-use system (Kula & Gunalay 2012; Soto-Pinto et al. 2010; Thangata & Hildebrand 2012). Depending on land-use type, changes in vegetation change the SOC accumulation. Changes beneficial to SOC are an increase in the rate of organic matter production, placing of organic matter deeper in the soil, and enhancing physical protection and aggregation (Post & Kwon 2000). Tree-based land-use systems have greater potential of SOC sequestration than agronomic crops (Nair et al. 2009). Trees have the potential of producing larger quantities of aboveground and belowground biomass compared to shrubs or herbs. More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma et al. 2007). Inclusion of trees in a treeless system changes some functional mechanisms such as total productivity, rooting depth and distribution, and litter quantity and quality (Jackson et al. 2000; Jobbágy & Jackson 2000).

According to Montagnini and Nair (2004), the tree components of agroforestry systems are potential sinks of atmospheric C due to their fast growth and productivity, high and long-term biomass stock, and extensive root system. By adding trees in the agricultural systems, agroforestry can increase the C storage capacity of the system (Kürsten 2000). Research indicates that by adding trees in grassland or pasture systems the SOC content can be increased considerably (Amézquita et al. 2004; Haile et al. 2008; Reyes-Reyes et al. 2002; Yelenik et al. 2004). Forests are land-use systems with high tree population and play a major role in C sequestration (Lal 2004a).

Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all SOC (Six et al. 2002). When forests are converted to a treeless system they lose SOC. The conversion of forest to agricultural system results in depletion of SOC by 20–50% (Davidson & Ackerman 1993; Post & Mann 1990). Trumbore et al. (1995) reported that, when tropical dry forest in eastern Amazonia was converted to pasture, it lost 13g SOC m^{-2} $year^{-1}$ within the top 10 cm of soil. In another part of eastern Amazonia, when tropical moist forest was converted to pasture it lost 30g SOC m^{-2} $year^{-1}$ within the top 40 cm (Desjardins et al. 1994). Similar results were observed by Veldkamp (1994) in tropical wet forests of Costa Rica, where it lost 90g SOC m^{-2} $year^{-1}$ within the top 50 cm of soil, when replaced with pasture. Opposite results were observed when treeless pastures were converted to forest land. Post and Kwon (2000) observed that when an agricultural field was changed to oak forest in the Great Lakes region of northern USA, the land gained 60g SOC m^{-2} $year^{-1}$ within the top 70 cm of soil. Brown and Lugo (1990) reported that when agricultural fields of Puerto Rico and US Virgin Islands were replaced with secondary forest, after 35 years of this change, SOC increased 80g m^{-2} $year^{-1}$ and 105g m^{-2} $year^{-1}$ within the top 25 cm and 50 cm of soil, respectively. Depending on the species diversity and plant density, considerable difference in SOC can also be observed between two tree-based systems.

In the same study mentioned above, Brown and Lugo (1990) observed that when agricultural fields were replaced with Mahogany (*Swietenia macrophylla*) plantation, after 50 years of this conversion, SOC increased only 40g m^{-2} $year^{-1}$ within the top 25 cm of soil, which was half of the secondary forest. Wauters et al. (2008) found 101t ha^{-1} and 52t SOC ha^{-1} within the top 60 cm of soil in rubber plantations of Brazil and Ghana, respectively. In a study of four year old mixed stands in Puerto Rico, Parrotta (1999) reported different SOC amount in a 0-40 cm depth range resulting from the combination of trees. The mix of eucalyptus with casuarina resulted into highest SOC (61.9t ha^{-1}). In another study of eleven year old agroforest in West Oregon, USA, in a soil depth of 0-45 cm, Sharrow and Ismail (2004) noted the SOC to be 95.89t ha^{-1}. However, in a five year old agrisilviculture (Swamy & Puri 2005) in central India, the SOC was found to be only 27.4t ha^{-1} even in a 0-60 cm soil depth range, much lower than mixed stands in Puerto Rico.

In a five year old alley cropping with *Leucaena* in West Nigeria, Lal (2005) found the SOC to be 13.6t ha^{-1} only in a 0-10 cm depth. However, in a thirteen year old alley cropping of south Canada, the SOC figure was quite low (1.25t ha^{-1}) even though soil depth considered for this study was 0-40 cm. The reason for the lower potential of SOC sequestration might be attributed to the temperate climate of the study area. However, universal conclusion cannot be drawn that SOC potential is higher in tropical region because in a tropical region of Costa Rica, the nineteen year old alley cropping could store only 1.62t ha^{-1}, which is slightly higher than that of alley cropping in Canada. Takimoto et al. (2008) studied three agroforestry systems in West African Sahel and found that the fodder bank was superior to two other systems, i.e. live fence and park land, in terms of SOC. They found that the fodder bank could store 33.4t ha^{-1} in six years while the parkland requires 33 years to store the same amount of SOC. This review clearly indicates that SOC varies with agroforestry types and tree species utilized. Nair et al. (2009) urged that the large differences in SOC values among the land-use systems are a reflection of the biophysical and socio-economic characteristics of the system parameters and methodological artefacts, i.e. soil depth considered.

Overall the impact of any agroforestry system on soil C sequestration depends largely on the amount and quality of input provided by tree and non-tree components such as crop residues of the system and on properties of the soils themselves, such as soil structure and their aggregations. Even though soil organic carbon is important as above- and belowground biomass carbon in climate change mitigation, compared to biomass C, the SOC does not change much, especially in Nepalese farming context, where crops and forests residues are not left to decay but used as fuels and food for cattle. It is assumed that there is not much difference in SOC in different farming systems under study. Therefore, this PhD research did not cover the SOC sequestration potential of the agroforestry-based farming system of Dhanusha district, Nepal.

2.3.3. Agroforestry, Clean development mechanism (CDM) and reducing emission from deforestation and forest degradation (REDD+)

CDM refers to the clean development mechanism, one of the market-based mechanisms designed under the Kyoto protocol (UNFCCC 1998). The CDM has recognised reforestation and afforestation as a climate change mitigation strategy (Maraseni 2007). Under reforestation/afforestation activities of CDM, the annex-I countries would buy carbon credits from non-annex developing countries to compensate the GHG emissions in their own countries following the industrial activities (Takimoto et al. 2010). Broadly, agroforestry can be considered as a kind of afforestation/reforestation. Therefore, agroforestry practice is one of the potential areas that farmers from developing countries could benefit from by participating in a carbon trading mechanism such as CDM (Jose 2009). However, there are certain criteria that should be met to be eligible for CDM projects. The most crucial criterion is the definition of a forest under CDM. According to the CDM of the Kyoto Protocol, a "forest" is an area of more than 0.5–1.0 ha with a minimum "tree" crown cover of 10–30%, with "tree" defined as a plant with the capability of growing to be more than 2–5 m tall (UNFCCC 2002). The other two criteria used in defining a forest, i.e. height and area, are not a problem for any agroforestry to be eligible for CDM projects. However, the range of crown cover as specified in the definition is somewhat of serious concern because individual countries have adopted different definitions of a forest depending on their political and socioeconomic contexts and that they may fall within the range specified by the CDM or beyond, i.e. > 30%. Even if the definition of a forest adopted by individual countries falls within this range, involving smallholder farmers of developing countries in CDM would not be cost-effective because CDM involves a high transaction cost from project design to project completion which small-holder farmers cannot afford (Takimoto et al. 2010).

Similarly, an emissions reduction mechanism such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) policy and Agriculture, Forestry and Other Land Use (AFOLU) under the UNFCCC, has further increased the importance and the role of agroforestry in climate change mitigation (Thangata & Hildebrand 2012). Developing countries can be benefited from REDD+ mechanism because it involves creating mechanisms to make payments to developing countries for reducing emissions from deforestation and forest degradation (Hoang et al. 2013). However, Dhakal (2009) urged that developing countries may not be befitted from REDD programme given the fluctuating price of carbon in the international market.

CDM, which is being implemented in developing countries, targets energy efficiency and renewable energy projects in the energy sector and afforestation and reforestation projects in forestry sector under specific requirements (Costa-Junior et al. 2013). However, deforestation and forest degradation in developing countries, which is a major source of GHG emissions, were not included in the Kyoto mechanisms. This was due to uncertainty regarding forests having permanent carbon storage as they can be cut, burned, logged or degraded, thereby releasing their carbon to the air in the future, and because avoiding deforestation has a high risk of leakage (Fearnside 2001; Moutinho et al. 2005). Therefore, idea of reducing emissions from deforestation in developing countries, also known as RED, was first introduced at the COP-11 to the UNFCCC held in Montreal in 2005 (UNFCCC 2006). The RED become REDD+ at the COP-15 in Copenhagen, Denmark in 2009 (Hoang et al. 2013). REDD+ is primarily about reducing atmospheric carbon dioxide emissions by addressing deforestation and forest degradation and conserving and maintaining forest carbon stocks in developing countries (UNFCCC 2008). However, the goal of REDD+ is not achievable unless there exists a harmony between forest and farm (agriculture) because agricultural expansion is the major driver of deforestation and forest degradation. One plausible option of harmonization would be the intensification of agricultural land, which may stop farmers to encroach forest land for agricultural purposes (Phalan et al. 2011). The other reliable option would be introduction of agroforestry based farming practice, which reduces the pressure on natural forest and supports in forest resource conservation and hence enhances carbon stocks (Jose 2009; Nair et al. 2009; Thangata & Hildebrand 2012) since REDD+ mechanism goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in reducing emissions. Agroforestry contributes to the REDD+ program in many ways. Agroforestry satisfies the three major issues related to carbon dynamics: additionality, permanence, and leakage (Karsenty et al. 2012; Nair et al. 2009; Thangata & Hildebrand 2012).

As urged by Thangata and Hildebrand (2012), putting some of the agricultural land under tree planting by farmers would definitely address the issue of additionality. Agricultural soils usually have less soil organic matter and therefore less below ground carbon (BGC) than natural ecosystems (Nair et al. 2009). Study has shown the agroforestry option has more BGC, which is important in the permanence principle. Thangata and Hildebrand (2012) concluded that with the adoption of agroforestry, a semi-forest system, BGC increases, thereby increasing soil C. The third issue that agroforestry can address is the issue of leakage because of project based approach of reducing deforestation and forest degradation because the project based approach does not address the drivers of deforestation but only erect fences around forests, which inevitably lead to the displacement of pressure for deforestation elsewhere (Karsenty et al. 2012). Adoption of agroforestry would definitely stop farmers from creating pressure on non-project forests (Thangata & Hildebrand 2012).

2.3.4. Agroforestry and GHG emissions

Up to this point, the potential of agroforestry systems in carbon sequestration in biomass and in the soils was reviewed and also the factors responsible for causing variation in sequestration potential were discussed. In the following section, the other side of the coin i.e. GHG emissions from agroforestry system is discussed. Agroforestry is not just about trees but is an integrated land-use that combines agricultural crops with perennial tree crop and livestock. Agricultural activities such as paddy cultivation, use of chemical fertiliser and fossil fuels for harvesting and post harvesting and livestock, are associated with GHG emissions (Bhatia et al. 2004; Chadwick 2005).

Even though carbon fluxes in agroforestry systems are well documented, this is not the case for other trace GHGs such as nitrous oxide (N_2O) and methane (CH_4). Legumes play a prominent role in agroforestry and are effective in improving the nutrient status of nitrogen-depleted soils. Recent studies have shown that nitrogen (N) inputs derived from agroforestry practices such as improved fallow (IF) can exceed the agronomic requirements of subsequent crops. This may result in volatilisation of excess N in the form of N_2O (Choudhary et al. 2002; Palm et al. 2002). N_2O is one of the most important trace gases and has a global warming potential (GWP) 298 times higher than that of CO_2. Thus, there is growing concern that the wide-scale use of woody legumes might result in significant amounts of N_2O emissions in the atmosphere.

Similarly, ungulate production and cultivation of rice paddies in agroforestry systems can produce significant quantities of CH_4 on a global scale (Dixon 1995). More research is therefore needed to clearly understand the implications of agroforestry, vis-à-vis the emission of trace gases. The actual carbon balance of any agroforestry system can be assessed without estimating emissions from the system. Therefore future research is required to gain an adequate understanding on emission of other GHGs, especially N_2O and CH_4, in agroforestry systems and more powerful methods to implement cost/benefit analyses of agroforestry-based GHG mitigation and to define incentives for wide scale adoption of agroforestry systems (Albrecht & Kandji 2003).

In the following section a review on sources and factors responsible for emissions of N_2O and CH_4 from the agroforestry system is discussed based on the studies from agriculture because agroforestry is a part of agriculture.

Farm inputs and GHG emissions

Most agricultural activities (e.g. machine operations, fertilization, tillage and pest control) have a range of environmental impacts, including decreases in soil and water quality through excessive application of fertilizers and biocides, as well as the production of GHGs, mainly CO_2, N_2O and CH_4 (Koga et al. 2006). Intensive tillage operations lead to a depletion of soil C pools, resulting in turn in large CO_2 emissions from the soil to the atmosphere (Lal 1997; Lal & Kimble 1997; Paustian et al. 1997). Overall, agricultural activities contribute a large percentage of GHG emissions: about 90% of N_2O, 70% of CH_4 and 20% of CO_2 (Bouwman 1990).

Application of synthetic fertilisers, livestock manure and planting of nitrogen fixing crops has been the constant sources of N_2O and CH_4 emissions (Bouwman et al. 2002; Bouwman 1996; Stehfest & Bouwman 2006). About 1.25% of nitrogen applied in the field is lost in the form of N_2O during de-nitrification (IPCC 2006). N_2O is directly and indirectly emitted through nitrification and de-nitrification processes as a result of N fertilizer application (Bouwman 1996; Sawamoto et al. 2005). Improving soil N nutrition through fertilization of crops increases N_2O emissions from soils and sometimes decreases the soil CH_4 sink (Castro et al. 1994; Hütsch 1996). High input of N and soil compaction can result in the reduction of sink strength of soils for CH_4 and even conversion of soils from a sink for atmospheric CH_4 into a source (Palm et al. 2002).

The production and use of synthetic fertiliser (Nitrogen, Phosphorus and Potash) has increased globally. In case of synthetic fertiliser, it contributes to GHG emissions during its production, packaging, storage and distribution (Maraseni & Cockfield 2011a) because fossil fuels are used for these activities and fossil fuels are the major source of human-induced emissions (Koga et al. 2003). In case of N-fertilizer, N_2O is resealed from the soil.

Similarly, the trend of pesticides use (insecticides, herbicides and fungicides) has skyrocketed in some developing countries. Maraseni and Cockfield (2011a) reported that one kilogram of insecticide, herbicide and fungicide could generate 18.7kg CO_2, 23.1kg CO_2 and 14.3kg CO_2, respectively. In arable land farming systems, the emission of GHG that affects global warming occurs through fossil fuel consumption. Under mechanized cropping systems, on-farm CO_2 emissions are derived from fuel-consuming operations such as tractor operations, transportation by truck and grain harvest by threshers (Koga et al. 2003; Maraseni & Cockfield 2011a; Parashar et al. 1991).

Irrigation is as important as fertilizers in achieving high yields. On a global scale, 17% of irrigated cropland leads to 40% of the total production (Postel 2000). Yet irrigation is a very C-intensive practice (Lal 2004b). The emission from irrigation is largely determined by the amount of energy required to pump one unit of water. The energy required depends on numerous factors including total dynamic head (based on water lift, pipe friction and system pressure), the water flow rate and the pumping system efficiency (Lal 2004b). Dvoskin et al. (1976) assessed fuel consumption for lifting irrigation water in several regions of the western US. The C emission ranged from 7.2 to 425.1kg C ha^{-1} for 25 cm of irrigation and from 53.0 to 850.2kg C ha^{-1} for 50 cm of irrigation.

Paddy cultivation and GHG emissions

Rice is the most important staple food crop in most Asian countries. About 91% of the total global production of rice is produced in Asia (FAO 2009a). Despite the rice crop being the main source of livelihoods, the rice paddy has been a source of environmental degradation because it emits a significant amount of CH_4 into the atmosphere (Guo & Zhou 2007). CH_4 emissions from the rice paddy are dependent on soil characteristics and land and crop management such as cropping pattern, rice varieties, mode of irrigation and fertilizer application (Amstel & Swart 1994; Guo & Zhou 2007).

CH_4 emissions from the paddy field are influenced by fertilizer type, rate of application and application technique. For example, Schutz (1989) reported lower CH_4 emissions with ammonium sulphate. The same result was observed with urea, but for this type of fertilizer, the application technique was also important, i.e. emissions decreased when urea was incorporated at depth, while they increased following surface application. Overall, substituting ammonium sulphate for urea as N fertilizer resulted in a 25–36% reduction in CH_4 emissions. Phosphogypsum applied in combination with urea reduced CH_4 emissions by 72%. Following application of rice straw compost, CH_4 emissions increased by 23–30% and by 162–250% after application of fresh rice straw (Corton et al. 2001). CH_4 emissions vary significantly with rice varieties because of their specific physiological characteristics and also differ between plant growth stages. Approximately 78% of emissions occur at the reproduction stage and about 90% of CH_4 emissions from rice paddies are released by the rice plant (Seiler et al. 1983).

Rice paddy water management considerably affects CH_4 emissions. Intermittent irrigation reduced CH_4 emissions by 15% with respect to permanent flooding during the dry season (Adhya et al. 2000). Mid-season drainage reduced CH_4 emissions by 43% because the flux of oxygen into the soil created aerobic conditions, unfavourable to methanogenic bacterial activity (Corton et al. 2001), however, N_2O emissions are increased (Guo & Zhou 2007).

Livestock and GHG emissions

Livestock is the integral part of the subsistence farming in most developing countries including Nepal. Livestock has been the source of food (protein), and income globally. The global livestock population has increased over time following the increased demand of meat and milk. Livestock, particularly the ruminant animals, are responsible for emitting CH_4 and N_2O from agriculture (Guo & Zhou 2007). CH_4 is released during enteric fermentation, storage and after application of livestock manure in the agricultural fields. N_2O is released during manure handling from storage to application through the process of nitrification and de-nitrification.

Non-ruminant domesticated animals also produce methane through enteric fermentation; in this case, the process takes place in the large intestine and the amount produced is much lower. Schils et al. (2005) reported that the CH_4 emissions by ruminants account for some 84% of total emissions by livestock. Globally, it is estimated that livestock and their waste contributes about 80Gt CH_4 year^{-1} to the atmosphere, that is about 16% of the total global atmospheric CH_4 emissions (Guo & Zhou 2007). In addition to the type of digestive system, the animal's feed intake also affects methane emissions (Guo & Zhou 2007). A higher feed intake generally leads to higher methane emissions. Feed intake is related to animal size and weight, growth stage and rate, and production.

2.4. Agroforestry economics

2.4.1. Agroforestry and farm productivity

Farm productivity is of prime importance as it is associated with farmers' livelihoods globally. It is generally measured either as yields per land unit or gross output value per land unit, which does not consider the input value (cost) associated with the farm production. However, this farm productivity, although a partial productivity, is found widely used in the literature (Bardhan 1973; Bhalla 1988; Bhalla & Roy 1988; Chayanov 1966; Newell et al. 1997; Sampath 1992; Sen 1966). Use of this partial productivity is misleading because it does not take into account the profit of farm enterprise. Even a higher productivity has a lower profitability. Therefore, the output to input ratio offered by Norsworthy and Jang (1992) proposed a more representative method called total factor productivity (TFP), which is more an economic ratio rather than just a physical ratio and could reflect more precisely the farm productivity. However, the partial productivity was found much used in the literature.

The overall farm productivity depends on farm size, farm type, labor, capital, land quality, use of farm inputs and technology (Bhalla 1988; Bhalla & Roy 1988; Chand et al. 2011). However, the relationship between farm size and farm productivity per unit land was found to be inverse, i.e. the bigger the farm size, the lower the farm productivity, a negative relationship (NR). This relationship is much debated and discussed in the literature. After Sen (1962), several researchers have re-examined the validity of this negative relationship in developing countries and the results are mixed. A large number of studies during the 1960s and 1970s provided convincing evidence that crop productivity per unit of land declined with increase in farm size (Bardhan 1973; Berry 1972; Mazumdar 1965; Rao 1966; Saini 1971; Sen 1964) which provided strong support for land reforms, land ceiling and various other policies to support smallholders on the grounds of efficiency and growth. Subsequently, various analysts started exploring reasons or factors for higher productivity of smallholders (Berry & Cline 1979; Binswanger & Rosenzweig 1986; Dong & Dow 1993; Frisvold 1994; Jha et al. 2000) and some of them even questioned the negative relationship between farm size and productivity.

Bhalla and Roy (1988) observed that the negative relationship between farm size and productivity weakened and disappeared when soil quality was included in their study. Chadha (1978) analysing farm level data for three agro-climatic regions in Punjab for 1969-70, reported that the negative relationship had ceased to hold in more dynamic zones. Ghose (1979) argued that an essential precondition for the existence of the negative relationship phenomenon is technical backwardness implying that with advances in technology the negative relationship will vanish. Similar to this, Deolalikar (1981) observed that the inverse size-productivity relationship cannot be rejected at low levels of agricultural technology in India, but can be rejected at higher levels. Rudra (1968) concluded that there is no scope for propounding a general law regarding farm size and productivity relationship. One recent study by Bhandari (2006) in Nepal's *terai* showed a positive relationship between farm size and productivity, rejecting the argument that in Nepal, small farms appear to be more efficient and productive than large farms. Therefore, the NR once considered as 'stylized fact' is not 100% stylized fact. Similar results were found from the studies carried out both in developed and developing countries (Bhalla 1988; Hooper et al. 2002; Knopke et al. 1995).

All studies cited above reveals a mixed result with regards to NR between farm size and productivity. Studies that supported the negative relationship explained that small farms are more fertile and get access to better irrigation and high labour availability, which ultimately results in higher productivity on small farms. Those that disagree with the negative relationship explained that if factors such as irrigation and land quality are controlled, the relationship disappears and large farms appear to be more productive than small one. However, most of the studies above used aggregated data at national and regional level, where the chance of controlling the factors affecting productivity is very low. Also these studies are based on major cereal crops, i.e. rice and wheat, but farmers in most developing countries including south Asian countries grow multiple crops.

In Nepal's *terai* where this PhD study was carried out, farmers not only grow rice and wheat but also vegetable, sugarcane, horticultural crops and tree crops in considerable amounts. Therefore an integrated productivity data at farm level is required to assess the relationship between farm size and productivity. Further, the technology such as farm machineries such as tractor, and thresher also influence the farm profitability as these tools reduce the labour cost (Chand et al. 2011). Agroforestry is an emerging land management technology in the study area. Inclusion of such technology might have affected the productivity relationship.

2.4.2. Agroforestry and profitability

As discussed earlier, a range of factors including social, biophysical, demographic and institutional, and policy factors influences adoption of any agroforestry intervention. However, consideration of these factors only would not guarantee the adoption because studies have shown that farmers are more concerned with profitability of such intervention over the existing practices, and discard the less profitable one (Cockfield 2005; Franzel et al. 2001; Sinden & King 2009). It would not be fair, however, to conclude that the profitable enterprises have higher adoption rate because several agroforestry technologies that appeared profitable at plot level (experimental plots) have lower adoption rate at farm level and in some cases farmers have discontinued them (Adesina & Chianu 2002). Therefore, even a profitable practice needs to be tested at farm level and adoptability of such practice needs to be judged taking into consideration all the above-mentioned factors. An integrated study that considers both profitability issue and other issues (social, biophysical, demographic and institutional, and policy) could guarantee a higher adoption rate than any other studies that consider either profitability or other issues.

There is a wealth of literature related to economics of agroforestry, particularly focusing on profitability (Current & Scherr 1995). Theoretically it is believed that agroforestry is more profitable than any other land uses: plantations and cultivation (Benjamin et al. 2000; Nair 1997), however, empirical studies have shown that this is not the case. Current et al. (1995) found that even though the majority of agroforestry intervention in the Central America and the Caribbean region were more profitable, there were few agroforestry practices that appeared to be less profitable than cultivation. In another study carried out in the Philippines, maize mono cropping was found to be generating higher NPV than maize-tree system (Bertomeu 2006). Similar results were found in Eastern Zambia in a comparative study of improved fallow vs maize mono-cropping (fertilized) (Franzel 2005). The profitability of any tree-based farming system mainly depends on the growth (productivity) of the tree component, ecological interaction of the tree component with the field crops, and the monetary value of the tree in the local market (Bertomeu 2006).

Some other studies have favoured agroforestry over other competitive land uses. Benjamin et al. (2000) found that agroforestry was superior in terms of return to land as compared to forestry and traditional agriculture in mid-western America. Similar result was found by Franzel (2005) in a study of woodlots versus maize mono-cropping carried out in Tanzania. In another study in Costa Rica by Mehta and Leuschner (1997), the net return of land was found to be higher in coffee with trees than in coffee only. Ramírez et al. (2001) also found agroforestry to be financially more attractive than monoculture plantations in Central America.

Various studies in Nepal showed that agroforestry could increase the sustainability of the Nepalese farming system (Amatya & Newman 1993; Garforth et al. 1999; Neupane & Thapa 2001). However, all these studies, except that of Neupane and Thapa (2001), are focused on the soil fertility management and erosion control under the subsistence-based Nepalese farming system rather than the costs and benefits of the technology to farmers. The fact is that Nepalese farmers are not interested in adopting any agriculture technology where the sole objective is to control erosion or improve soil fertility, unless that provides income to households (Acharya et al. 2008). One of the important considerations, therefore, is that the introduced technology/practice should give better financial return to farmers to make the technology/practice adoptable among farmers, as discussed earlier. Research in shifting cultivation areas of Bangladesh found that agroforestry provided a better alternative both ecologically and economically to shifting cultivation (Rahman et al. 2007; Rasul & Thapa 2006). Studies by others (Adesina et al. 2000; Brady 1996;

Brown 2006; Fischer & Vasseur 2000) also documented the promise of agroforestry as an alternative to slash-and-burn agriculture in different parts of the world.

Based on the studies reviewed above, three major conclusions can be drawn. Firstly, agroforestry is not always a profitable intervention. Several factors including soil fertility and tree related factors, such as productivity potential of the tree chosen, ecological interaction of the tree with field crops and market value of the tree are more crucial to determining the profitability of any agroforestry intervention compared to forestry and cultivation. Secondly, the social benefits, such as greenery, soil erosion control, biodiversity conservation, and GHG mitigation that agroforestry intervention can provide to society are completely ignored in these studies; only tangible benefits are considered while performing economic significance of agroforestry systems.

The third conclusion is related to the methodology used to measure the financial viability of farming systems. All studies cited above have used net present value (NPV) as common financial criterion to evaluate different farming systems. Some studies (Betters 1988; Duguma 2013; Keca et al. 2012; Rasul & Thapa 2006) have used internal rate of return (IRR), benefit-cost ratio (BCR) and equivalent annualized income (EAI) as financial indicators in addition to NPV. Very few studies (Franzel 2005; Rasul & Thapa 2006) applied ‘return-to-labour’ as an indicator of financial attractiveness of the system. Out of these five indicators found in agroforestry literature, two criteria, i.e. NPV (return-to-land) and return-to-labour are of prime importance because these two are the scarce resources. For the study area being constrained by these two major factors of production, i.e. land and labour, this study used NPV and ‘return-to-labour’ as major financial indicators while assessing the viability of agroforestry-based farming system in Nepalese context.

2.5. Conclusions

This review documents the existing body of knowledge and gaps in adoption, carbon dynamics and economics in the field of agroforestry. The review clearly indicates that adoption of any land management technology is location-dependent and there exists a methodological gap in defining adoption and identifying the factors affecting adoption. In the case of carbon dynamics in agroforestry, the review documents a plethora of studies from both tropical and temperate latitudes and reveals a clear research gap in that it is lacking study towards improving the agroforestry practice so that both economic and environmental (carbon sequestration, reductions of GHG emissions) goals can be achieved. In case of GHG emissions, the agroforestry literature is completely silent, more emphasis is on tree component rather than emission-causing farm activities within the agroforestry systems. Regarding economics of agroforestry, the productivity related literature has been extensively reviewed. The review reveals that the issue of negative relationship has not been addressed properly.

In terms of financial performance of agroforestry over other competitive land uses mainly plantations and agriculture, the results are mixed. It cannot be concluded that agroforestry interventions are always financially attractive. Empirical studies showed that in many cases agroforestry appeared less attractive. Further, the environmental benefit of agroforestry has not been properly addressed while evaluating agroforestry systems. Therefore, the agroforestry-based farming systems are required to re-evaluate to see its potentiality in terms of traditional tangible benefits and environmental benefits i.e. carbon sequestration. The review showed that there was no such research carried out where agroforestry was judged from both benefits. A more comprehensive study is deemed necessary to address the abovementioned gaps and therefore this research was conducted. Considering the identified research issues and specified objectives, the next chapter develops a detailed methodology of the study.

Chapter 3

Research Design and Methods

3.1. Introduction

In the chapter one, the research problems have been identified. In this chapter, the methods used to address those problems are discussed. The research, in particular, attempts to answer three major questions: 1) How and what motivated the farmers towards adopting an integrated farming system such as the agroforestry-based farming system at landscape level; 2) What factors significantly explain the variation in adoption of such integrated farming systems at household level; and 3) Which farming system could be more climate-smart and financially more attractive in terms of NPV, B-C ratio and return-to-labour in the long run in the context of climate change. The research is comprehensive in nature because it has covered all variable costs and benefits and different sources and sinks of three major greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The data for the study were collected during a field study from May to August 2010. The study was conducted in the Dhanusha district of Nepal. In order to address the study objectives precisely, both the qualitative and quantitative research techniques were applied to collect the required data. A number of questions, such as how the traditional farming system evolved into the integrated farming system such as agroforestry, what drivers played crucial roles behind this evolution, what tree species farmers preferred to grow on their farms and how the agroforestry evolved this way varied from one farm household to another in terms of integration were answered through the focus group discussion. It was crucial to address these questions because the prime objective of this study was to assess the carbon dynamics of different agroforestry systems that farmers have practiced by growing the trees they preferred.

Quantitative research techniques involved household survey and tree measurements. The household survey was done to mainly collect data related to demography, farm production (trees, field crops, livestock and horticultural crops), farm size, livestock and land ownership, and tree growing pattern. Also the data related to costs associated with production were collected from household survey. The tree measurements involved measuring diameter and height of the preferred trees to estimate the biomass. The procedures of household survey and tree measurements are discussed in detail in the following section.

3.2. Study district and descriptions

This study was conducted in the southern foothills of the Churia Hills, Dhanusha (350 -27.50 N and 85.50 – 86.20 E) Nepal during May through August 2010. The Dhanusha District is located in the central development region of Nepal and 350 km southeast of the capital city, Kathmandu. It shares a border with India in the south. Elevation is approximately 95 m (above sea level). The climate is sub-tropical with three distinct seasons; spring, monsoon and winter. Mean monthly minimum/maximum temperature is 9.3/21.40 C in January and 26.7/39.60 C in April. The average annual rainfall is 2199 mm (DDC 2009). Hence, crops and trees can have relatively high growth rates where the soils are sufficiently fertile. It covers an area of 119,000 ha, out of which 76,792 ha of land is under agriculture. The district is administratively divided into one municipality and 101 village development committees (VDCs) (DDC 2009).

Dhanusha was selected as a study district because the farmers have been involved with private forestry (tree growing on private land). It has the highest numbers of registered (with the district forest office) private forests of any region. Within that district, the project area of the Terai Private Forest Development Association (TPFDA) was selected as a study site. The project covers an area of 10,500 ha of nine village development committees (VDCs) namely Bengadawar, Dhalkebar, Pushpalpur, Bharatpur, Yagyabhumi, Hariharpur, Naktajhijh, Sakhuwa Mahendranagar, and Laxminiwas (Figure 3.1). The TPFDA with support of Nepal Agroforestry Foundation (NAF) has been promoting the agroforestry-based farming system in these VDCs since 1998. The TPFDA area was selected because this is the only NGO in the district working in the field of integrated land-use management such as agroforestry. The study site is near the east-west highway, providing access to major centres and therefore markets, with five VDCs on the both sides (north and south) of the highway and the rest located south of the highway, on a feeder road.

3.3. Study methods

The study method has two parts. The first part describes the detailed procedure and methods adopted to document the development of farming systems and assess the drivers of development (evolution) at landscape level and also factors affecting adoption of agroforestry-based farming systems at farm level (sub-heading 3.3.1). The second part describes the methodology adopted to collect the data required for bio-economic evaluation of the farming systems in the study area (sub-heading 3.3.2).

3.3.1. Study methods - part I

3.3.1.1.Focus group discussion with agroforestry farmers

In order to better understand the farming history (the evolving process) and land management practices, one focus group discussion (FGD) was conducted with agroforestry farmers. The FGD is a widely used tool in agricultural research (Nkamleu & Manyong 2005; Raut et al. 2011). A set of focus-group discussion topics was developed prior to conducting the focus groups (Table 3.1). Forty-five farmers above forty-five years of age, both male and female, with substantial experience in agriculture and agroforestry (five participants from each VDC) were selected. Following the suggestion received during informal discussions with some elderly people in the study area, people under forty-five years of age were excluded from the focus groups. The age ranged from 45 to 75. The session lasted about two hours, with twenty minutes spent on each topic.

Written comments were accepted from farmers who felt more comfortable expressing their opinions that way. Following the meetings, the notes of discussion were consolidated, creating a consensus description of the focus group results. The focus group identified five major components and fifteen sub-components of the farming system in the study area (Table 3.4). The purpose of this was to assess the level of agroforestry adoption at farm level. This was particularly important to develop the index value as a proxy of adoption level.

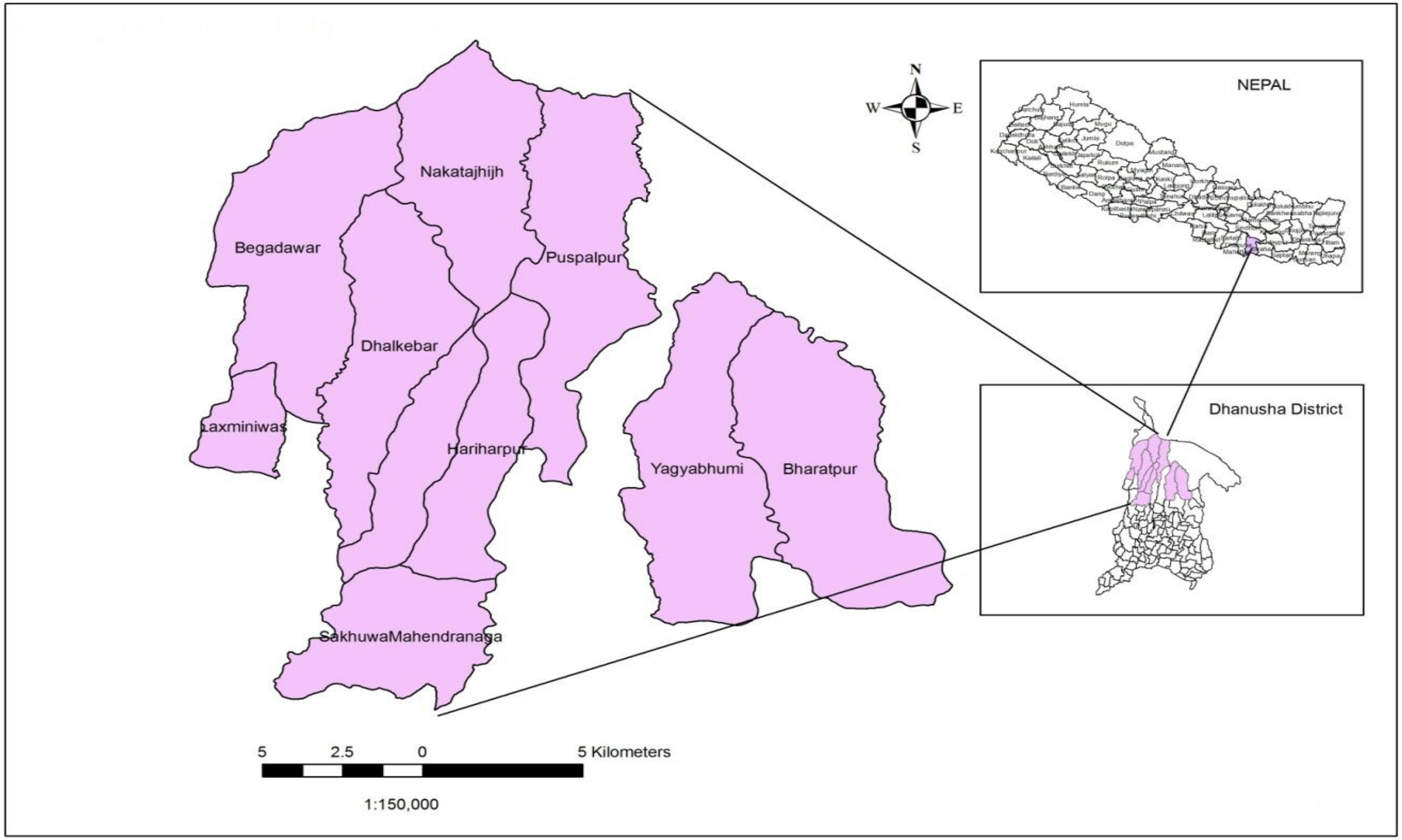

Figure 3.1: Showing study VDCs of Dhanusha District, Nepal

Table 3.1: Topics for focus group discussion

1. Can you divide the total years of farming (from 1950 to 2010 - 60 years) into different farming periods? Please note there should be some visible change in farming between the periods.
2. Document the farming history in terms of crop composition and crop diversification and other agricultural activities in different time periods.
3. What might be the drivers of change in different time periods?
4. What are the components (livestock, trees, vegetable, etc) that you have integrated into your farming system?
5. What are the crops (field-crops, tree crops, fruit crops, cash crops, vegetables) that you produce at present? List the names of the crops produced.
6. How diversified is each component? (number of field crops/year, number of livestock by type, distribution of tree on the farm etc.)

In case of preference ranking for fodder and timber, a set of discussion topics was developed prior to conducting this discussion also (Table 3.2). The group identified five and six characteristics for the tree species to be a good source of timber and fodder, respectively. The participants were asked to rank the tree species. Ranks from 1 (excellent performance) to 5 (poor performance) against each characteristics/ criteria for each timber and fodder species for selecting top five preferred species. In case of the tree species with equal preference score, the focus group was asked to make a rational comparison between the tied species and rank them accordingly.

Table 3.2: Topics for discussion for preference ranking

1. What are the plant species found in your area (including shrubs and fruit tree species)?
2. Which plant species are used as fodder?
3. Which species are used as timber?
4. What should be the characteristics to be a good fodder?
5. What should be the characteristics to be a good timber?
6. Why farmers prefer one particular plant species most for fodder and timber?

3.3.1.2.Expert level discussion

In order to develop a scale to categorise the existing farming systems based on the components that farmers have integrated into the system, one meeting was organised with the experts. A group of ten government and non-government experts, holding at least master degrees in a relevant discipline, being involved with development organizations and working in the relevant fields of forestry, agriculture, and livestock, participated in the discussion. A set of discussion topics was developed prior to the meeting (Table 3.3).

Table 3.3: Topics for discussion at the expert's meeting

1. How do you evaluate the system components? (Please give a score for each component out of 1.00 based on the economic importance of the components on farmers' livelihood.)
2. What score will you give for each sub-component of the system components and why?
3. How do you categorise the farming systems based on the scale (0.00 to1.00)?

The expert group judged the system components to have equivalent economic importance and hence an equal value (0.2) was assigned to each component with the sum of values of the five components equal to one. Based on the extent of sub-components in terms of diversification (in case of livestock, agricultural crops and vegetable) and distribution (in case of forest tree crops and fruit crops), a certain score was assigned to each sub-component out of the maximum value, i.e. 0.2. Fully convinced that the diversification/distribution is positively related to the integration, the experts assigned value to each sub-component accordingly (Table 3.4). There are three sub-components of agricultural crops based on the Crop diversity index (CDI). CDI refers to the number of field crops per year. Based on group consensus CDIs of more than 6, from 4 to 6 inclusive and ≤3 was assigned the values of 0.20, 0.15 and 0.10, respectively. Similarly, Livestock diversity index (LDI) was used to assess livestock diversification.

Table 3.4: Components and sub-components of the agroforestry system in the study area of Dhanusha District, Nepal

System components	Sub-components	Value assigned
Agricultural crops (0.20)	*Crop diversity index (CDI) = ≤ 3*	0.10
	Crop diversity index (CDI)= 4 to 6	0.15
	Crop diversity index (CDI) = > 6	0.20
Livestock (0.20)	*Livestock diversity index (LDI)= 0*	0.00
	Livestock diversity index (LDI)=1 ≤ 2	0.10
	Livestock diversity index (LDI)= 2- 4	0.15
	Livestock diversity index (LDI)= > 4	0.20
Forest tree crops (0.20)	*Trees raised around homestead*	0.05
	Boundary plantation	0.05
	Alley cropping (bund plantation)	0.05
	Agroforests	0.05
Fruit crops (0.20)	*Home garden (Fruit trees only)*	0.10
	Home garden with cash crops intercropped	0.20
Vegetable (0.20)	*Subsistence scale*	0.10
	Commercial scale	0.20

The LDI refers to number of livestock species. Four possible LDIs were identified; 0, ≤ 2, ≤ 4 and > 4 with the weightings 0.0, 0.10, 0.15 and 0.20, respectively.

The forest tree crops were divided into four sub-components based on their distribution patterns on the farm. According to agroforestry farmers, they prefer to plant a particular plant species for the particular niche. For example, they raise *Artocarpus lakoocha*, which is bigger than other fodder species, around the homestead while small sized tree species such as *Leucaena leucocephala* are preferred for alley cropping. Large sized tree species such as *Anthocephalus chinensis*, *Gmelina arborea* are more suitable for boundary plantations while

Eucalyptus camaldulensis is preferred most for block plantations. This sort of distribution pattern is positively related to diversification and level of integration. Therefore, a value of 0.05 was given to each sub-component.

The fourth component "fruit tree crops" has two sub-components of fruit tree crops only, and fruit tree crops intercropped with cash crops with the values of 0.10 and 0.20, respectively. Likewise, for the component 'vegetable crops', two sub-categories were identified; subsistence and commercial and the values of 0.10 and 0.20 were allocated respectively (Table 3.4). The agroforestry farmers perceive that the commercial vegetable farming is more diversified than the subsistence one because they tend to select a variety of vegetables based on market demand while very few selected vegetables are grown in the case of subsistence vegetable farming only for household consumption.

Once the values were assigned, a scale ranging from 0.00 to 1.00 was developed to categorize the farming systems as; 0.0-0.25 (simple agriculture), 0.25 -0.50 (less integrated), 0.50-0.75 (medium integrated) and above 0.75 (highly integrated) (Figure 3.2). The scale was adopted from Ajayi and Kwesiga (2003).

No integration										High integration
0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

Figure 3.2: Scale used to categorise the farming systems in the study area

3.3.1.3.Household survey

A structured questionnaire was used for a household survey (Appendix A). The household survey was conducted to mainly collect data related to the farm and household including family size, labour force, farm size, plantation area, use of farm inputs, source of energy, sources of GHG emissions and tree density. More importantly data related to livestock diversity, Field crops diversification (FCD), Cropping intensity (CI), mixed cropping (MC), distribution of forest trees and extent of vegetable farming were collected through this household survey. The FCD, CI and MC were calculated following the formula given below. Costs and benefits associated with each field crops were collected through questionnaire surveys. Out of 2000 households associated with the TPFDA, a sample of 200 households was randomly selected using a random table. The household heads were the respondents for this study. Out of 200, 12.5% were female respondents. Pre-testing of the questionnaire for the household survey was done through a pilot survey in a village in the study area through face-to-face interview with the heads of the selected households. A few modifications were made following the pre-testing. The data were collected on pre-structured questionnaires through face-to-face interview with the household heads.

$$FCD = (p_1 + p_2 + p_3 + \ldots\ldots + p_n)/\mathrm{N_c} \ldots\ldots \;(3.1)$$

[Adopted from Rasul and Thapa (2004)]

Where,
FCD = index of field crop diversification; P_1 = proportion of sown area under crop 1;

P_2 = proportion of sown area under crop 2; P_3 = proportion of sown area under crop 3; P_n = proportion of sown area under crop n; and N_c = number of crops.

$$CI = \sum (a_1 + a_2 + a_3 + ...a_n) / A \times 100 .... (3.2)$$

Where,

CI = index of crop intensity; a_1 = sown area under crop 1; a_2 = sown area under crop 2; a_3 = sown area under crop 3 and A = total farm area

$$MC = a_{mc} / A ...... (3.3)$$

Where, MC = index of mixed cropping; a_{mc} = area under mixed cropping and A= total farm area

3.3.2. Study Methods - part II

3.3.2.1. Estimating carbon sequestration of agroforestry-based farming system

(A) Tree measurement

Before field measurement was commenced, the rotation age of these five timber species based on farmers' practice were documented through the focus group discussion (FGD). Since it was not feasible and practical to measure trees of each age class, some representative age classes at a certain interval, including the rotation age that famers have currently adopted to harvest their tree products, were chosen for each species (Appendix B, Table B.1). The starting age for the measurement was guided by whether the tree was high enough to measure diameter at breast height. Interpolation of the data was done wherever required based on the known points (Maraseni 2007).

Permanent plot vs chronosequence

Establishment of permanent plot is a very widely used method to study the vegetation dynamics such as plant abundances and growth pattern, species composition, species associations, and plant–plant replacements over time (Myster 1993; Pickett 1982). However, the establishment and long term monitoring of permanent plots is not feasible since there may be no replicate plots of the same age available, no possibility to set up plots at the right time, and no financial or institutional support to sample plots for years on a regular basis (Myster & Malahy 2008). In such cases, many have turned to the use of chronosequence as an alternative, which substitutes space for time (Desjardins et al. 2004; DeWalt et al. 2003; Gehring et al. 2005; Howorth & Pendry 2006; Leon et al. 2003; Muñiz-Castro et al. 2006; Picket 1989; Van Kanten et al. 2005; Vieira et al. 2003; Wick et al. 2005). Since the permanent plots are not available in the study area, the chronosequence stands of selected agroforestry tree species were used to collect the data. Since the tree stands are located at the same altitude, on the same bedrock and with similar topography and climate (Cole & Van Miegroet 1989; Klinger & Short

1996; Thuille & Schulze 2006), the authors assume that the selected stands may have a minimum variability in stand characteristics.

Growth predicting variables

Diameter at breast height (DBH), tree height (H), wood density (D) and basal area (BA) are the predicting variables that are used to derive the allometric equation, which is used to estimate the biomass of the standing trees. The three predicting variables *viz.* DBH, H and D were required to be measured in the field excluding the basal area to predict the biomass of the selected tree species according to the growth equations chosen for this study. A diameter tape was used to measure DBH in centimetres. For height measurement, the trees were assumed to be truly vertical and the study area being levelled; only the top angle was measured with the help of clinometers. Height was calculated by using the simple height and distance formula as follows; tan θ = P/B (θ = Top angle, P = Perpendicular (height) and B = Base). This gives the height of a tree above eye-height of the observer. Therefore, eye-height of 1.5 meters was added to the height calculated by the above formula to get the actual height of the tree. Height was calculated in meters. The tree-specific wood density was taken from the literature.

Tree sampling

For each tree species, DBH of twenty-one individual trees for each age class in the Annex-B, Table B.1 was measured. For *Dalbergia sissoo*, ten stands of different age class (from age 4 to age 30) were selected while for *Gmelina arborea* (from age 4 to age 21) nine stands were selected. Similarly for *E. camaldulensis* (from age 4 to age 20) seven stands, and for *Anthocephalus chinensis* (from age 3 to age 16) and *Melia azedarach* (from age 3 to age 17) eight stands each were selected. In each stand, three trees having three different height categories (small, medium and high) were purposely selected. To avoid bias while selecting representative trees for each height category, farmers were asked to select the trees because the author assumed that farmers were very aware of the quality of tree growth on their farm and could judge unbiased as small, medium and high. Crown cover of each sampled tree was also measured. Two measurements of the crown were taken; longest width and shortest width of the crown, and later the average of the two measurements was considered to calculate the crown coverage (Appendix B, Table B.2).

(B) Estimating biomass of agroforestry tree species

Above- ground biomass (AGB) estimation

A plethora of allometric equations has been developed to estimate/predict the biomass of standing trees (Alamgir & Al-Amin 2008; Brown & Lugo 1992; Crow & Schlaegel 1988; Gary W 1996; Luckman et al. 1997; Negi et al. 1988; Pastor et al. 1984; Payandeh 1981; Wang 2006). These prediction equations would obviate to a great extent the necessity of destructive sampling. The destructive sampling, on the one hand, is reliable, provided the samples are representatives of the stand, but on the other hand, it is impractical, time consuming and expensive due to its destructive nature, large dimensions and amount of biomass that is usually processed (Tyagi et al. 2009; Verwijst & Telenius 1999). Consequently, allometric equations are found very widely used in the literature to predict the biomass of standing trees (Roshetko et al. 2002; Takimoto et al. 2008). Therefore, for this study also, instead of destructive sampling, the allometric equations have been used to estimate the biomass of the selected agroforestry tree species and fruit tree species that farmers have planted on their farms for commercial as well as subsistence purposes. However, using these equations is not free of risk since it involves a certain level of error and hence the predicated values are more likely to be either over- or underestimated. It is further sensitive when carbon is to be estimated in standing trees and therefore it is very important to select the right biomass equations to avoid the likelihood of estimation errors due to the use of improper models.

Two types of models are available; general and specific. General models are developed from the data of several tree species. Ogawa et al.(1965) developed a single biomass equation for four forest stands in Thailand; a dry monsoon forest, a mixed savanna monsoon forest, a savanna forest and tropical rain forest. Similarly, more recently Brown et al. (1989) constructed two different models, one for moist forests and one for wet forests. Hairiah et al. (2010) reported that using general models results in overestimation (sometimes double the correct amount). In addition, these models are based on the data collected from the very dense forest. The allometry of the trees grown under dense conditions is different from the tree grown sparsely as in the agroforestry systems and the tree density greatly influences the allometry (Harrington & Fownes 1993). Therefore, location and species-specific growth models would give more precise estimation.

A number of species-specific models have been developed to estimate the individual tree species biomass, suitable to particular soil types, land use and biophysical conditions including climate (Alamgir & Al-Amin 2008; Onyekwelu 2004; Specht & West 2003; Swamy et al. 2003; Ter-Mikaelian & Korzukhin 1997; Wang 2006; Xiao & Ceulemans 2004). Since the location as well as species-specific equation gives the better result (Crow & Schlaegel 1988), for this study, the species-specific allometric equations have been used to estimate the biomass of the standing trees. But unfortunately the species-specific model for each species is not available. Only for those species having an economic as well as commercial value as timber and fuelwood, have the biomass models been constructed, such as *D. sissoo, E. camaldulensis, G. arborea, Tectona grandis* etc. but for those tree species recently emerged as a source of timber such as *M. azedarach* and *A. chinensis*, such models are still lacking. These two species fall under the top five timber species in the study area in terms of abundance. For the biomass estimation of these two species, the biomass equations (Chave et al. 2005), recommended by the World Agroforestry Centre (ICRAF) for the agroforestry systems in sub-tropical climate, has been used.

Estimating biomass of Eucalyptus cameldulensis

In order to estimate the biomass of *E. camaldulensis*, the allometric equations developed by Hawkins (1987) has been used (Table 3.5). Hawkins (1987) felled a total of eighty-eight trees of different DBH classes of *E. camaldulensis* from two different locations of Nepal's *terai*, Adhabhar and Sagarnath located at 80 and 20 kilometre west respectively from the study district, *Dhanusha*. The purpose of selecting sample trees from different locations was to capture the variation in growth because of site quality (soil) and to increase the applicability of the models. The trees used to develop this model ranged from 5 cm to 50 cm in DBH.

Table 3.5: Equations used for biomass estimation of *E. camaldulensis* of study area, Dhanusha

Tree components (Y) in kg	Biomass equations	Adjusted R^2
Stem	$-2.7421+2.5632\times Ln\ DBH$	99.1
Branch	$-4.4173+2.4768\times Ln\ DBH$	79.0
Stem and branch	$-2.5055+2.5318\times Ln\ DBH$	98.1
Leaf	$-4.1242+2.1966\times Ln\ DBH$	81.9
Total	$-2.2660+2.4663\times Ln\ DBH$	99.7

Source: Hawkins (1987)

Where,
DBH = Diameter at breast height (cm)
R^2 = Coefficient of determination

Estimating biomass of Dalbergia sissoo

Hawkins (1987) also developed biomass models for *D. sissoo* that can be applicable to Nepal's *terai* to estimate the biomass of the standing *sissoo* trees. But by using these equations, only stem and branch biomass can be estimated because no allometry is established to estimate leaf biomass. Since the objective is to estimate the above- and below-ground carbon content that a tree can capture, using these equations would definitely underestimate the total biomass (above- and below-ground biomass).

There are a number of studies done in Northern India regarding the development of biomass equations of this species, once a very popular agroforestry species (Kaur et al. 2002; Lodhiyal & Lodhiyal 2003; Singh et al. 2011). Since the work of Lodhiyal and Lodhiyal (2003) was done for this species in the Bhabar belt of Bihar, which is relatively nearer to the research site than the other two (Kaur et al. 2002; Singh et al. 2011), these equations were used to find the belowground biomass of *D. sissoo* (Table 3.6). In addition, there are a number of reasons for selecting Lodhiyal and Lodhiyal (2003) over Singh et al. (2011) and Kaur et al. (2002) to estimate the biomass for this study.

a. The age of the stand used to derive this allometry is 15 years, which exactly coincides with the harvest age of *Sissoo* in the study area.
b. The biomass equation of Singh et al. (2011) has higher r^2 (0.9789) but the size of trees used to derive this equation was less than 10 cm in diameter while the average size of the *Sissoo* tree in the study area was 25.4 cm. Since the equation is a linear type, extrapolation beyond the range of the tree size used to develop the equation is not justifiable (Crow & Schlaegel 1988).
c. The third equation i.e. developed by Kaur et al. (2002) did not mention r^2 of the equation. Coefficient of determination (r^2) is one of the most common statistics used to compare biomass equation (Crow & Schlaegel 1988). Further, the site where this study was done is a nutrient rich and high water table site. Use of this model to estimate the biomass in a nutrient poor and low water table site such as the study area will result in overestimation (Koerper & Richardson 1980).

d. The trees used in this model development ranged from 5 cm to 60 cm in DBH.

Table 3.6: Equations used for biomass estimation of *D. sissoo* of study area, Dhanusha

Tree components (Y) in kg	Biomass equations	Adjusted R^2
Stem	*22.0780+ 2.8541×DBH*	95.3
Stem bark	*4.2900 + 0.5538× DBH*	95.3
Branch	*4.7404 + 0.6164× DBH*	95.3
Leaf	*1.7329 + 0.2238× DBH*	95.3

Source: Lodhiyal and Lodhiyal (2003)

Where,
DBH = Diameter at breast height (cm)
R^2 = Coefficient of determination

Estimating biomass of Anthocephalus chinensis, Melia azedarach and *Gmelina arborea*

In order to estimate the biomass of these three agroforestry species, as stated earlier, the biomass equation recommended by the ICRAF and developed by Chave et al. (2005) has been used. Specific gravity (wood density - 0.50g cm^{-3}) of *M. azedarach* was adopted from Kataki & Konwer (2002) who studied thirty-five tree species in north-east India to determine the fuel value of these species based on calorific value and wood density. In the case of *A. chinensis*, there have been extensive studies with regards to determining the wood density (Francis 1994; Kataki & Konwer 2002; Krisnawati et al. 2011). The value ranged from 0.26 to 0.62 (0.26, 0.29, 0.31, 0.34, 0.37 and 0.42, 0.46, 0.56, 0.62,) varying in age and distance from the pith. The wood density increases with age where it is higher near the pith and decreases gradually towards the periphery. Therefore, the average value (0.40) was taken for *A. chinesiss* for this study. For *G. arborea*, 0.43g cm^{-3} was used (FAO 1997). The regression model proposed here is valid in the range of 5-156 cm for DBH (Chave et al. 2005) and the average DBH of these two tree species did not exceed this range.

$$AGB = \mathrm{p} \times \exp\left(-1.499 + 2.148 \ln(D) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3\right)$$

Where,

AGB = above ground biomass (kg)
D = Diameter at breast height (cm)
p = Wood specific gravity (g cm^{-3})

Estimating biomass of fruit tree species

Mango, jackfruit and lychee are the major fruit trees grown in the study area. Mango is the most dominant fruit tree, covering more than 90% of the total fruit trees grown by the farmers, followed by jackfruit and lychee. For these fruit trees too, no species-specific biomass equations were found. Therefore, the model developed by Brown et al. (1989) has been used in the present investigation. The literature revealed that this method is a non-destructive and is the most suitable method (Alves et al. 1997; Brown 1997; Chavan & Rasal 2010; Schroeder et al. 1997). The equation used in the present investigation is as follows. The average wood density of these three fruit trees species was taken from FAO (1997) as follows:

Mango (*Mangifera indica*): 0.52 and 0.59 = (0.52+0.59)/2= 0.55g/cm^3
Jackfruit (*Artocarpus heterophyllus*) = 0.60 g/cm^3
Lychee (*Litchi chinensis*) = 0.88 g/cm^3

$$Y = \exp(-2.4090 + 0.9522 \ln(D^2HS))$$

Where,

Y= Average biomass for a fruit tree (in kilogram)
D= Average diameter at breast height (in centimetre)
H= Average height of the fruit tree (in meter)
S= Average wood density (gram/cm^3)

(C) Below-ground biomass (BGB) estimation

Das and Chaturvedi (2008) conducted a study of some common agroforestry tree species (*Acacia auriculiformis, Azadirachta indica, Bauhinia variegate)* in Bihar, India to estimate the proportion of belowground biomass with respect to the above-ground biomass. They found that the ratio (root to shoot) ranged from 0.22 (*B. variegate*) to 0.33 *(A. auriculiformis*), with the average ratio being 0.27. The ratio for *A. indica* was found to be 0.27. The average root to shoot ratio (0.27) was found to be higher than the generally used ratio (0.25) (Haripriya 2001; Haripriya 2003; IPCC 1996). Generally agroforestry trees are sparsely grown compared to the trees grown in the forest and that forces trees to accumulate more biomass to the lower part of the tree to protect them from uprooting because of wind pressure. Therefore, this figure (0.27) was used to find the belowground biomass of the agroforestry trees in the study area.

3.3.2.2. Estimating greenhouse gas (GHG) emissions from the agroforestry system

At the onset of the GHG estimate, it is necessary to define the sources of emission from the agroforestry system in the study area. There are several sources of emission from agricultural fields; irrigation, livestock, paddy cultivation, legume crop cultivation, manure, fertilizer and fossil-fuels related, and farm-machinery related including machinery production (Bhatia et al. 2004). However, this study only considers four sources because they are major in the study area; 1) Methane (CH_4) emission from paddy fields; 2) CH_4 and Nitrous oxide (N_2O) emission from livestock; 3) Carbon-dioxide (CO_2), N_2O and CH_4 emissions from farm inputs; 4) CO_2, N_2O and CH_4 emissions from household activities. Emissions related to other farm inputs such as pesticides/insecticides and indirect N_2O emissions induced by leaching of NO^- or NH_3 volatilization were not included in the analysis as these were considered to be negligible (Flessa et al. 2002; Kramer et al. 1999).

(A) CH_4 emission from paddy fields

Flooded rice field is one of the major sources of CH_4 emission from agriculture (Bhatia et al. 2004). The amount of methane released from paddies varies widely since it depends on the method adopted for cultivation, paddy cultivars, the climate, and soil types (Amstel & Swart 1994; Bhatia et al. 2004). Therefore, the location-specific CH_4 emission factor which is derived from considering all the affecting variables would result in more precise estimation of methane release from paddy fields. Since there is no such study carried out to date in the study area to estimate the emission factor of CH_4 for the paddy fields, using the IPPC default values, would be a more rational choice than choosing some other values developed elsewhere. Out of seven paddy fields as defined by IPCC (1996), the study area paddy field falls under two categories; Rain-fed drought prone (RF-DP) and irrigated intermittently flooded-multiple aeration (IR-IF-MA). The corresponding value for each category are 6.95 ± 1.86 and 2.01 ± 1.49g CH_4 m^{-2} (Gupta et al. 2009) and these figures have been used for this study to estimate the annual methane emission from the paddy fields.

(B) Emission from Livestock

CH_4 emission from enteric fermentation

Livestock manure and enteric fermentation are the sources of N_2O and CH_4 emissions (Yamaji et al. 2003). The amount of CH_4 emissions through enteric fermentation is largely determined by the type and weight of the animal, the kind and quality of feed, the energy expenditure of the animal and environmental conditions (Shibata & Terada 2010). The body weight is largely determined by age and quality of feed. In most Asian countries livestock are raised under worse conditions than their European and American counterparts, i.e. livestock are given less food and it is of low quality and thus they weigh less, so they emit less CH_4 $head^{-1}$ (Singh & Mohini 1996; Yamaji et al. 2003). Therefore, using the emission factor of 47-118kg CH_4 $head^{-1}year^{-1}$ for European and American cattle (Houghton 2001) would definitely overestimate the CH_4 emission from Asian cattle. Since there is no country-specific emission factor in the case of Nepal, the work of Singhal et al. (2005), India was more applicable for this study because the livestock management system is very much similar in these two countries. Further, they have estimated the emission factor explicitly by age and species of livestock. Using the specific (age and species) factor is more reliable than the overall average emission factor irrespective of age and livestock type. Therefore, the following emission factors proposed by Singhal et al. (2005) were used in this study to estimate the CH_4 emission from enteric fermentation (Table 3.7).

Table 3.7: Emission factors used to estimate the total CH_4 emissions from enteric fermentation

Type	Category	Sub-category	CH_4 emissions (kg head^{-1}year^{-1})
Cattle	Female	0-12 months	7.39
		1-3 years	15.39
		Milking	35.97
	Male	0-12 months	7.6
		1-3 years	16.36
Buffalo	Female	0-12 months	6.06
		1-3 years	17.35
		Milking	76.65
	Male	0-12 months	5.09
		1-3 years	14.78
Goat	Female	< 1 year	2.83
		> 1 year	4.23
	Male	< 1 year	2.92
		> 1 year	4.99

Source: Singhal et al. (2005)

CH_4 and N_2O emissions from manure management

Emissions from manure are affected by the type of manure management systems (Shibata & Terada 2010). Several management systems have been documented in IPCC (2006). Substantial CH_4 emission may occur when manure decomposes in an anaerobic environment (Flessa et al. 2002). In the study area, livestock manure is typically stored for a period of several months in unconfined piles or stacks. This type of system is termed as solid storage by IPCC (2006). The following IPCC equation was used to estimate the annual CH_4 emission factor for each livestock category, i.e. buffalo, cattle (dairy and non-dairy) and goat.

$$EF_{(T)} = (VS_{(T)} \times 365) \times [Bo_{(T)} \times 0.67\,kg m^{-3} \times \sum MCF_{S,K}/100 \times MS_{(T,S,K)}]$$

Where,
$EF_{(T)}$ = annual CH_4 emission factor for livestock category *T*, kg CH_4 animal^{-1} yr^{-1}
$VS_{(T)}$ = daily volatile solid excreted for livestock category *T*, kg dry matter animal^{-1} day^{-1}
365 = basis for calculating annual volatile solid (VS) production, days yr^{-1}
$Bo_{(T)}$ = maximum methane producing capacity for manure produced by livestock category *T*, m^3 CH_4 kg^{-1} of VS excreted
0.67 = conversion factor of m^3 CH_4 to kilograms CH_4
$MCF_{(S,k)}$ = methane conversion factors for each manure management system *S* by climate region *k*, %
$MS_{(T,S,k)}$ = fraction of livestock category *T*'s manure handled using manure management system *S* in climate region *k*, dimensionless

The IPCC default values of VS $_{(T)}$, Bo $_{(T)}$, MCF $_{(S, k)}$ and MS $_{(T, S, k)}$ were used while estimating the emission factors by animal categories. By using the above equation, the following emission factors were estimated for each livestock category of the study area (Table 3.8).

Table 3.8: Emission factors of each livestock category to estimate the annual CH_4 emission from manure management

Sn	Livestock category	CH_4 emission factor (kg animal^{-1}year^{-1})
1	Dairy cattle	3.30
2	Non-dairy cattle	1.40
3	Buffalo	3.03
4	Goat	0.16

In the case of N_2O, the IPCC (2006) default value of 0.005 kg N_2O-N kg^{-1} nitrogen excreted was used to estimate the total N_2O emissions from livestock manure (solid waste + urine) management (solid storage). The daily manure and urine excretion (kg day^{-1}) for each livestock species is given in the Table 3.9. This figure (0.005 kg N_2O-N kg^{-1}) is widely used in literature when the country-specific emission factor is not available (Swamy & Bhattacharya 2006). N_2O-N was later converted into N_2O (by multiplying 1.57, molecular weight of N_2O/atomic weight of N_2 = 44.01/28.01) and then into CO_2e (Maraseni & Cockfield 2011a).

Table 3.9: Daily excretion (kg day^{-1}) and percentage of Nitrogen in manure and urine

Livestock	Manure	% of Nitrogen in manure	Urine	% of Nitrogen in urine
Buffalo	12	0.33	9	1.2
Cattle	10	0.25	6	0.9
Goat	0.51	0.83	1	1.6

Source: Pilbeam et al. (2000) and FAO (1992)

(C) CO_2, N_2O and CH_4 emissions from farm inputs

Emissions from agricultural soil due to use of farmyard manure (FYM) and chemical fertilizer

Farmyard manure (FYM) and chemical fertilisers are the major sources of N input on the farmland of the study area. N_2O emission from the crop field is largely affected by soil types, crop and land management, mode of fertiliser application and distribution and amount of precipitation (Dobbie et al. 1999; Flessa et al. 2002; Kaiser et al. 1998). However, several studies indicated that there exists a relationship between N input and N_2O emissions. Bouwman (1996) and Flessa et al. (2002) estimated that 1.25% (± 1%) of the total N input was resealed as N_2O-N year^{-1}. The emission factor of 1.25% N_2O–N is also currently recommended by the IPCC for estimating direct N_2O emissions from agricultural soils (IPCC 2006). Therefore, this widely used figure has been used for this study also.

To estimate the amount of N input from the farmyard manure and urine, the following table developed by Pilbeam et al. (2000) and FAO (1992) was adopted. In case of urine, 50% is lost during storage (FAO 1992), and therefore only 50% was considered while estimating N_2O emissions from soil due to urine application. The total amount of chemical fertilizer applied was collected from household survey. After calculating the total amount of N_2O –N, it was converted into N_2O and then into CO_2e. The daily excretion of manure and urine for the young cattle, buffalo and goat was assumed to be half that of the mature animals.

CO_2, N_2O and CH_4 emissions related to production, packaging, storage and transportation of synthetic fertilisers

Five types of fertiliser viz. Urea, diammonium phosphate (DAP), ammonium sulphate, and muriate of potash (MOP) and zinc sulphate were used in the study area. These fertilisers release greenhouse gases at different stages of their life cycles from production to application (Maraseni et al. 2009). Therefore, to estimate the total emission, The following CO_2e emission factors (Table 3.10) for the production, packaging, storage and transportation of each kilogram of fertiliser element were used (Maraseni & Cockfield 2011a).

Table 3.10: CO_2e emission factors for the production, packaging, storage and transportation of each kilogram of fertiliser element

Fertilizer element (fe)	kgCO_2e kg^{-1} fe
Nitrogen (N)	4.77
Phosphorus (P)	0.73
Potassium (K)	0.55
Sulphur (S)	0.37

The total amount of chemical fertiliser used in a year at household level was collected from the household survey. The actual amount of Nitrogen, Potash and Phosphorus was calculated on the basis of percentage of each element present in these chemical fertilisers (Table 3.11).

Table 3.11: Percentage of nutrients in the chemical fertilisers

Fertiliser	Nitrogen (%)	Potassium (%)	Phosphorus (%)	Sulphur (%)	Zinc (%)
Urea $CO(NH_2)_2$ or CH_4N_2O	46				
DAP $(NH_4)_2HPO_4$	18		46		
Ammonium sulphate $(NH_4)_2SO_4$	21			23	
Muriate of potash		60			
Zinc sulphate $ZnSO_4$				14	33

Source: Haque et al.(2011)

CO_2, N_2O and CH_4 emissions related to production and consumption of fossils fuels

Diesel is the only fuel used by machineries such as tractor (for discing and transportation purposes) and thresher for crop harvesting in the study area. The total GHG emission during the production and combustion of one litre of diesel is 3.15 kg CO_2e (Maraseni & Cockfield 2011a). GHG emissions also occur during the transportation of fuels, but in this study they are not considered, as they are negligible (Maraseni et al. 2007). About 14.4% of out of 3.15kg CO_2e, which is machinery-related emissions (Maraseni & Cockfield 2011b), was added to get the actual estimation of emission from use of fossil fuels.

(D) CO_2, N_2O and CH_4 emissions from household activities

The household activities in this section refers to the biomass burning that farmers of the study area have practiced for cooking and heating purposes since long ago. The biomass burning, which is associated with greenhouse gas emissions, included burning of crop residue, cow dung and fuelwood. In the following section, the methods of estimating emissions from these activities are discussed. The emission factor used to estimate GHG emissions from biomass burning is summarised in Table 3.12.

N_2O and CH_4 emissions from crop residue burning

Field burning and domestic burning of crop residues are two common practices in the Asian region (Li et al. 2007; Zhang et al. 2008). Field burning is done to enable tillage and seeding machinery to work effectively and also to eliminate waste after harvesting, while domestic burning is for cooking and heating purposes (Badarinath et al. 2009; Li et al. 2007). Whatever the purpose, the burning of crop residues releases the greenhouse gases (CO_2, CH_4 and N_2O, CO, SO_2) into the atmosphere (Andreae & Merlet 2001; Li et al. 2007).

Having very insignificant global warming potential (GWP), CO and SO_2 are not included in the analysis. CO_2 emissions from crop residue burning is not considered as net increase because CO_2 emissions are completely recycled and equivalent mass of CO_2 is removed from the atmosphere in subsequent growing seasons (Edwards et al. 2004) and therefore CO_2 was excluded while estimating GHG emissions from the residue burning. In the study area, mainly three crop residues (corn stover, wheat straw and rice straw) are used for heating and cooking purposes. Corn stover is the most prominent one followed by wheat straw. The residues are burnt in the traditional cook-stoves: open fire stove (*Agenu*) and mud stove (*Chulo*).

The review of literature revealed that a plethora of studies were done with regards to estimating the emissions caused by crop residue burning following the use of different location specific cook-stoves, broadly categorised as improved and traditional stoves (Bhattacharya et al. 2000; Brocard et al. 1998; Cao et al. 2008; Cofala et al. 2007; Edwards et al. 2004; Johnson et al. 2008; Johnson et al. 2009; Johnson et al. 2010; Joshi et al. 1989; Smith et al. 2000; Smith 1994). Using emission factors developed elsewhere may result in higher uncertainty in emission estimation because the emission factor is greatly influenced by variation in stoves used, cook’s skill and attention level, heat required by different food types, moisture content of the crop residues, combustion temperature, ambient conditions, fuel types and property and fire management (Cao et al. 2008; Roden et al. 2006; Zhang & Smith 1996). Therefore, the emission factor of 2.51 g CH_4 kg^{-1} dry matter (Bhattacharya et al. 2000) for the traditional cook-stoves in the case of Nepal was used to estimate CH_4 emission from rice straw burning. Emission factors of 3.4 and 4.4 g kg^{-1} dry matter was used to estimate the methane emission from wheat and maize residue burning respectively (Table 3.12). In case of N_2O estimation, since there is no literature documenting the N_2O emission factor for burning of crop residues using the traditional cook-stoves in the case of Nepal, the emission factors (Li et al. 2007) for wheat and rice straw (0.07g N_2O kg^{-1} dry matter) and for corn stover (0.14g N_2O kg^{-1} dry matter) have been used (Table 3.12).

Table 3.12: Emission factors (g kg^{-1}) used to estimate emission from biomass burning in the study area

Fuel type	CO_2	CH_4	N_2O	Source
Fuelwood	1139.09	8.18	0.06	Bhattacharya and Abdul Salam (2002), Bhattacharya et al. (2000) and Smith et al. (1993)
Agricultural residues				
Maize	1350.0	4.4	0.14	Li et al. (2007)
Wheat	1470.0	3.4	0.07	Li et al. (2007)
Rice	1106.91	2.51	0.07	Bhattacharya et al. (2000)

Estimating crop residue production in the study area

There are two indirect methods of estimating crop residue biomass; straw to grain ratio (Gupta et al. 1979; Stout 1989) and harvest index (HI) (Linden et al. 2000; Preston & Schwinn 1973). The HI is defined as grain dry matter divided by the total harvestable biomass (Linden et al. 2000). Either method is equally used to estimate the biomass (Graham et al. 2007). However, these methods estimate the total residue biomass.

In order to better estimate the actual amount of corn residue that is used for burning, the biomass of stalk and cob is required, but excluding another two components of corn stover, husk and leaf, since husk and leaf are not used as fuel. Most literatures give the total residue biomass estimation, which is an overestimation in the case of corn stover biomass estimation for this study. Therefore, the work of Pordesimo et al. (2004) was found to be quite suitable for this study because they have estimated five parts (grain, stalk, leaf, cob and husk) of corn stover separately. The grain, stalk, leaf, cob and husk constitute of 45.9%, 27.5%, 11.4%, 8.2% and 7.0% of the total harvestable biomass (X), respectively (Pordesimo et al. 2004). These figures were therefore used to estimate stover biomass separately and later the stalk biomass and cob biomass was summed up to estimate the actual stover biomass (Z). The dry grain yield (Y) and the percentage of the actual stover biomass (Z) burnt as fuel was collected from the household survey.

$$\text{Harvest index (HI)} = Y/X$$
$$\text{Stalk biomass (SB)} = X \times 27.5/100$$
$$\text{Leaf biomass (LB)} = X \times 11.4/100$$
$$\text{Cob biomass (CB)} = X \times 8.2/100$$
$$\text{Husk biomass (HB)} = X \times 7.0/100$$
$$\text{Actual amount of biomass (Z)} = SB + CB$$

The harvest index of rice and wheat varies with varieties. The index is influenced by temperature and fertiliser (Donald & Hamblin 1976; Prasad et al. 2006). Mae (1997) found that the index for rice ranged from 0.3 (traditional varieties) to 0.5 (semi-dwarf high yielding varieties) in a study carried out in Thailand. In another study in Florida, USA, Prasad et al.(2006) found the average harvest index of fourteen improved varieties of rice ranged from 0.2 (high temperature) to 0.47 (ambient temperature) depending on the environment. In a study carried out in Orissa, India, the average harvest index based on the three consecutive years' production data of the semi-dwarf high yielding variety (*surendra*) was found to be 0.47 (Thakur et al. 2010). Similarly, the harvest index of wheat ranged from 0.27 (traditional varieties) to 0.39 (semi-dwarf improved varieties) according to Donald & Hamblin (1976). In another study carried out in Ontario, Canada based on the three consecutive years' production data of thirty different varieties of winter wheat, the average harvest index was found to be 0.38 (Singh & Stoskop 1971). However, the harvest indices of the two Indian wheat varieties, *Kalyansona* and *Moti* were found to be 0.39 and 0.45 respectively (Sinha et al. 1982).

The review of literature revealed that the harvest index of wheat varied from 0.27 to 0.45 being influenced by crop varieties, management practices and geography. But Smil (1999), instead of producing a crop-specific harvest index, has produced a combined harvest index (0.40) for the cereal crops. In Nepal, this harvest index is widely used to estimate the crop residue of rice and wheat (Pilbeam et al. 2000). Since this figure falls within the range of the previous findings, the index value of 0.40 was used for this study to estimate the crop residue of rice and wheat grown by farmers in the study area. The grain yield and the percentage of residues burnt as fuel were collected from the household survey.

CO_2, N_2O and CH_4 emissions from fuelwood burning

Emission factors are widely used to estimate emissions from fuelwood burning. Since the emission factors are largely influenced by several factors such as fuel type and property, type of stove used and environment, selecting the right one is crucial to minimize uncertainty while estimating the emissions from fuelwood burning. There are several emission factors produced ranging from species specific to general (Ann Kristin 2006; Delmas 1994; Johnson et al. 2008; Smith 1994). The species–specific factor is applicable only when single fuelwood species is used as a fuel. But in the study area, farmers use several fuelwood species together. Hence, the use of species-specific emission factor would definitely result in higher uncertainty. Therefore, the general emission factors would better serve the objective of this study. However, some conditions such as what type of fuelwood species and stoves were used and the physical environment (temperature) of the location needs to be taken into consideration before selecting such factors for any study. For example, the CH_4 emission factor of fuelwood burning varies from 1.7g CH_4 kg^{-1} to 18.9g CH_4 kg^{-1}

depending on the type of stoves used (Bhattacharya & Abdul Salam 2002). Similarly, N_2O emission factor also varies from 0.05g N_2O kg^{-1} to 0.09g N_2O kg^{-1} by the type of stoves used (Bhattacharya & Abdul Salam 2002).

Tree species influences the emission factor because fuelwood species also vary with locations. For example, the works of Joshi et al. (1989) and Smith (1994) in Manila, Philippines found the CH_4 emission factors of fuelwood burning to be 8g CH_4 kg^{-1} and 9g CH_4 kg^{-1} respectively, while Bhattacharya & Abdul Salam (2002) found 18.9g CH_4 kg^{-1} in Bangkok, Thailand. Brocard et al. (1998) found the emission factors for CH_4 and N_2O to be 2.0g CH_4 kg^{-1} and 0.04g N_2O kg^{-1} only in West Africa because of higher combustibility of fuelwood species and that resulted in a low amount of PIC (products of incomplete combustion). Therefore, for this study, the emission factor of CH_4 (8.18g kg^{-1}) proposed by Bhattacharya & Abdul Salam (2002) for Nepal in the case of traditional cook-stoves has been used to estimate the methane emission from fuelwood burning.

For N_2O emission estimation, the widely used factor (0.06g N2O kg^{-1} dry matter) proposed by Smith et al. (1993) has been used since there is no country-specific emission factor produced for Nepal so far. Also choosing this figure seems logical because the figure falls within the range (0.02g N_2O kg^{-1} to 0.09g N_2O kg^{-1}) of previous findings. The annual fuelwood consumption (number of *BHARI*) per household was collected from the household survey. Fuelwood is measured in terms of *BHARI* in the study area. The average weight of a *BHARI* was 32 kg, which was determined through measuring 100 individual *BHARIs*, randomly selected from the sampled households.

3.3.2.3. Evaluating the agroforestry-based farming system - a cost-benefit analysis approach

The widely used approach in evaluating any agroforestry-based farming system in terms of profitability and feasibility is Cost-benefit analysis (CBA) approach (Alam et al. 2010; Current et al. 1995; Duguma 2013; Keca et al. 2012; Kurtz et al. 1991). In the study area, the farming system is very complex, comprising of four components such as forest tree crops, horticulture crops, livestock, and agricultural crops (field crops). Therefore, the component-wise cost and benefits were required to analyse the feasibility and the profitability of different farming systems at a farm level. Broadly, there exist mainly two types of farming practice in the study area; conventional agriculture that excludes trees and agroforestry-based farming system that integrates trees with agricultural crops. A detailed household survey was performed to collect data related to costs and benefits of each farming system. The detailed procedure of estimation of costs and benefits is described below.

(A) Determining the production cycle of an agroforestry system of the study area

The production cycle of conventional agriculture and agroforestry-based farming systems varies considerably. The production cycle of a conventional agriculture annual while in agroforestry systems there are both annuals and perennials, including fruits and timber trees and therefore the production cycle of an agroforestry system is longer than one year. The most convenient approach of determining the production cycle of an agroforestry system is the harvest age of the tree component of the system. However, in the study area, the harvest age varies with tree species. For example, *E. camaldulensis* is harvested at age ten while *D. sissoo* is harvested at age fifteen based on farmers' practice. Choosing either ten or fifteen would result in an incomplete picture of the farm enterprise. Therefore, a 30-year time horizon, which is the multiple of ten and fifteen and also the harvest age of some fruit trees, i.e. mango, lychee and jackfruit, was chosen to make the cost-benefit analyses of conventional agriculture and different agroforestry-based farming systems comparable. During this period the conventional agriculture would complete thirty production cycles.

(B) Estimation of costs and benefits of agroforestry tree crops

Most farmers in the study area have integrated a number of tree species on their farm. However, only the five species i.e. *E. camaldulensis, D. sissoo, G. arobrea, M. azedarach* and *A. chinensis* were considered for cost-benefit analysis, given the high economic importance of these tree species in the study area. To estimate the benefits from tree crops, the biomass was estimated by using allometric equations. The revenue from the sale of poles, small-size timber, fuelwood and carbon was the benefit of agroforestry tree crops. The price of tree biomass (small size timber and poles) is based on the price fixed by the contractor, which is farm-gate price. In the study area it is a common practice that farmers sell tree products to the local contactor. Therefore, the contractor's price was used for the small size timber and poles sold and consumed (Annex B, Table B.3). The benefit of carbon sequestration was estimated by prevailing international market price. It was assumed that the tree density by species would remain the same for thirty years and the production of trees would not be affected by sudden disease outbreak and environmental hazards. In a 30-year time horizon, there would be three rotations for *E. camalulensis*, two for *D. sissoo*, three for *M. azedarach*, two for *G. arborea* and three for *A. chinensis*.

The major costs included labour, forestry tools and inputs (seeds/seedlings). Labour is required for land preparation, pitting, planting, weeding, fuelwood harvesting, and timber harvesting. Both household labour and hired labour was considered as labourers. Since there is no practice of the use of insecticides/pesticides and water irrigation for tree crops, the cost associated with these activities was assumed to be zero. The forestry tools used in harvesting are axe and saws. The net benefits from tree crop were calculated as follows:

$$NB_{tc} = B_{timber} + B_{fuelwood} + B_{carbon} - C_{inp} - C_{lab} - C_{tools}$$

Where NB_{tc} the net benefits from tree crops; B_{timber} the income from timber; $B_{fuelwood}$ the income from fuelwood; B_{poles} the income from poles; B_{carbon} the income from carbon sequestration; C_{inp} the costs of inputs; C_{lab} the costs of labour; C_{tools} the costs of forestry tools.

(C) Estimation of costs and benefits of agricultural crops (field crops)

The major field crops in the study area for all types of farming systems were paddy, maize, wheat, millet, sugarcane, mustard, pulses such as lentil, cowpea, *Gahat* and gram and vegetables. However, there was a considerable variation in the cropping pattern, crop diversification, cropping intensity and mixed cropping across different farming systems. This variation largely determines the costs and benefits that actually accrue to farmers. To estimate the benefits from agricultural crops, the production related data (grain and residue production and area under each crop) was collected from household survey. The crop yield productivity data is presented in the

Appendix C, table C.1. It was assumed that the crop-wise production and cropping pattern would remain constant for thirty years. The benefits from grain yield and crop residue was estimated by using farm-gate and factory-gate prices of individual agriculture produce (Appendix C, Table C.2).

The cost data was collected for each field crop from household survey questionnaire (Appendix A) and cost estimation is presented in the Appendix D, Table D.1. The major costs included labour, inputs (seeds, fertilizers, insecticides/pesticides, and irrigation), agricultural tools (Appendix C, Table C.3), use of farm machineries and GHG emissions. Both household labour and hired labour were used. The cost of labour was estimated based on the opportunity cost of labour, which was based on the prevailing rates of payment for wage labourers. The amount of seeds, fertilizers and insecticides/pesticides and the number of every agricultural tool that farmers purchased and their life span were collected from household survey. The cost of inputs, use of farm machineries and agricultural tools was based on the local market price that prevailed at the time of data collection. The net benefits from agricultural crops were calculated as follows:

$$NB_{ac} = B_{grain} + B_{residue} - C_{inp} - C_{tools} - C_{emissions}$$

Where NB_{ac} the net benefits from agricultural crop production; B_{grain} the income from grain yield; C_{inp} the costs of inputs; C_{lab} the costs of labour; C_{tools} the costs of agricultural tools; $C_{machineries}$ the costs of using farm machineries such as tractor and thresher; $C_{emissions}$ the costs of GHG emissions from agriculture.

(D) Estimation of costs and benefits of fruit production

Mango, jackfruit and lychee are the only fruits trees considered in this study since they are the most extensively cultivated tropical fruits with high commercial value in the study area. Therefore, other fruit species such as guava, papaya and citrus fruit species were excluded from the analysis since they are less abundant in the study area. To better estimate the benefits from fruit trees in an entire production cycle of an agroforestry system, simplifying assumptions were made. In the study area there are a variety of mango tree that start bearing fruits at different age. For example the *Bombay green* starts bearing fruits at age six, *Amrapali* starts at age three while *kalkatia* starts at age seven.

The other two fruit species, i.e. lychee and jackfruit, also start bearing fruit at age six. Since the Bombay green, the most extensively cultivated mango species in the study are, starts fruit-bearing at age six, the authors assume that a mango tree starts bearing fruit at age six in the study area irrespective of species. For all the tree fruit crops, the yield gradually increases until age fifteen, remains constant (which is maximum yield) until age twenty-five and gradually decreases after twenty-five. This variation in production capacity was considered while estimating year-wise production potential of each fruit crop. Also it was assumed that the yield would not be affected by any disease outbreak and environmental hazards such as drought, heavy rainfall and high temperature. Another important aspect considered was the alternate bearing of mango. Only 25% of the last year’s yield was assumed to be yield for this year (i.e. if it was 100 kg last year, this year production would be only 25 kg).

The tangible benefits that fruit trees provide were fruit, fuelwood at the end of the production cycle and the carbon. The farm-gate price was used for fruit and fuelwood while for carbon the prevailing international market price was considered. The cost of fruit production included labour and inputs i.e. chemical fertilizers and farmyard manure. Both household labour and hired labour were used. Labour was required for land preparation, pitting, planting, weeding, manure application and fuelwood harvest at the end of the harvest cycle, i.e. age thirty. Other inputs such as irrigation and use of pesticides/insecticides were very rare and therefore it was not considered in CBA. The opportunity cost of land was not included because the study did not aim at comparing horticulture with other land-use such as agriculture. The cost and benefits estimation is presented in the Appendix D, Table D.3. The net benefits from fruit-tree crop were calculated as follows:

$$NB_{fc} = B_{yield} + B_{fuelwood} + B_{carbon} - C_{inp} - C_{lab}$$

Where NB_{fc} is the net benefits of fruit cultivation; B_{yield} the gross returns from fruit yield (consumed + sold); $B_{fuelwood}$ the income from fuelwood; B_{carbon} the benefits from carbon credit; C_{inp} the costs of inputs; C_{lab} the costs of labour.

(E) Estimation of costs and benefits of livestock

The major livestock kept in the study area are buffalo, cattle (cow and ox) and goat. Even though the livestock-keeping in the study area is subsistence type, a simple population dynamics model was developed based on purchase and sales of livestock and birth rate for a 30-year period and the death rate was assumed to be zero during this time. The livestock population was predicted based on the number of milking livestock at the time of data collection (Appendix E, Tables E.1 and E.2). Farmers keep buffalo for meat and milk, cow for milk only, ox for draught purposes and goat for meat. Therefore, the benefits that accrued to farmers from livestock-keeping included income from milk and meat, draught service and the live sale of livestock while the costs that accrued to them included livestock purchase, labour, and animal health and veterinary cost. The cost of feed is assumed to be zero because there is no practice of buying feed in the study area. Crop residues, grain and other agricultural by-products are used as animal feed. The following assumptions were made with consulting livestock experts and through focus group discussion in order to estimate the costs and benefits in a 30-year time horizon:

- A female buffalo reaches maturity at age three and gives first-birth at age four then continues to give birth at an interval of eighteen months and the sex ratio is assumed to be 50:50. Farmers sell the old female buffalo at age ten and buy a young one. There would be twenty calves (ten male and ten female) with first-birth being a female in a 30-year time horizon. The male buffalo is assumed to be sold at age three while the female buffalo (born of mother buffalo) is assumed to be sold at age four, after first-birth. It is also assumed that a female buffalo gives milk for at least ten months of the year at the rate of 4.5 litre day^{-1}.

- A female goat reaches maturity within six months and gives first-birth at age one and continues to give birth annually at the average rate of two kids each birth. The sex ratio is assumed to be 50:50 as in the case of buffalo. Farmers sell the old female goat at age ten and buy a young one. There would be sixty kids (thirty female and thirty male) produced in a 30-year time horizon. Both female and male kids are assumed to be sold at age one.

- Similar assumptions were made for cows also but the old cow is not saleable in the market because of the religious value of a cow in Hindu society. It was assumed that she would give milk for nine months of the year at the rate of 3.0 litres day^{-1}. In the case of oxen, a pair of oxen is assumed to be kept until the pair reaches fifteen. There would be two pairs of oxen in a 30-year time horizon.

All benefits from livestock were estimated based on the prevailing market price of livestock and livestock products at the time of data collection. The estimation of cost and benefits from livestock is presented in the Appendix D, Table D.4. The net benefits from livestock keeping were calculated as follows:

$$NB_{ls} = B_{ls} + B_{lsp} + B_{lsd} - C_{ls} - C_{lab} - C_{lsh} - C_{emissions}$$

Where NB_{ls} the net benefits from livestock; B_{ls} the income from livestock sale; B_{lsp} the income from livestock products; B_{lsd} the income from livestock draught; C_{ls} the costs of livestock purchase; C_{sc} the costs of shed construction; C_{lab} the costs of labour C_{lh} the costs of livestock health; $C_{emissions}$ the costs of greenhouse gas emissions.

(F) Estimation of carbon credits

Carbon sequestered by trees was calculated by using the tonne-year accounting method (Cacho et al. 2003).The total annual amount of carbon was further divided by a constant 100 (Fearnside 1997) following the rules of permanence to calculate actual greenhouse gas emission reduction by the tree biomass. A value of \$10.00 t^{-1} CO_2e for both carbon uptake and GHG emission was used as a base case to see the effect of carbon price on NPVs of farming systems under study. A couple of scenarios were run for different C prices to see their impacts on NPV.

(G) Selection of discount rate to calculate the discounted cash flow (DCF)

All the costs and benefits mentioned above do not occur at base year of the production cycle of thirty years. Those monetary values that accrue in the future must be discounted appropriately. Choosing an appropriate discount rate is very crucial as it determines the relative impacts of current and future costs and benefits. Increasing the discount rate decreases the influence of future costs and benefits while increasing the impact of the early costs (i.e. establishment costs) on the final result. Usually, the rate of return required by the investor is taken as the discount rate, typically approximated as the weighted average cost of capital (WACC) (Manivong & Cramb 2008) and risk factor may be added to the WACC(Ramírez et al. 2001). Also it is a common practice to include the effects of inflation while calculating the real discount rate (Ericsson et al. 2006). In most reviewed studies the discount rates ranged between 3.5% and 7%, very few have used a discount rate higher than 10% y^{-1} (Kasmioui & Ceulemans 2012, 2013; Tharakan et al. 2005).

Some studies (Faúndez 2003; McKenney et al. 2011) provided the assumptions justifying the chosen discount rate, while others took a value from literature (Kuemmel et al. 1998; van den Broek et al. 2001) or did not provide the provenance of the chosen rate at all (Styles & Jones 2007; Styles et al. 2008). The assumptions underlying the discount rate differ significantly among the reviewed studies. For instance, one study (Ericsson et al. 2006) took the discount rate of the national bank (5.5%y^{-1}), subtracted the inflation rate (0.8% y^{-1}) and added a risk premium (1.3% y^{-1}) to achieve a real discount rate of 6% y^{-1}, whereas Rasul and Thapa (2006) used comparatively higher discount rate -12% (11% - the national interest rate for agricultural credit, and 1% - the additional cost in the process of obtaining credit) to evaluate agroforestry and shifting cultivation (*jhum*). The same discount rate was considered to reflect the cost of capital in some forestry projects of the neighboring country of India (Rasul & Thapa 2006). The Agricultural Development Bank of Nepal has also fixed the interest rate of 12% for agricultural credit (http://www.adbl.gov.np/uploads/file/PDF/ Intrest_rate_2069-05-01.pdf). Therefore, for this study 12% discount rate was used to analyze the NPV of farming systems under study.

(H) Intra-year timing for DCF analysis

Regarding intra-year timing, generally in DCF analysis capital outlays are timed for year 0 (the beginning of the year) and operating costs and project revenues are timed for the ends of the years. But in this study it was assumed that both costs and benefits occurred at the end of the year. In case of capital outlays, particularly, the purchase of farm tools does not occur at the beginning of the year only, farmers buy them whenever they need at any point of time of the year. Similarly, project revenue from sale of livestock and livestock products i.e. milk occur at any time of the year, milk sale starts in the beginning of the year and remains until the end of the year. Therefore, for this study, all costs and benefits were assumed to occur at the end of the year.

(I) Criteria used to evaluate the performance of farming systems in the study area

Return-to-land and return-to-labor were the criteria considered for evaluation for different agroforestry systems.

Return-to-land

Given the scarcity of land, both private and social objectives are to maximize returns per unit of land. Return to land is expressed by Net present value (NPV), which determines the present value of net benefits by discounting the streams of benefits and costs back to the base year. The NPV of each farming system was calculated using the following formula:

$$NPV = \sum_{n=1}^{30} (B_t - C_t)/1 + r)^t$$

Where, NPV is the Net present value; B_t is the component-specific benefits (field crops, agroforestry tree crops, horticultural crops and livestock) accrued over thirty years; C_t is the component-specific costs incurred over thirty years; t is the time period; r is the discount rate (12%).

Return-to-labor

Smallholder households seek to maximize return to household labor, as it is their main asset. Therefore, return to labor, calculated by subtracting the material costs from the gross benefit and dividing the proceeds by the total person-days, following

Fagerstroem et al. (2001), was also used to compare the benefits of conventional agriculture and different types of agroforestry-based farming systems.

(J) Sensitivity analysis

The NPV test described above explains only about the relative efficiency of a given project, given the data input to the calculations. If these data change, then clearly the results of the NPV test will change too. This change is necessary because of uncertainty and risks associated with future costs and benefits. In all *ex ante* cases of cost benefit analysis, the analyst must make predictions concerning the future physical flows and future relative values. None of these predictions is made with perfect foresight. Therefore, an essential final stage of any *ex ante* cost benefit analysis is to conduct sensitivity analysis. This means recalculating NPV when values of certain key parameters are changed. Changes in discount rate, price of inputs and outputs were done to conduct the sensitivity analysis of different agroforestry systems of the study area.

3.4. Conversion factor (CF) for CO2e and biomass carbon estimation

Two conversion factors were used in this study; one for estimating the carbon content in tree biomass and the other for estimating the greenhouse gas emissions in terms of CO_2e. The CF of 0.5 (Penman et al. 2003) was used to estimate the carbon content in the tree biomass while the Global warming potential (GWP) of each greenhouse gas (CO_2 = 1, CH_4 = 25 and N_2O = 298) based on a 100-year time horizon was used to estimate the total greenhouse gas emissions in terms of CO_2e (IPCC 2007).

3.5. Conclusions

This chapter detailed the methodology adopted for this study. Both primary and secondary data sources were used to achieve the study goals. Focus group discussion, which is widely used in agriculture and agroforestry related studies, was used to document the history of farming systems and major driving forces behind the evolution of agroforestry based farming system in the study area. For successful intervention of agroforestry program, farmers' choice on tree species is very crucial and preference list was obtained from the focus group discussion. One of the objectives of this study was to compare economic performance and GHGs dynamics of farming systems in the study area and hypotheses were set accordingly. To achieve this goal and to be compatible with the research hypothesis, an expert level discussion was done to categorise the farming systems into different types based on the level of integration of systems components within the farming system and allometric equations and most relevant default values for GHGs estimation were identified through extensive literature review. Detailed review was necessary because even a small error in selecting such default values would lead to bigger error in GHG estimation and may lead to either overestimation or underestimation and test of hypothesis would be questionable. Therefore, as far as possible the country specific default values were used and where not possible, universally accepted IPCC default values were used. In case of carbon estimation in tree biomass, both species-specific and general allometric equations were used. The economic performance was measured with two criteria i.e. return-to-land and return-to-labour.

The first section described the study overview with detailed information of the study area. The second section was focused on the study methods, which was divided into two sub-headings. The first part dealt with development and adoption of agroforestry-based farming systems while in the second part was discussed the methodology of estimating cost and benefits from farming systems to conduct the bio-economic evaluation of these farming systems.

Chapter 4

Household and Farm Characteristics and Evolution of Agroforestry-based Farming System

4.1. Introduction

Agroforestry is being recognized as a sustainable land management practice because of its potential role in climate change mitigation through enhanced carbon sequestration. Promotion of such a promising land use is crucial for the present as well as future generation. Against this background, in this chapter, how a simple mono-cropped farming system at the beginning of the settlements (1950) in the study area evolved into a highly integrated farming system such as agroforestry is discussed. Also, the factors that played a role in its evolution are highlighted. Finally the existing agroforestry-based faming systems are grouped into different categories based on the level of integration of different system components and these agroforestry systems are analysed to see the differences and similarities by using some important farm and household characteristics.

4.2. Farming history (from 1950 to 2010)

The total of sixty years of farming were divided into four different time periods based on some visible changes in crop composition and diversification. In the following section, the changes that farmers witnessed in farming practice during this time span are discussed. The summary of farming history and factors of land-use intensification is presented in the Table 4.1.

4.2.1. Farming practice (1950 to 1965)

The study area was sparsely populated with the indigenous people, the *Madhesi* community, and heavily forested for the most part. Therefore, only a few scattered patches of land were used as agriculture. Land was not scarce for agriculture because the forest land could be converted easily into agricultural land. Farming was the only livelihood. Initially the newly converted land was highly fertile as a result of high organic carbon content and therefore the intensity of disturbance such as ploughing and hoeing was relatively limited. Maize, mustard, pigeon pea, groundnuts and sweet potato were the major crops, with the latter two being the most extensively cultivated.

Farmers adopted a very simple farming practice of one crop in a year, with the land in fallow for the rest of the time. Livestock-keeping was an integral part of farming in this period. Household needs such as timber, fuelwood, leaf litter, and fodder for livestock were fulfilled from the nearby forest and therefore there were no trees retained deliberately on the private land except for a few trees that grew naturally. Only about 5% of households had promoted some horticultural trees in the form of a home garden, with the most common of these being a mango garden. Having a home garden indicated a high social status.

There was no irrigation, chemical fertiliser application, or use of pesticides or insecticides, and there was no intercropping. The farming practice during this period was an organic agriculture. In the present context of heavy agricultural reliance on synthetic chemical fertilisers and pesticides that have had a serious impact on public health and environment (Pimentel et al. 2005), this type of farming practice was more environment-friendly and supportive to augmenting ecological processes that foster plant nutrition yet conserve soil and water resources. However, this type of practice was subsistence-oriented. According to the participants, the main objective of farming in this period was to fulfil the basic household need for food. As farmers were not aware of new farming technologies, and there were no transportation facilities, there was little scope for marketing opportunities for the commodities that the farmers would produce.

4.2.2. Farming practice (1965 to 1980)

Sweet potato and groundnuts were largely displaced by sugarcane and tobacco by the end of 1960s, with the establishment of a local cigarette factory and sugar mills. The factory and the mill provided farmers with seeds and seedlings of tobacco and cuttings of sugarcane through a subsidy with a buy-back guarantee. The development of markets and the provision of subsidies encouraged farmers towards higher production and they started applying chemical fertilisers along with farmyard manure, mainly urea, di-ammonium phosphate (DAP), tri-ammonium phosphate (TAP) and potash, and these are still in use. During this period some farmers also started planting paddy rice where sources of irrigation were available. New varieties, popularly known as modern varieties (MVs), of rice and maize were introduced to Nepal in 1965 and spread throughout the *terai* in mid 1970s.

With the adoption of new crop varieties, the application of chemical fertilisers became more pronounced. Farmyard manure (FYM) alone was not enough to take advantage (high yield) of the improved varieties. The organic agriculture gradually became inorganic with the advent of new crop varieties in the study area. The introduction of improved varieties brought a significant change in farming system during this period in the study area. Farmers started an intensive farming. Mixed cropping and intercropping, with mixes such as mustard with cowpea, lentil and *Khesari* (a type of pulse crop) were more common. This further increased the use of agricultural inputs, mainly irrigation water and chemical fertilisers.

4.2.3. Farming practice (1980 to 1995)

This period was characterised by further land intensification. The introduction of modern varieties of wheat changed the farming pattern in the area. This enabled the farmers to switch from the traditional rice-fallow rotation to an intensive production system in which rice and wheat were double-cropped within the same year. Lentil and cowpeas were intercropped with wheat where irrigation was available. Mustard as a cash crop, and once a good source of income, was replaced by this rice-wheat farming. Farmers started cultivating vegetables on a commercial scale in place of maize and also established a fruit garden, popularly known as a home garden.

The farming practice became more diversified than before during this period. However, this type of crop diversification was not just the result of adopting new crop varieties. There was a major driving force behind this change; infrastructure development. The opening of the east-west highway created a new market for the farmers linking them with big market centres in the country, which motivated farmers towards vegetable farming. The farming practice became further intensified in the late 1980s when some large-scale farmers introduced tree planting on their farms. The major driver behind the introduction of trees on farms as a part of a farming system was the institutional factor. The establishment of a forestry project named the *Sagarnath* Forestry Development Project (SFDP) motivated the large-scale farmers towards planting trees on their farms. The project had initiated a huge plantation of *Eucalyptus camaldulensis*, an exotic species to Nepal and locally known as *Sapeta* and *Dalbergia sissoo*, locally known as *Sisau* with dual objectives of replacing degraded forest land with plantation forests and augmenting the domestic supply of fuelwood and timber.

4.2.4. Tree based farming practice (1995 – 2010)

In this period, with the development of major highways opening up potential new markets for produce, vegetable farming became more extensive with tomatoes, potatoes and coriander intercropped with the previously dominant sugarcane. Tree planting gained momentum following the establishment of the Terai Private Forest Development Association (TPFDA), an NGO with technical support from the Nepal Agroforestry Foundation (NAF), in 1998. The TPFDA formally organised farmers. Farmers were provided with training on agroforestry including nursery preparation, selection of tree species and planting techniques. It also provided training on vegetable farming, livestock management, and home garden management. Some other important training included soil conservation measures such as gully control, flood control and fertility management. Following the training, farmers were provided with necessary materials including nursery materials, and seeds and seedlings of fodder and timber species, vegetables and horticultural crops. Improved male goats were distributed to some selected farmers to improve the local breeds of goat through crossbreeding. These sorts of technical support and extension services encouraged farmers to bring diversification in their farming.

Until mid-1980s, only the naturally grown trees, particularly the fodder trees, were seen on the farm. However, after the TPFDA's support, farmers started cultivating some new tree species: *E. camaldulensis* and *D. sissoo* (already introduced by the SFDP), *Anthocephallus chinensis, Tectona grandis, Leucaena leucocephala, Bauhinia variegata, Syzygium cuminii, Ceiba pentandra, Morus alba*, and *Guazuma ulmifolia*. At the beginning of the settlements (during 1950-1965 period), very few field crops were a livelihood option for farmers and now livelihood options are much more diversified, as farmers not only produce field crops but also vegetable crops, tree crops, horticultural crops, livestock and cash crops.

Table 4.1: Summary of farming practices adopted by farmers of the study area from 1950 to 2010

Periods	Major crops	Land-use intensification	Major drivers
1950 to 1 965	Maize, mustard, pigeon pea, ground nuts and sweet potato	- One crop in a year, with the land in fallow for the rest of the time - Low input farming (minimum tillage, no irrigation, no chemical fertiliser)	
1965 to 1980	Sugarcane, tobacco, potato, mustard, and improved varieties of paddy and maize	- Intercropping with mixes such as mustard with cow pea, lentil and *khesari* (a type of pulse crop) and maize with millet - Sugarcane and tobacco introduced as cash crops - Two crops in a year - Goat introduced in the area - Use of chemical fertilisers to maintain land productivity	- Population growth following the migration from the hills and India - Institutional support (subsidy, buy-back guarantee and extension program to make farmers adopt new varieties of field crops) -Technology
1980 to 1995	Improved varieties of paddy, maize and wheat, sugarcane, tobacco, lentil, cow peas and some tree species (*E. cameldulensis* and *D. sissoo*)	- Wheat-rice double cropped in irrigated land - Multiple cropping (maize with millet + rice and mustard with cowpea and/or lentil) in a year - Lentil and cow peas intercropped with wheat where irrigation available - Production of vegetables at commercial scale - Use of chemical fertilizer, pesticides/insecticides more pronounced - Trees introduced into farming system by large farmers	- Infrastructure (opening of the east-west highway) - Institutional (government sponsored plantation program)

Periods	Major crops	Land-use intensification	Major drivers
1995 to 2010	Improved varieties of rice and maize suitable for both the winter and rainy season, improved wheat, sugarcane, vegetables, tree crops, legume crops (cow pea, lentil etc) and fruit crops	- Rice-rice-wheat triple cropped in irrigated land - Tree crops integrated extensively into the farming system - Millet and tomato intercropped with maize - Lentil/cowpea/gram intercropped with wheat - Vegetables such as coriander, tomato, potato intercropped with sugarcane - Use of farm machineries (tractors, threshers) for farm land preparation - High input farming	- Infrastructure (development of feeder roads that link with the main highway, and good means of transportation such as tractor, bullock cart, and public transportation) - Institutional (technical support and extension services from the local institution) - Limited and/ or no access to the natural forest (scarcity of timber, fodder, fuelwood in the natural forest)

4.3. Farmers' preferred tree species for agroforestry

Thirty-seven different trees species were used by the farmers for timber, fodder, fuelwood and fruits. There are fourteen tree species primarily used as timber, eleven tree species as fodder and twelve tree species as fruits. Farmers use most species for fuelwood except for ones such as *Khaksi, Ceiba pentendra, Bombax ceiba,* and *Moringa oleifera* (Table 4.2). Designing an agroforestry requires assessing the farmers' preference of tree species because the tree is the main component of any agroforestry system. The introduction of new tree species in the study area provided an ample opportunity to assess farmers' choices between the naturally grown (local) and introduced species. The findings of this study suggest that farmers in the study area preferred the introduced tree species to the local ones.

4.3.1. Farmers' preferred timber species

Out of top five timber species, three were introduced, i.e. *E. camaldulensis, T. grandis and A. chinensis*. However, *A. chinensis* is not an exotic species as is *E. camaldulensis* and *T. grandis* but new to the study area. The focus group discussion placed *E. camaldulensis* first in the preference list while *C. pentendra* was placed last. *G. arborea, A. chinensis, T. grandis* and *M. azedarach* were ranked second, third, fourth and fifth, respectively (Table 4.3). *E. camaldulensis* and *A. chinensis* were rated highest for "fast growth" and "marketability" while *G. arborea, T. grandis* and *M. azedarach* were ranked highest for "disease/termite resistance" followed by *E. camaldulensis* and *A. chinensis*. For "durability", *G. arborea*, and *T. grandis* scored highest followed by *M. azedarach*. *E. camaldulensis* was the only species that was rated highest for "growing well in marginal land". Out of five, *E. camaldulensis* was ranked highest for the three criteria "fast growth", "marketability" and "growing well in marginal land" (Table 4.3).

4.3.2. Famers' preferred fodder species

In case of fodder tree species, three out of the top five were introduced, i.e. *M. alba,* L. *Leucocephala* and *G. ulmifolia*. However, *M. alba* is not an exotic species as is L. *Leucocephala* and *G. ulmifolia* but new to the study area. The group discussion placed *L. leucocephala, A. lakoocha, G. ulmifolia, M. alba* and *G. pinnata* in the preference list from the first to the fifth, respectively. *L. leucocephala, A. lakoocha,* and *G. ulmifolia* scored highest for "nutrient content". Farmers gave the highest preference to *L. leucocephala, G. pinnata* and *M. alba* as "easy to establish" followed by *A. lakoocha,* and *G. ulmifolia*. In terms of "tree vigour", *A. lakoocha* was the only species securing the highest rank, while the only species scoring highest for 'fast growth' and "easy harvest" was *L. lucocephala*. For the criterion "growing well in marginal land", none of the top five species received the highest ranking. Farmers gave a score of 2 (second highest) for *L. leucocephala* for this criterion. Based on the overall score, *P. latifolia* was least preferred even though farmers gave the highest preference rate for "tree vigour" for this species (Table 4.4).

Table 4.2: Plant species found in the study area

Sn	Local name	Scientific name	Uses	
			Primary	Secondary
1.	*Sapeta*	*Eucalyptus camaldulensis* Dehnh.*	Timber	Fuelwood
2.	*Gamhari*	*Gmelina arborea* Roxb.**	Timber	Fuelwood and fodder
3.	*Kadam*	*Anthocephalus chinensis* Lam.*	Timber	Fuelwood and fodder
4.	*Sisau*	*Dalbergia sissoo* Roxb.*	Timber	Fuelwood
5.	*Sagwan*	*Tectona grandis* Linn.*	Timber	Fuelwood
6.	*Siris*	*Albizia* sp.**	Timber	Fuelwood and fodder
7.	*Nim*	*Azadirachta indica* L.**	Timber	Fuelwood
8.	*Bakaino*	*Melia azedarach* L.**	Timber	Fuelwood and fodder
9.	*Dabdabe*	*Garuga pinnata* Roxb.**	Fodder	Fuelwood
10.	*Ginderi*	*Premna latifolia* Roxb.**	Fodder	Fuelwood
11.	*Khanayo*	*Ficus semicordata* Buch.-Ham. ex Sm.**	Fodder	Fuelwood
12.	*Ipil Ipil*	*Leucaena leucocephala* Lam.*	Fodder	Fuelwood
13	*KHAKSI*	NA**	Fodder	
14.	*Tanki*	*Bauhinia purpurea* L.**	Fodder	Fuelwood
15.	*Koiralo*	*Bauhinia variegata* L.**	Fodder	Fuelwood
16.	*Badahar*	*Artocarpus lakoocha* Roxb.**	Fodder	Timber and fuelwood
17.	*Karma*	*Adina cordifolia* Roxb.**	Timber	Fuelwood and fodder
18.	*Jamun*	*Syzigium cuminii* (L.) Skeels*	Timber	Fuelwood
19.	*Mahuwa*	*Madhuca indica* J. F. Gmel.**	Timber	Fuelwood
20.	*Kapok*	*Ceiba pentandra* L.*	Timber	Fodder
21.	*Kimbu*	*Morus alba* L.*	Fodder	Fuelwood
22.	*Khayar*	*Acacia catechu* (L. f.) Willd.**	Timber	Fodder and fuelwood
23.	*Gazuma*	*Guazuma ulmifolia* L.*	Fodder	Fuelwood
24.	*Simal*	*Bombax ceiba* L.**	Timber	Fodder
25.	*Amala*	*Phyllanthus emblica* L.**	Fruit	Fuelwood

Sn	Local name	Scientific name	Uses	
			Primary	Secondary
26.	*Harro*	*Terminalia chebula* Tetz.**	Fruit	Fuelwood
27.	*Barro*	*Terminalia belerica* L.**	Fruit	Fuelwood
28.	*Khasreto*	*Ficus roxburghii* Wall**	Fodder	Fuelwood
29.	*Aanp*	*Mangifera indica* L.**	Fruit	Timber and fuelwood
30.	*Rukh katahar*	*Artocarpus heterophyllus* Lam.**	Fruit	Fuelwood and fodder
31.	*Kagati*	*Citrus* sp.**	Fruit	Fuelwood
32.	*Bhogate*	*Citrus* sp.**	Fruit	Fuelwood
33.	*Sitafal*	*Annona squamosa* L.**	Fruit	Fuelwood
34.	*Sarifa*	*Annona reticulata* L.**	Fruit	Fuelwood
35.	*Lychee*	*Litchi chinensis* Sonn.*	Fruit	Fuelwood
36.	*Sajana*	*Moringa oleifera* Lam.**	Fruit	
37.	*Amba*	*Psidium guajava* L.**	Fruit	Fuelwood

* = Introduced species; ** = Local species

Table 4.3: Farmers' preferred timber species in the study area of Dhanusha District, Nepal

Characteristics/ criteria	*E. camaldulensis*	*G. arborea*	*A. chinensis*	*T. grandis*	*M. azedarach*	*A. indica*	*A. catechu*	*A.* sp.	*A. indica*	*D. sissoo*	*B. ceiba*	*S. cuminii*	*A. cordifolia*	*C. pentandra*
Fast growth	1	2	1	4	3	2	4	2	4	3	1	4	3	2
Marketability	1	2	1	2	3	2	4	3	3	2	3	3	3	4
Disease/ termite resistance	2	1	2	1	1	2	2	2	2	5	4	3	3	3
Growing well in marginal land	1	3	3	3	3	3	2	3	2	2	2	2	3	4
Durability	3	1	3	1	2	3	1	3	2	2	4	2	2	5
Total score	8	9	10	11	12	13	13	13	13	14	14	14	14	18
*Initial ranking**	*I*	*II*	*III*	*IV*	*V*	*VI*	*VI*	*VI*	*VI*	*VII*	*VII*	*VII*	*VII*	*VIII*
Final ranking	*1st*	*2nd*	*3rd*	*4th*	*5th*	*6th*	*7th*	*8th*	*9th*	*10th*	*11th*	*12th*	*13th*	*14th*

* does not give the clear ranking as there is a tie between and among some species

Table 4.4: Farmers' preferred fodder species in the study area of Dhanusha District, Nepal

Characteristics/ criteria	*L. leucocephala*	*A. lakoocha*	*G. ulmifolia*	*M. alba*	*G. pinnata*	*B. purpurea*	*B. variegata*	*F. semicordata*	*F. roxburghii*	*Khaksi*	*P. latifolia*
Fast growth	1	2	2	2	2	2	2	3	2	1	4
Tree vigour	3	1	3	2	2	3	4	3	3	3	1
Nutrient content	1	1	1	5	4	3	3	3	4	5	5
Easy harvest	1	3	2	2	2	2	2	2	2	4	4
Growing well in marginal land	2	3	4	3	4	4	3	3	3	3	3
Easy to establish	1	2	2	1	1	2	2	3	3	3	3
Total score	9	12	14	15	15	16	16	17	17	19	20
*Initial ranking**	*I*	*II*	*III*	*IV*	*IV*	*V*	*V*	*VI*	*VI*	*VII*	*VIII*
Final ranking	*1st*	*2nd*	*3rd*	*4th*	*5th*	*6th*	*7th*	*8th*	*9th*	*10th*	*11th*

* does not give the clear ranking as there is a tie between some species

4.4. Farm and household characteristics of agroforestry-based farming system in the study area

Following the scale developed by the expert group, the prevalence of land-use types was examined. About 12.5% of farmers were engaged with a subsistence-based agriculture system (SAS) while 32.5% had practiced a less integrated agroforestry system (LIS). Another 32.5% of farmers were engaged in medium levels of an integrated agroforestry system (MIS) and 22.5 % have adopted a highly integrated agroforestry system (HIS). In the following section the distinguishing features of these three agroforestry-based farming systems are discussed only because the simple agriculture-based farming was beyond the scope of this study. There were certain farm and household characteristics that were responsible in shaping the type of agroforestry systems in the study area (Table 4.5).

4.4.1. Landholding size across three agroforestry-based farming sytems

Land is the fundamental source of livelihood for the people in the study area. The average farm size varied with the type of agroforestry that farmers are adopting. The farm size is greatest in type HIS agroforestry, and is three times larger than that of type LIS agroforestry. The difference in farm size was statistically significant ($p < 0.05$). Farmers primarily grew food crops including rice, wheat, maize, and millet, cash crops including sugarcane, tobacco, ginger and turmeric, horticultural crops including mango, lychee and jackfruit, and vegetable crops including leafy vegetables, beans, and some vegetables from the cucurbitaceae family including pumpkin, zucchini, ivy gourd, bottle gourd, bitter melon, snake gourd, and sponge gourd. Rice is one of the important food crops in the study area. The average rice cultivation area ranged from 3.9 katha (LIS) to 18.6 katha (HIS). The difference in rice cultivation area was statistically significant ($p < 0.05$) across these systems (Table 4.5).

4.4.2. Tree species diversity and tree density

The diversity of tree species has increased with a concurrent increase in integration level. Diversity Index (DI) was used to assess species diversity in these systems. The tree species were more diversified (DI = 1.6) and more evenly distributed (EI = 0.47) in the type HIS agroforestry as compared to type LIS and type MIS (type LIS, DI = 0.85, EI = 0.28 and type MIS, DI = 1.2, EI = 0.37) (Table 4.5). Trees were grown and managed in different niches in the study area. Four types of niches were identified: alley, tree stand, boundary plantation, and trees that were raised around the homestead. There was no boundary plantation established in the LIS agroforestry, and farmers raised more trees in the alley while trees were distributed in all niches across MIS and HIS agroforestry systems, with more trees as agroforest.

Table 4.5: Selected farm and household characteristics in the study area of Dhanusha District, Nepal

Agroforestry types Farm characteristics	LIS (n = 65)	MIS (n = 65)	HIS (n = 45)
Tree species diversity	0.85	1.2	1.6
Tree species evenness	0.28	0.37	0.47
Average farm size (ha)	0.77[a]	1.5[b]	2.6[c]
Average rice cultivation area ([d]*Katha*)	3.9[a]	9.7[b]	18.6[c]
Average amount of chemical fertilizer (kg ha^{-1} $year^{-1}$)	169.0[a]	284.2[b]	321.5[c]
Average duration of irrigation (hours ha^{-1} $year^{-1}$)	126[a]	165[b]	201[c]
Average duration of farm machinery use (hours ha^{-1} $year^{-1}$)	28.5[a]	37.8[b]	54.3[c]
Average home to forest distance (kilometres)	5.7[a]	7.4[b]	12.6[c]
Average annual fuelwood consumption (tonne)	3.1[a]	4.4[a]	3.8[a]
Fuelwood collection from natural forest (%)	30.0	9.0	1.5
Fuelwood collection from private sources (%)	70.0	91.0	98.5
Use of other energy sources (LPG and Biogas) (% households)	12	18	37

Note:
This table only presents the data from agroforestry-based farming systems i.e. HIS, MIS and LIS and therefore excludes the SAS.

Means in a row with different superscripts are significant at $p < 0.05$. [d]30 *Kathas* = One hectare (ha)

HIS = highly integrated agroforestry-based faming system; MIS = medium integrated agroforestry-based farming system and LIS = less integrated agroforestry-based farming system

4.4.3. Intensity of farm inputs use in three agroforestry-based famring systems

The major farm inputs included chemical fertilisers, irrigation and use of farm machineries. The chemical fertilisers included urea, DAP, TAP, zinc, potash, and ammonium sulphate and farm machinery that were in use in the study area were tractor and thresher. The tractor was used for field preparation and thresher was used for the harvesting of crops. There was an increase in the amount of these inputs with increase in integration level. Farmers in the study area used chemical fertilisers along with farmyard manure to augment the farm yield. The per hectare fertiliser application was highest in HIS agroforestry, which was significantly higher ($p < 0.05$) than that applied by LIS and MIS agroforestry systems. Likewise, the average hours of machinery use per hectare was significantly higher ($p < 0.05$) than that used by LIS and MIS systems. In case of irrigation, the HIS agroforestry system required more hours of water supply per hectare than that of LIS and MIS systems. The difference in mean hours of irrigation was statistically significant ($p < 0.05$) across the three agroforestry systems (Table 4.5).

4.4.4. Effects of location of farm household on land use intensification

The distance between the farmer's home and the forest played an important role in determining the level of land intensification. The HIS agroforestry had the farthest distances between forest and home of all three systems and for MIS the distance was further than that for LIS. The mean home-to-forest distance of farm households that have adopted the highly integrated agroforestry (HIS) was 12.5 kilometres, while those who had adopted the less (LIS) and medium integrated agroforestry (MIS) were 5.6 and 7.4 km, respectively. The difference in distance was statistically significant ($p < 0.05$).

4.4.5. Major sources of energy used in the study area

Fuelwood is the most common source of energy that farmers in the study area use for cooking as in other parts of Nepal and South Asian region. Fuelwood was obtained mainly from two sources; private sources including trees and crop residues, and natural forest including community forest. The percentage of fuelwood use from these sources varied with agroforestry types. Over 90% of the fuelwood need of the farmers who had adopted MIS and HIS agroforestry systems was fulfilled from the private source alone. Thirty percent of the fuelwood need of the farmers who had adopted LIS agroforestry was fulfilled from natural forests (Table 4.5).

Besides fuelwood, there were some other energy sources that farmers used in the study area. These sources included biogas, and liquefied petroleum gas (LPG). The percentage of households using biogas and LPG combined was highest for HIS agroforestry compared to MIS and LIS.

4.5. Discussion

The farming history clearly indicates that farming practice in the study area has evolved since 1950 from very simple mono-cropping to multi-cropping, and to more integrated tree-based farming system. This had occurred as a result of several factors, not just population growth. If we consider population pressure as a primary factor accelerating land-use changes, as argued by Boserup (1965), the population has grown steadily in the study area during the last few decades, particularly due to inward migration from the mid-hills. This has certainly forced farmers to adopt more intensive farming through introducing field crops such as maize, wheat, rice and sugarcane in different time periods. However, the results have suggested that population pressure alone was not responsible for the changes evident in farming practice in the study area.

Farmers started cultivating rice only when there was irrigation water available. They further extended rice cultivation into upland areas when new rain-fed rice varieties were developed. Sugarcane and tobacco were introduced in the study area in 1970 following the opening up of the sugar mills and cigarette factories that supported farmers with seeds and seedlings with subsidies and buy-back guarantees for the products. Goat farming was introduced in mid 1960s when people from the mid-hills migrated into the study area; and as a result, farmers started protecting the fodder trees that had grown naturally on their farms in order to feed their goats. Therefore, the analysis suggests that infrastructure development (irrigation facilities), technology (new varieties of rice), institutional support (subsidy, buy-back guarantee) and in-migration (goat keeping) were the main factors that brought changes in farming practice in the 1965-1980 period. This finding is in agreement with the work carried out in Bangladesh (Rasul et al. 2004), Southeast Asian countries (Rasul & Thapa 2003) and Nigeria (Adesina & Chianu 2002).

Further changes took place in farming practices between 1980 and 1995 in terms of crop diversification and land-use intensification. Farmers started vegetable farming on a commercial scale. This study finding suggests that this change was accelerated by the opening up of the east-west highway that provided opportunity to the farmers of the study area to be linked with big market centres such as Narayangarth, Pokhara and more importantly with Kathmandu, the capital city of Nepal. A number of researchers (Allan 1986; Reardon et al. 2001) have emphasised the role of infrastructure and access to market centres as important factors as these developments help to broaden the scope for new crops and the changes in farming practices. Another notable change in farming practices during this period was the introduction of new tree species. This change was influenced by a government-sponsored project, the *Sagarnath* Forestry Development Project (SFDP) that initiated a huge plantation of *E. camaldulensis*, and *D. sissoo*. This motivated some large farmers towards integrating these timber species into their private land. Only a very few farmers having landholdings above 6.0 hectares had started this tree planting, because tree planting on the farm meant reducing the land available for growing field crops, and hence decreasing food security. Therefore, small, medium and even most large farms did not adopt this technology.

As suggested by many researchers (Mercer 2004; Patel et al. 1995; Scherr 1995), those farmers who adopted tree planting were more likely to have some other necessary "risk capital", in addition to more land, such as more labour and larger incomes, to facilitate risky investments in unproven technologies like tree planting. In the focus groups, besides these resource endowments (labour, land and income) constraints, the participants indicated some other reasons for farmers failing to adopting this new technology. These included a lack of awareness of the benefits of trees, as compared to field crops, and a lack of knowledge and skills regarding tree planting.

Other authors in this field have argued that skills and knowledge transfer to farmers about new technology played an important role in agricultural development (Hayami & Ruttan 1971; Raut et al. 2011), and the findings of this study also reinforce this argument. Farmers, once reluctant, are now encouraged to plant trees on their farms as a result of training, extension services, follow up support and material support provided to them. These support services were provided by the local NGO, the Terai Private Forest and Development Association (TPFDA). Approximately 88% of the farm households of the study area were engaged with this tree-based farming system. However, the extent of tree planting, vegetable farming and fruit-tree raising varied with farm households. To understand this variation, the farm and household characteristics need to be understood.

This study found there was a distinct variation in some farm and household characteristics between these agroforestry-based farming systems. These included use of farm inputs, cropping intensity, tree species diversity, tree density, tree distribution pattern, and use of energy sources. The amount of fertiliser applied, the hours of irrigation and the hours of farm machinery use were highest in the highly integrated agroforestry, because this land was cropped most intensively and hence required more farm inputs to maintain productivity. Trees were more widely distributed in the HIS agroforestry than in LIS. More trees (by percentage) were promoted in the alleys in the LIS agroforestry, while it is the tree stand in use in HIS agroforestry. This difference is largely determined by the size of the farm - for small farmers (0.77 ha) it is not feasible to allocate more land for the tree stands, because this would decrease the land area for growing field crops and cause food insecurity and therefore, the small farmers (LIS adopters) prefer tree planting in the alley (along the terrace bunds) to the tree stands. This is the reason why LIS adopters still depend on natural forest to fulfil 30% of their fuelwood need while HIS largely depends on their private sources (98%). The MIS adopters collect 9% of their fuelwood needs from the natural forests. There is another reason for the insignificant dependence of HIS and MIS adopters on natural forests for fuelwood: use of LPG and biogas. However, due to data insufficiency it is difficult to estimate how much fuelwood is substituted by these alternative energy sources at household level. The proximity of the LIS adopters from the natural forest might be another prominent reason why these farmers still rely on forest for fuelwood.

Beside these farm characteristics, there are several other factors that played a role in the evolution of different types of agroforestry systems in the study area. Farmers who had adopted the highly integrated agroforestry system were found to be significantly different ($p < 0.05$) from farmers who had adopted less integrated and medium integrated agroforestry systems in terms of farm size, and home-to-forest distance. This study finding also reinforces the previous finding (Barker 1997) that resource-rich farmers are apt to change, as their accumulated wealth enables them to make investment into new technology adoption. The resource-rich farmers (2.6 ha) in the study area were also engaged in the highly integrated agroforestry. Likewise, the distance from home to the forest was also an important factor determining the level of land-use intensification in the agroforestry system in the study area. The farm households that were based at distant locations to the forests were engaged in highly integrated agroforestry, while the farmers living close to the forest had adopted less integrated agroforestry. When farmers could fulfil their day-to-day needs, including fuelwood, fodder, litter and timber from the easily accessible forest, they were less interested in diversifying field crops and land-use intensification (Sapkota & Oden 2008).

4.6. Conclusions

The present day farming practice, the agroforestry-based farming, is the result of several factors that contributed to land-use change in different time periods of farming history of the study area. The finding of this study has clearly demonstrated that the institutional support has been the major driver of change in each period of farming history, and infrastructure development was equally contributing to land-use change in the study area. The institutional support included skills and information transfer, material support, secured market, follow up support and extension services while infrastructure included road networks and irrigation facility. However, there are some factors that posed constraints to adopting highly integrated agroforestry-based farming system including farm size, agricultural labour force and farmers' capacity for using farm inputs.

In Nepal most youths, the main agricultural labour force, go abroad for work and the study area is no exception to this. Nonetheless, our finding strongly indicates that if farmers are provided with necessary training, skills and knowledge about the new farming technology and supported with necessary materials, they are willing to adopt such technology. But still, the government should provide some programs focusing on the small-holder farmers who are generally risk-averse so that they could switch from the less integrated to highly integrated agroforestry system. The program may include subsidy in farm inputs (irrigation, farm machinery etc.). Overall this chapter threw light on understanding current and historic patterns of farming systems in the study area and this information could be quite useful in the development of effective technological and institutional interventions to enhance the livelihoods of small-holder farmers through appropriate agroforestry intervention.

Chapter 5

Deriving An Index of Adoption Rate and Assessing Factors Affecting Adoption of An Agroforestry-based Farming System

5.1. Introduction

In the previous chapter the evolution of the agroforestry-based farming system was documented with a special emphasis on identifying the main drivers of its evolution at landscape level. In this chapter the factors that affect the famers' decision about adoption of such a complex farming system is discussed. There are a number of factors responsible for making adoption decisions. The study area farmers integrated multiple farm practices; field crops, horticulture, vegetable, livestock and trees for their livelihoods. The farm households are potential adopters of any number and combination of these farm practices. In such a case the binary models would not fit properly to study the factors influencing adoption. An index value, a proxy for level of adoption of agroforestry-based land management practice (AFLMP) was required to be calculated based on the number of practices adopted at household level. Therefore, the aim of this chapter is to describe the method of the adoption index (AI) development with a special emphasis upon identifying the factors that explain variation in adoption of such a promising land use system.

This chapter is divided into five sections. Section 5.2 gives a brief theoretical perspective on adoption. In Section 5.3 details the methodology adopted to develop an adoption index (AI) is discussed. Section 5.4 covers results of the study and discussion and conclusions are given in Sections 5.5 and 5.6, respectively.

5.2. Factors affecting farmers' adoption decision: theoretical perspectives

The agroforestry-based farming system is an integrated land management practice that aims for land resource conservation and improving land productivity through integration/introduction of tree crops with agriculture and livestock. However, the adoption of this sort of practice is influenced and constrained by several factors.

According to induced innovation theory, as population densities rises and/or demand for agricultural products increases, the resulting land pressures induce adoption of technological and institutional innovations to intensify land use for sustaining their livelihood (Binswanger & Ruttan 1978; Boserup 1965; Pingali et al. 1987; Ruttan 1997). Other researchers argued that only the population growth cannot be an inducing factor that motivates farmers towards adopting new land management practice but there are several factors; socio-economic, institutional and technological inducing farmers to adopt new agricultural innovations/technologies (Adesina & Chianu 2002; Rasul & Thapa 2003; Raut et al. 2011).

Ali (1995) considered the land management practice at a given time and space to be the function of constraints imposed by physical environment and technological capabilities to reduce and modify the constraints. Adoption of a new land management practice takes place as a result of combined influence of institutions and technologies because institution plays an effective role in creating scientific and technical knowledge and also facilitates the implementation of new technology in agricultural production (Hayami & Ruttan 1971; Rasul & Thapa 2003). Brady (1996), however, argues that the availability of resources (natural, human, technological, capital), constraints (biophysical, socioeconomic) and the policy environment (including land rights, land tenure, subsidies, taxes, commodity prices, and marketing opportunities) influence land-use change.

Adopting a new practice is a complex process involving four different stages; awareness, interest, evaluation and finally adoption, each influenced by various biophysical, personal, socioeconomic and institutional factors (Rogers & Shoemaker 1971). Farmers' individual attitudes, characteristics, feelings and inspirations greatly influence the adoption decision (Giampietro 1997; Valdivia & Poulos 2009). Those who have knowledge of the practice and perceived problems with environment and concerns about future generations are more likely to be interested in adoption of new land management technology such as agroforestry and older farmers are less interested in adoption of such innovative measures (Valdivia & Poulos 2009). Demographic characteristics of farm households, including household labour force size (Rauniyar 1998) and social background (caste, ethnicity etc.), and resource endowments such as land, livestock and savings also play important roles (Pattanayak et al. 2003; Paudel & Thapa 2004; Tiwari et al. 2008; Tiwari et al. 2009). People whose primary source of income is not agriculture are less concerned about land management compared to others whose livelihood derives mainly from agriculture (Raut et al. 2011).

5.3. Model description

Farmers of the study area have adopted the agroforestry-based land management practice. They have integrated trees, horticulture, field-crops, vegetables, and livestock into their farming system to a varying degree. There were identified twenty-three practices (technologies) characterising the integration level of agroforestry-based land management practice (AFLMP) (Table 5.1). Farmers have adopted a number of combinations of these technologies varying from one farm household to another. Since one of objectives was to assess factors explaining the variation in adoption of AFLMP and the measurement of dependent variable (adoption index) is ratio in scale, the multivariate linear regression model would serve the purpose. The dependent variable, adoption of agroforestry-based land management practice, is hypothesized as being influenced by a set of independent variables; $X_1, \ldots X_n$ (Table 5.2), which is described below. The model is specified as follows:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + ------- + b_n X_n$$

Where,
Y is the dependent variable (adoption of agroforestry-based land management practice),
b_0 is the intercept, $b_1, b_2, \ldots, b_n$ are the coefficients of explanatory variables $X_1, X_2, \ldots, X_n$.

Sixteen explanatory (independent) variables were selected (Table 5.1). A multi-collinearity test was performed to see whether the selected independent variables are correlated to one another. The correlation matrix presented in Table 5.3 shows that multi-collinearity was a bit of a concern, since some of the explanatory variables were strongly correlated with each other. The test revealed that the variables 'Respondent's experience on agroforestry' (X_{11}), 'household head's experience on agroforestry, (X_{12}), 'family size' (X_4) and 'number of agricultural labour force' (X_5) (Table 5.3) were found to be highly correlated and therefore two variables X_{13} and

X_4 were dropped from the model since they showed low degree of correlation with the dependant variable (Tables 5.1 and 5.3).

Altogether nine variables were found to be highly correlated with the dependent variable and less correlated with independent variables. They included level of education (X_1), number of agricultural labour force (X_5), farm size (X_6), distance of home to government forest (X_7), availability of irrigation water (X_{10}), household's experience in agroforestry (X_{12}), number of agroforestry related training received by family members (X_{14}), frequency of visits by extension workers (X_{15}) and expenditure on farm input purchase (X_{16}).

Household head's education (HHH_EDU)

The level of education of the household's head largely determines whether or not they adopt any new technology (Pattanayak et al. 2003; Tiwari et al. 2009). A farmer with a higher education level is more likely to adopt new technologies than less educated farmers (Adesina et al. 2000; Tiwari et al. 2008). Technology such as improved fallow practice is knowledge and management intensive technology, requiring the ability to manage them properly to achieve optimum results (Matata et al. 2010). It is, therefore, expected that HHH_EDU is positively related to adoption of agroforestry-based land management practice.

Age of household head (AGE_HHH)

The variable age is generally expressed in two ways: average age of the family and age of the household head (Pattanayak et al. 2003). In rural areas of Nepal household decisions are made by the household head and therefore the variable AGE_HHH was used in this model instead of the average age of all household members. Empirical studies suggest that age is both positively and negatively related to adoption decision (Pattanayak et al. 2003; Sood & Mitchell 2009). However, for this study, it is hypothesized that age is positively related to the adoption decision because adopting a new technology is essentially a dynamic process of learning through observation and experimentation as farmers learn about optimal management through their own and neighbours' experiences (Cameron 1999; Foster & Rosenzweig 1995). Older famers are more experienced than the younger farmers.

Gender of household head (GEN_HHH)

Agroforestry technologies are gender-biased. Men are more likely to adopt such technologies than women (Adesina & Chianu 2002). Female farmers are less likely to use new technologies (Adesina 1996). In male dominant societies such as rural areas of Nepal, it is expected that male-headed households have higher chances of adoption (Tiwari et al. 2008). Therefore, it is hypothesized that gender (male) is positively related to adoption of agroforestry-based land management practice.

Table 5.1: Selected explanatory variables used to develop an adoption model for the study area of Dhanusha district

Variables	Description	Minimum	Maximum	Mean	Std. deviation
Education (X_1)	Total years of schooling of the household head (in years)	0.0	16.0	5.7	5.1
Age (X_2)	Age of the respondent (in years)	20.0	67.0	41.8	10.9
Gender (X_3)	It's a dummy variable (1= male, 0 otherwise)	-	-	-	-
Family size (X_4)	Number of family members/household	3.0	26.0	7.6	2.6
Labour force (X_5)	Household labour force involved in agroforestry (no./household)	1.0	12.0	4.2	1.8
Farm size (X_6)	Total area of farmland (hectare)	0.1	6.1	1.5	1.1
H_GF_ dist (X_7)	Distance of home to government forest in kilometres	1.0	22.0	8.1	4.2
Erosion hazard (X_8)	Risk of erosion in the farmland (Very high or high =1, 0 otherwise)	-	-	-	-
Flood hazard (X_9)	Risk of flooding in the farm land (Very high or High =1, 0 otherwise)	-	-	-	-
Irrigation (X_{10})	Absence or presence of irrigation facility (Yes =1, 0 otherwise)	-	-	-	-
Respondents' experience (X_{11})	Number of years' involvement in agroforestry practice of the household head	2.0	32.0	8.5	5.9
HHs' experience (X_{12})	Number of years' involvement in agroforestry practice of the sample farm households	2.0	50.0	10.8	7.6
H_H_ Distance (X_{13})	Distance of home to highway in kilometres	0.04	10.00	4.13	2.76
Training (X_{14})	Number of agroforestry related trainings obtained by the sample farm household during 1999-2009	0.0	12.0	4.0	2.5
Frequency of visits (X_{15})	Number of visits by extension workers during 1999-2009	2.0	16.0	8.4	2.7
Expenditure on farm input purchase (X_{16})	Amount of money spent on farm input purchase in Nepalese rupees	0.0	4697.0	1456.9	672.4

Family size (FAM_SIZE)

Most agroforestry technologies are labour intensive technologies, requiring more labour force (Carter 1996). Therefore, it is expected that larger family size is positively related to the adoption decision.

Agricultural labour force (AGRI_FORCE)

The number of economically active family members is more important than the total family size (Paudel & Thapa 2004) and therefore it is expected that the larger size agricultural labour force positively influences the adoption decision.

Farm size (FARM_SIZE)

Household assets such as landholding size have a positive influence on agroforestry adoption (Alavalapati et al. 1995; Pattanayak et al. 2003; Salam et al. 2000; Sood & Mitchell 2009). Therefore, it is hypothesized that the farm size is positively related to adoption decision.

Distance from home to the government forest (H_GF_DIS)

Farmers living farther from the forest are more likely to adopt tree planting than those living close to the forest (Sapkota & Oden 2008). In the study area, tree planting including home garden is the major technology adopted by the farmers. Therefore, it is expected the closer proximity is negatively related to farmers' adoption decision.

Erosion hazard (ERO_HAZ) and flood hazard (FL_HAZ)

The farm households experiencing more erosion and flood problem are more likely to adopt conservation technologies including agroforestry (Adesina & Chianu 2002; Tiwari et al. 2008). Therefore, it is expected that households having more erosion and flood problems are motivated to adoption of the technologies that reduces the risk of erosion and flooding such as agroforestry-based land management practice. This is also a dummy variable (1 = very high or high, 0 = otherwise).

Availability of irrigation water (IRRI_WAT)

In the study area, there were certain farming technologies that require irrigation water such as paddy rice cultivation, wheat cultivation, vegetable farming and sugarcane cultivation. Therefore, it is expected that availability of irrigation water determines the level of adoption of agroforestry-based land management practice.

Household head's experience in agroforestry (HHH_EXP)/Household's experience in agroforestry (HH_EXP)

The number of years that the farmer (the household head) and the household have been practicing agroforestry positively influences adoption decisions (Adesina & Chianu 2002; Mercer et al. 2005). The household heads and the households that have been practicing agroforestry are more likely to be aware of different types of agroforestry technologies, possibly due to better contacts with agroforestry extension projects and extension workers or through learning from other farmers. Therefore, it is expected that the increased number of years of experience in agroforestry positively influences the adoption decision.

Distance from home to highway (H_HW_DIS)

Having a good access to the main highway means having a good access to the market centres where farmers sell their farm products. Therefore, it is hypothesized that the closer proximity to the highway is positively related to adoption decision. In the case of a single technology adoption such as alley farming, the farther the farm household is from the highway the greater is the probability of adoption (Adesina & Chianu 2002).

Training (TRAIN)

Most farmers are risk averse and reluctant to adopt new technologies. The support services such as extension services and training help farmers reduce risk and build confidence to adopt such technologies (Gray et al. 2004; Pattanayak et al. 2003; Paudel & Thapa 2004). Therefore, it is hypothesized that training is positively related to adoption of agroforestry-based land management practice.

Visits by extension workers (EXT_VISIT)

Frequency of visits of extension workers with farmers greatly influences the adoption decision because being intermediaries between the concerned agency and the farmers, extension workers make farmers aware of the advantages of locationally suitable land use and management technologies, and persuade them to adopt. Contact with extension workers allows farmers greater access to information about the technology, through greater opportunities to participate in demonstration tests (Atta-Krah & Francis 1987; Carter 1996; Whittome et al. 1995). Therefore, it is hypothesized that visits by extension workers positively influences adoption decisions.

Expenditure in farm input purchase (EXP_INPUT)

Income largely determines the farmers' expenditure. Resource rich farmers can take risk with investment of unproven technologies (Barker 1997). Therefore, it is expected the greater the expenditure, the higher the chance of adopting agroforestry-based land management practice.

5.3.1. Dependent variable (adoption of agroforestry-based land management)

Tree crop, horticultural crop, livestock and field-crops were identified as system components through the focus group discussion. Under each system component, there were a number of practices (technologies) adopted by farmers to conserve their land resources and maintain farm production (Table 5.2). A score of 1.0 was assigned to the practice adopted by farmers and 0.0 to the practice not adopted by them. An index value for each system component based on the number of practices under each component was calculated. Here is how the index value was developed.

$$IV_T = \sum_{t=1}^{6} t/n ....(5.1)$$

Where,
IV_T = Index value for tree crop
n= total number of practices i.e. 6
t = number of practices adopted by individual farmer

$$IV_L = \sum_{l=1}^{4} l/n .... (5.2)$$

Where,
IV_L = Index value for livestock
n = total number of livestock species i.e. 4
t = number of livestock species kept by individual farmer

$$IV_A = \sum_{a=1}^{13} a/n ....(5.3)$$

Where,
IV_A = Index value for agricultural crops
n = total number of agricultural practices i.e.13
t = number of practices adopted by individual farmer

$$AI = \sum (IV_T + IV_L + IV_A)/3 .... \quad (5.4)$$

Where,
AI = adoption index

This adoption index (AI) was used as dependent variable as a proxy measure of the adoption of agroforestry-based land management practice (AFLMP).

5.3.2. Procedure and scientific basis of adoption index (AI) development

Anley et al. (2007) used lengths of conservation structures as a proxy of conservation efforts to determine the factors influencing adoption of soil and water conservation measures. Similar proxy variables such as tree density (number of trees ha^{-1}), area covered by trees (ha) and length of bunds with trees (m ha^{-1}) (Pisanelli et al. 2008) could be used to study the factors explaining the adoption of agroforestry-based land management practice, however, agroforestry is not just trees but is an integrated land management practice that includes agriculture and livestock (Garforth et al. 1999). Therefore using only trees (number of tree ha^{-1}, area under tree crop, and percentage of tree cover area) as a proxy would be a bias. To avoid this bias in analysis, some index value that could represent all components (trees, agriculture and livestock) equally is necessary. Being integral parts of an agroforestry system, an equal weightage was given to each component while developing the index value (formula 5.1).

Farming system in the study area is not that simple. There are a number of activities (practices) under each system component, making the system more complex. In the case of the component “tree crops”, there are a number of variations in terms of arrangement of trees/vegetation within the farming system. From the focus group discussion, six types of tree arrangement were documented; homestead agroforestry (trees raised around the homestead), windbreaks (trees raised around the farm boundary and home garden), alley (trees raised in the alley), woodlot (trees raised as a tree stand), buffer strips (vegetation raised between farmland and waterways to avoid flooding and control erosion) and home garden (fruit orchard). These agroforestry types are the common practices in the tropics (Alavalapati et al. 2004). Since the farm productivity varies with tree species and their management regime, each management regime was treated as a separate agroforestry technology (Table 5.2). The index value for the tree crops (IV_T) was calculated as shown in the formula 5.1 for each household surveyed.

Likewise, in order to derive an index value for the component “livestock”, the livestock diversity (number of livestock species) was considered rather than total number of livestock per household. Since the aim is to document the practices within the component “livestock”, simply the size would not fit into this model. Therefore, livestock diversity was documented through field survey, considering each livestock species as a separate practice as detailed in the Table 5.1. The index value for the livestock (IV_L) was calculated as shown in the formula 5.2 for each household surveyed.

For the third component “agriculture crops”, each crop that farmers cultivated was considered as a separate practice because each crop had its own significance in soil fertility management. For example the use of legume crop would enhance the soil fertility through nitrogen fixation. Further to this, the nutritional need also varies with crop types and hence rational use of available nutrients can be expected and this would help in soil fertility maintenance. The index value for the agricultural crops (IV_A) was calculated as shown in the formula 5.3 for each household surveyed. Once the index value (IV) was calculated separately for the three components, the adoption index (AI) was derived by using the formula 5.4 for each household surveyed.

Table 5.2: Land management practices used for construction of the index (adoption of agroforestry-based land management practice)

System components	Practices
Tree crop	*(t_1)*Homestead agroforestry (1)
	*(t_2)*Wood lot (2)
	*(t_3)*Alley cropping (3)
	*(t_4)*Wind breaks (4)
	*(t_5)*Buffer strips (5)
	*(t_6)*Home garden (6)
Livestock	*(l_1)*Buffalo keeping (7)
	*(l_2)*Ox and cow keeping (8)
	*(l_3)*Goat keeping (9)
	*(l_4)*Other livestock (sheep, pig) keeping (10)
Agricultural crop	*(a_1)*Paddy cultivation (11)
	*(a_2)*Maize cultivation (12)
	*(a_3)*Wheat cultivation (13)
	*(a_4)*Millet cultivation (14)
	*(a_5)*Sugarcane cultivation (15)
	*(a_6)*Mustard cultivation (16)
	*(a_7)*Sesame cultivation (17)
	*(a_8)*Tobacco cultivation (18)
	*(a_9)*Vegetable farming (19)
	*(a_{10})*Lentil cultivation (20)
	*(a_{11})*Cowpea cultivation (21)
	(a_{12})GAHAT cultivation (22)
	(a_{13})RAHARI cultivation (23)

Table 5.3: Correlation matrix of variables used in agroforestry model for farmers of Dhanusha district

Variables	Avg. index	Education	Age	Gender	Family size	Labour force	Farm size	H_GF distance	Erosion	Flood hazard	Irrigation	Res_ experience	HHs experience	H_ highway distance	No. of trainings	No. of visits	Expenditure on farm input
Average index	1.000																
Education (X_1)	0.585	1.000															
Age (X_2)	0.067	-0.157	1.000														
Gender (X_3)	0.219	0.194	0.112	1.000													
Family size (X_4)	0.335	0.185	0.191	0.140	1.000												
Labour force (X_5)	0.574	0.302	0.148	0.118	0.714	1.000											
Farm size (X_6)	0.673	0.482	0.149	0.228	0.278	0.486	1.000										
H_GF distance (X_7)	0.513	0.490	-0.056	0.144	0.203	0.230	0.438	1.000									
Erosion (X_8)	-0.070	-0.115	0.171	-0.202	-0.089	0.008	-0.003	-0.122	1.000								
Flood hazard (X_9)	0.033	0.076	0.125	-0.268	0.090	0.156	0.148	-0.058	0.385	1.000							
Irrigation (X_{10})	0.635	0.290	0.045	0.025	0.112	0.336	0.458	0.286	0.045	0.095	1.000						
Res_ experience (X_{11})	0.270	0.193	0.132	0.108	0.116	0.182	0.409	0.215	-0.133	0.040	0.230	1.000					
HHs_ Experience (X_{12})	0.531	0.415	0.052	0.226	0.138	0.273	0.496	0.434	-0.127	0.018	0.306	0.677	1.000				
H_ highway distance (X_{13})	-0.136	-0.001	-0.266	-0.103	-0.031	-0.047	-0.010	0.145	-0.127	-0.158	-0.049	-0.027	-0.125	1.000			
No. of trainings (X_{14})	0.510	0.358	-0.007	0.199	0.318	0.384	0.411	0.355	-0.106	-0.031	0.270	0.198	0.464	0.018	1.000		
No. of visits (X_{15})	0.532	0.394	0.109	0.091	0.184	0.255	0.367	0.330	-0.086	0.057	0.352	0.164	0.391	-0.161	0.422	1.000	
Expenditure on farm input (X_{16})	0.501	0.378	0.018	0.078	0.149	0.192	0.372	0.297	-0.134	0.075	0.360	0.077	0.190	-0.212	0.385	0.387	1.000

5.4. Results

5.4.1. Predictions of the model

Nine independent variables that were strongly correlated with the dependent variable, (adoption of agroforestry-based land management practice, Y) were entered step by step in the regression model. Except for the variable, '*training',* all the remaining eight variables had significantly influenced the adoption of agroforestry-based land management practice (Table 5.4). The model has increased its explanatory power with addition of explanatory variables. With all variables included, the power of the model has increased from 44.9 to 74.9%. The model has a very high explanatory power since about 75 % of variation in adoption of agroforestry-based land management practice (AFLMP) is explained by the model.

Even though the addition of two variables, '*household's experience in agroforestry'* and *'distance of home to government forest'* have significantly influenced the adoption, the overall increase in adjusted R^2 is visibly low indicating that a very slight variation is explained by these two variables in adoption of AFLMP. Out of eight variables*, 'farm size'* played the most powerful role in explaining the variation in adoption. About 45% variation is explained by the farm size alone in farmer's decision of AFLMP adoption. In other words, out of the total variation that the model could explain, nearly 60% variation is explained by the '*farm size'*. Four variables, namely, '*farm size', 'irrigation water',* '*education of household heads',* and *'agricultural labour force'* have a greater influence in decision-making about the adoption of the practice as these four variables explain 92% of the total variation (0.749) (Table 5.4).

Table 5.4: Model summary

Model	R^2	Adjusted R^2	Std. Error of the estimate	F ratio	Significance
1	.452[a]	.449	.12590	142.857	0.000
2	.587[b]	.583	.10959	122.454	0.000
3	.658[c]	.652	.10001	109.860	0.000
4	.703[d]	.696	.09349	100.713	0.000
5	.728[e]	.720	.08972	90.594	0.000
6	.741[f]	.731	.08793	79.943	0.000
7	.754[g]	.744	.08583	73.238	0.000
8	.761[h]	.749	.08492	66.043	0.000

a. Predictors: (Constant), Farm size in hectare
b. Predictors: (Constant), Farm size in hectare, Availability of irrigation water
c. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents
d. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents, Agricultural labour force (between 15 to 60 years of age)
e. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents, Agricultural labour force (between 15 to 60 years of age), Frequency of visits by extension worker in the last 10 years
f. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents, Agricultural labour force (between 15 to 60 years of age), Frequency of visits by extension worker in the last 10 years, Expenditure on farm input purchase

g. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents, Agricultural labour force (between 15 to 60 years of age), Frequency of visits by extension worker in the last 10 years, Expenditure on farm input purchase, Household's experience in agroforestry
h. Predictors: (Constant), Farm size in hectare, Availability of irrigation water, Education of respondents, Agricultural labour force (between 15 to 60 years of age), Frequency of visits by extension worker in the last 10 years, Expenditure on farm input purchase, Household's experience in agroforestry, Distance from home to government forest
i. Dependent Variable: Adoption index used as proxy

5.4.2. Determinants of adoption of AFLMP

The regression analysis revealed that adoption of AFLMP was significantly influenced by eight variables, namely*, 'farm size', ' availability of irrigation water', 'level of education', 'number of agricultural labour force', 'frequency of visits', 'expenditure on farm input purchase', 'household's experience in agroforestry',* and *'distance of home to government forest'* (Table 5.5). These factors can be broadly grouped into three categories; personal and household characteristics of the farmers, resource endowments of the farmers and institutional factors.

Personal and household characteristics of the farmers

As hypothesized, education of the household head was found to be positive and having a significant influence on adoption of agroforestry-based land management practice. This implies that longer schooling of the HH head increased their ability to access information, and strengthened his/her analytical capabilities with new technology. Furthermore, a longer education leads to a better understanding of the new technology when reviewing the different extension materials, which enhanced adoption of improved technology such as agroforestry. Many authors report that education has a positive impact in the adoption of such soil conservation technology as agroforestry (Lapar & Ehui 2004; Tiwari et al. 2008).

Similarly, as expected the distance from home to the government forest was found to be influencing adoption decisions of farmers positively and significantly. This implies that people living close to the government forest have an easy access to the forest and can collect forest products such as timber, fuelwood, litter, fodder, fruits and many non-timber forest products and therefore they are reluctant to raise any tree crops on their farms. The effect of a household's experience on agroforestry technology was also found to be positive and significant, suggesting that farmers with substantial experience are more likely to adopt agroforestry because experience supports acquiring and enhancing knowledge. The farmer experimentation model developed by Foster and Rosenzweig (1995) showed that imperfect knowledge is a barrier to adoption.

Resource endowments of the farmers

The effect of holding size was found to be positive and have significant influence on adoption of agroforestry-based land management practice. The farm size appeared to be the most influential variable among the eight variables (Tables 5.4 and 5.5). Having irrigation facility also influenced adoption of agroforestry-based land management practice positively and significantly, suggesting that irrigation is vital to adoption of such integrated technology. Larger farms are intensively cropped and highly diversified (Chapter 6). This diversification and high intensity is caused by the irrigation facility that large farms were able to manage.

Institutional factors

Extension service proxied as frequency of visits by extension workers is an institutional factor. The model revealed that extension service had a positive influence in the adoption of agroforestry-based land management practice suggesting that farmers who receive more frequent services from the extension workers are more likely to adopt such farming technology.

Table 5.5: Coefficients of independent variables included in the model 8

	Unstandardized Coefficients		Standardized Coefficients		
Variables	B	Std. Error	Beta	t	Sig.
(Constant)	.134 (b_0)	.026		5.091	.000
Farm size in hectare (X_6)	.095	.008	.281 (b_1)	3.512	.001
Irrigation facility available in the farm (X_{10})	.022	.015	.148 (b_2)	6.271	.000
Education of household head (X_1)	.006	.002	.175 (b_3)	3.582	.000
Agricultural labour force (X_5)	.023	.004	.247 (b_4)	5.494	.000
Frequency of visits by extension workers in the last 10 years (X_{15})	.009	.003	.142 (b_5)	3.146	.002
Expenditure on farm input purchase (X_{16})	3.123./.E -5	.000	.124 (b_6)	2.753	.007
Household's experience in agroforestry practice (X_{12})	.003	.001	.122 (b_7)	2.589	.010
Distance from home to government forest (X_7)	.005	.002	.124 (b_8)	2.676	.008

Adjusted R^2 = 0.749

5.5. Final regression model and its implications

The final regression model that includes eight significant variables is presented below in a mathematical form. Since the explanatory power of the model is very high (about 0.75), use of this model in future research work would enhance the efficiency and saves time and money. There are certainly some other factors influencing adoption decisions. However, these final eight variables are the outcome of the rigorous process of model development as mentioned in previous section. It is, therefore, wise to consider this model while doing further studies in agroforestry adoption. Not only for research purpose, but also for implementation of any agroforestry intervention in a new area, this model could be a guiding model to select the right households so as to achieve the successful adoption of new technology.

$$AI = 0.134 + 0.281 \times X_6 + 0.148 \times X_{10} + 0.175 \times X_1 + 0.247 \times X_5 + 0.142 \times X_{15} + 0.124 \times X_{16} + 0.122 \times X_{12} + 0.124 \times X_7 ....(R^2 = 0.749)$$

Where,
AI = Adoption index; X_6, X_{10}, X_1, X_5, X_{15}, X_{16}, X_{12} and X_7 are defined in the Table 5.5.

5.6. Discussion

In studies of forestry, agroforestry and agriculture technology adoption, several variables, broadly grouped into five categories of farmer preferences, resource endowments, market incentives, bio-physical factors, and risk by Pattanayak et al. (2003), have been widely used and these variables have been evaluated for individual technologies adoption. However, as argued by Floyd et al. (2003), the results by individual technologies are useful only in identifying factors affecting adoption of the individual technologies, and are therefore limited in their ability to identify and describe the effects of, and the factors affecting, adoption of multiple technologies at farm level. Therefore, this model which is based on the index value that reflects the multiple technologies adoption needs to be judged against the findings of individual technologies adoption so that the relevance and significance of the method could be justified.

There are several factors affecting adoption and they are technology-specific. For example, low fertility of soil, high slope gradient of farm land, erosion and flood potential and size of livestock motivate farmers towards tree planting on their farm (Neupane et al. 2002; Pattanayak et al. 2003). The model suggests that these variables have no effect on farmers' adoption decisions, which is true because the study area farmers have raised trees not because their land is less fertile, highly sloppy, and prone to erosion and flooding. Except for a few households, most households have not experienced flood in the study area. It holds true that the farm land could be of poor quality in terms of bio-physical conditions to be supportive to promoting tree planting (Pattanayak et al. 2003) but it holds no significance at all that the farm land could be of poor quality to promote agroforestry-based land management practice. Similarly farmers prefer to raise trees in water-scarce areas but this model suggests that having a good source of irrigation water greatly influenced farmer adoption because farmers have raised agroforestry and horticultural trees not only in upland but also in low land with field crops that require irrigation water such as rice paddy, sugarcane, wheat and vegetables.

It was hypothesized there were some other variables that would have effects on farmer adoption decisions, but did not show such effects as expected. In male dominated societies, such as in rural areas of Nepal, it is expected that male-headed households are more adaptive to new technologies than female-headed (Adesina & Chianu 2002; Adesina 1996; Tiwari et al. 2008). Studies elsewhere have shown that gender plays a role in decision-making when it comes to the adoption of new technologies. The male-headed households are more likely to adopt new technologies such as tree planting and new crop varieties (Adesina et al. 2000; Doss & Morris 2000). Contrary to the previous findings, this study suggests that there is no such influence of gender on adoption of agroforestry-based land management practice. Paudel and Thapa (2004) reported that some household decisions such as land management are collectively made. Finding of this study also reinforces this argument.

Training was another variable used in this analysis to see its impact on decision making because it is expected having training on land management practice motivates farmers towards adopting such practice and plays an influential role in decision-making regarding land management (Paudel & Thapa 2004) but the finding of this study contradicts this. However, it might be too early to conclude that training had no effects on farmers' decision making because in the study area farmers have received such training in very recent years and therefore the effects of such training might not be reflected in their decision-making. *'Distance of home to highway'* was another variable hypothesized as increased distance would discourage farmers from adopting the agroforestry-based land management practice but the finding suggests that close to and far from the highway did not have affects on adoption decision of farmers. The reason might be the good road networks in the study area and farmers have good access to transport facilities, both public and private, and therefore they do not have problems with transporting their farm products. Tractors, bullock-cart, auto rickshaw, cycle, motorcycle and public vehicles are the means of the transport in the study area.

The farm size has a positive and significant influence on adoption decisions (Table 5.5), suggesting that farmers who possess larger landholdings are more likely to adopt AFLMP. The finding of this study coincides with the findings of Tiwari et al. (2008) and Pattanayak et al. (2003). This is because larger farm holders are more likely to make high investment in land management and can take high risk and can survive crop failures due to unfavourable conditions such as insect and pest outbreaks, hailstones, and excess rainfall (Amsalu & de Graaff 2007). Nowak (1987) also supported the theory that larger farms offer farmers more flexibility in their decision-making, more opportunity to new practices on a trial basis and more ability to deal with risk.

Education of the household heads has significantly influenced the adoption of AFLMP. The household heads that have got higher degrees of education obviously acquire more knowledge that leads to higher analytical capabilities. Education also helps them have better contact and rapport with several government and non-governmental organizations and obtain relevant information from them. This is the reason why higher education is associated with the tendency of adopting AFLMP. Agroforestry-based farming is a knowledge and management intensive technology, requiring ability to manage properly to achieve the optimum results (Adesina & Chianu 2002). It was found that education had a significant influence in a farmer's decision whether or not adopting the agroforestry-based land management practice and this finding was in agreement with several previous studies (Adesina & Chianu 2002; Lapar & Ehui 2004; Paudel & Thapa 2004; Sheikh et al. 2003; Tiwari et al. 2008).

Farmers with higher income have a high purchasing power. As hypothesized, farmers with high purchasing power (Expenditure in farm input purchase as a proxy) have a positive and significant influence on adoption decisions (Table 5.5). Adopting the AFLMP means increasing farm inputs such as fertilizer, pesticides/insecticides, improved seeds and seedlings and these inputs are linked with the income of the farm households. It is expected that farmers with higher income are encouraged towards investment in AFLMP. The finding of this study agrees with the finding of Kessler (2006), who found that a greater income from the same unit of land encourages farmers to invest in land management.

Visits by the extension workers are a kind of extension service which had a positive and significant influence on adoption decisions (Table 5.5). Contact with the extension workers allows farmers to learn more about the new technologies and helps them build up confidence to adopt such technologies. Extension workers help to clarify any doubts that farmer may have regarding the new practices and motivate them to adopt the new land management practice. This is the reason why there is tendency towards the adoption of the AFLMP when increased frequencies of visits by the extension workers occurs (Ison & Russell 2000). This is in agreement with the finding of (Adesina & Chianu 2002; Lohr & Park 1994; Norris & Batie 1987; Paudel & Thapa 2004).

'Availability of irrigation water', 'household's experience in agroforestry' and *'distance of home to government forest'* has also significantly influenced the adoption decision (Table 5.5). With the agroforestry-based farming system being an intensive type of farming, irrigation is very necessary to maintain the farm productivity and therefore farmers who have a regular source of water for irrigation are more likely to adopt this kind of land management practice. Likewise, farmers who have got long experience in agroforestry may have accumulated more knowledge of benefits of such land management practice from their accumulative years of experience and that motivates farmers to adopt more integrated land use system such as agroforestry-based land management.

Variable, *'distance of home to government forest'* was one of the least influential predicting variables of the model (Table 5.4). The households that are located far from the nearby forest tend to promoting trees on their farms (Sapkota & Oden 2008) and the extent of tree planting is influenced by the livestock number (Neupane et al. 2002). Since this study covers the adoption of multiple technologies including field adoption of crops varieties, which have nothing to do with distance of home to forest, this variable might have the lowest explanatory power on the farmers' decision of adoption of such a complex agroforestry-based land management. There is a tendency of introducing tree crops into the farm production system as the distance of home to government forest increases because the people living adjacent to an open access forest like government forest can get their basic needs of timber, fuelwood, fodder and other non-timber products from there quite easily and therefore they are reluctant to tree planting on the farm.

5.7. Conclusions

This model clearly indicates that the variables which are significant in the case of single technology adoption were non-significant in the case of farmer's decision about multiple technologies adoption, such as agroforestry-based land management practice. Since the model was verified with the field situation and found it to be representing the ground reality, it can be concluded that the Adoption index (AI) more truly reflected the proxy measure of the adoption of agroforestry-based land management practice rather than simply using the tree as a dependant variable. Therefore, this model would definitely have a wider applicability than the technology specific model. Policy recommendation based on such model could reflect the ground reality at micro (farm) level and such a policy intervention would be more successful.

Adoption of the agroforestry-based land management practice was significantly influenced by a range of factors. The regression model revealed that adoption of AFLMP was significantly influenced by farm size, education, expenditure in farm input purchase, availability of irrigation water, agricultural labour force, frequency of visits by extension workers, household's experience in agroforestry, and distance of home to the government forest.

From this study it appears that the knowledge base of the farmers greatly influences the adoption decision. Therefore, efforts to promote agroforestry-based land management practice should focus on interaction between farmers and extension workers so that farmers could get access to information regarding new farming technology that enhances the farm productivity and supports in mitigating land degradation. It is clear from the model that the level of adoption of AFLMP tends to decrease as the household is closer to the open access forest and therefore focus should be towards formulating the policies that can motivate the farmers living close to the forest towards adopting AFLMP. Such policy effort will not only give support in conserving forest resources and hence enhancing carbon sequestration but also give support in restoring land productivity of the farm.

Analysis and presentation of results by individual technologies, while useful in identifying factors and effects related to the individual technologies, is limited in its ability to identifying and describing the effects of, and the factors affecting, adoption at the farm level where farmers integrate several farming practices. Therefore, the model that was developed using the index value could better serve the purpose of analysing the factors influencing adoption decisions of farmers who have promoted a mix of farming technologies simultaneously. Although this research is directly applicable to the study site, more specifically to the households sampled in Dhanusha District, the findings could be helpful in understanding what the drivers could be that lead to adoption of the more integrated farming system such as agroforestry in similar areas (in Nepal's *terai*, southern Asia, and sub-tropical developing countries).

Out of eight variables influencing the adoption decision, resource endowment of the farmer, i.e. farm size, played a more important role than did personal and household characteristics and institutional factor. This implies that some policy intervention is required so that farmers can have access to larger farms. Cooperative (collective) farming could be one option to promote agroforestry-based land management practice in the study area. However, maintaining the large farms is a big challenge in Nepalese society because when sons get married, they prefer to separate, and the parents property (capital and land) are equally divided into sons and parents, which results into land fragmentation, leading to small size farms in the future. Therefore, maintaining large farms is a big challenge for planners and policy makers in the future without some progressive policy intervention that could attract farmers towards collective (joint) farming.

Chapter 6

Economic Evaluation of Agroforestry-based Farming Systems with and without Carbon Values

6.1. Introduction

In previous chapter, potentiality of adoption of the agroforestry-based farming system was analysed through multiple regression. For farmers to be motivated to adopt any farm technology, economic viability of the technology needs to be assessed. In this chapter, the economic viability of the agroforestry-based farming system is assessed in terms of return-to-land and return-to-labour against the prevailing subsistence agricultural system, first based on the tangible benefits and second by incorporating the greenhouse gases. A 30-year time horizon, which is one agroforestry cycle adopted by the farmers of the study area, is considered for the analysis.

Broadly this chapter is divided into four sections. In the first section, the net present value (NPV) is analysed from the tangible benefits for the four types of farming systems of the study area and sensitivity of NPVs is assessed with different key parameters; agroforestry (AF) crop yield, field crop yield, price of farm inputs and labour wage. In the second section, the NPV is again analysed with incorporating carbon value and sensitivity is analysed with different carbon prices. In the final two sections, discussions and conclusions are given.

6.2. Fundamental features of four farming systems of the study area

The existing farming systems of the study area were categorised into four, namely, subsistence agriculture system (SAS), less integrated agroforestry system (LIS), medium integrated agroforestry system (MIS) and highly integrated agroforestry system (HIS) (see Chapter 4 for details) for the purpose of identifying the best farming practice from both the livelihood and environmental point of view. In the following section some distinguishing features of each farming system are discussed.

6.2.1. Land-use pattern

Field crop production was the dominant type of land use in all farming systems. More than 55% of the farmland has been utilized for field crop production. However, the percentage of the farmland allocated for the field crop production varied with the farming system. About 89% of the farmland was under field crop production in subsistence agriculture. More than 25% of the farmland has been utilized as horticulture in the three agroforestry-based farming systems while more than 5% was as agroforests (woodlots). Mainly two patterns of tree planting were observed in all tree-based farming systems; I) agroforests (woodlots) and II) the trees raised in the bund, around homestead and boundary plantation.

A distinct variation was found in terms of tree density between these two patterns across the three systems. About 46% of the total trees were grown as pattern II in the less integrated system while this type of planting pattern accounts for only 41% and 36% in medium integrated system and highly integrated system, respectively. This sort of variation is attributed to the average landholding of each system; the higher the landholding size, the higher the area allocated for pattern I, and the less emphasis on pattern II and vice versa. The size of the farmland is negatively correlated ($r = -0.31$) with adoption of pattern II planting while the farm size is positively correlated ($r = 0.31$) with pattern I planting.

The main agroforestry tree species in these three systems were *Eucalyptus camaldulensis, Dalbergia sissoo, Gmelina arborea, Melia azedarach,* and *Anthocephalus chinensis*. The average number of trees grown in the highly integrated system was found to be significantly higher ($p < 0.01$) than in the other two systems. A considerable variation was found in terms of the density (number ha^{-1}) of each tree species across these three systems also (Table 6.1). *E. camaldulensis* was the dominant tree species in all three agroforestry-based farming systems. Overall more than 65% of the trees raised in the respective systems were *E. camaldulensis* (Table 6.1). However, this species accounts for more than 75% in the less integrated agroforestry system.

Table 6.1: Land-use pattern of the study farming systems

	Types of farming systems			
Farm attributes	HIS	MIS	LIS	SAS
Average farm size (ha)	2.59	1.52	0.75	0.55
Average field crop area (ha)	1.65 (64)	0.99 (65)	0.42 (56)	0.49 (89)
Average agroforest area (ha)	0.25 (10)	0.08 (5)	0.04 (5)	0.0 (0)
Average horticulture area (ha)	0.65 (25)	0.40 (26)	0.23 (31)	0.0 (0)
Average homestead area (ha)	0.04 (1)	0.06 (4)	0.06 (8)	0.06 (11)
Average tree density (number ha^{-1})*	233	146	144	0
E. camaldulensis	158 (68)	103 (71)	109 (76)	0
D. sissoo	26 (11)	10 (6)	5 (4)	0
G. arborea	12 (5)	3 (2)	4 (3)	0
M. azedarach	16 (7)	13 (9)	12 (8)	0
A. Chinensis	6 (3)	9 (6)	6 (4)	0

Figure in the parenthesis indicates percentage.
HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system
* includes not only five study species but also other trees grown on the farm

6.2.2. Tree distribution pattern

Based on mode of tree planting, the tree distribution pattern could be grouped into two categories namely agroforest (block plantation/woodlot) and tree raised beyond agroforest such as wind breaks, alley, homestead and buffer strips for the purpose of this study (Table 6.2) because the study objective was to evaluate the system performance at a whole-farm level, not between such different agroforestry tree patterns within the farming system. The distribution ratio was higher in the highly integrated agroforestry system than in other two systems (Table 6.2) indicating that the farmers who have adopted the HIS system were more inclined to agroforest promotion rather than raising trees beyond agroforest. The LIS system has the lowest ratio which indicates that the farmers who have adopted this system were more inclined to raising trees beyond agroforest. One prominent reason of this sort of distinct variation in terms of tree distribution among these systems could be the average farm size of each system because farmers with bigger farm size has allocated higher proportion of their land for agroforest as compared to those who have got smaller far size (Table 6.1).

Table 6.2: Distribution pattern of agroforestry trees on the farms of the study area

Distribution pattern	HIS	MIS	LIS
Agroforest	150 (64)	87 (59)	77 (54)
Tree beyond agroforest	83 (36)	60 (41)	67 (46)
Distribution ratio*	1.8	1.4	1.2

Figure in the parenthesis indicates percentage
HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system and LIS = less integrated agroforestry-based farming system
* Between number of trees under the 'agroforest' and 'trees beyond agroforest'

6.2.3. Variation in cropping pattern across four farming systems in the study area

Overall the main field crops cultivated in the all four systems were paddy, wheat, maize, sugarcane, mustard, lentil, pea, millet, *Gahat* and vegetables. However, considerable variation was found in cropping pattern among these systems. Specifically the legume crops lentil, pea and *Gahat* were not cropped in subsistence agriculture while mustard was excluded from the less and medium integrated agroforestry-based farming system. Amongst the field crops, more than 50% of the farm was occupied by cereal crops (paddy, wheat and maize) in the subsistence type agriculture, while in the other three tree-based farming systems; it was less than 40% (Table 6.3). The irrigated paddy, however, which is the major source of methane emission from agriculture, occupied more than 5% of the farm area in the highly integrated systems while this crop accounts for less than 3% in the subsistence agriculture. This figure is very important while analysing the comparative benefits of these farming systems from climate change mitigation perspective in the sections to follow.

The rain-fed paddy occupied more than 20% of the farm area in the subsistence agriculture while this crop accounts for less than 18% in all three tree-based systems. More than 25% of the farm area in the subsistence agriculture was occupied by sugarcane while this crop accounts for less than 25% ranging from (17 to 23%) in the three tree-based faming systems. This is because certain portion of the farm was occupied by the tree crops (both agroforestry and horticultural tree species) in these three farming systems.

Legume crops, including mustard and pulses including pea, lentil and *Gahat* represented more than 10% of the farm area in the highly integrated agroforestry system compared with less than 2% in the subsistence agriculture. Even though cultivation of legume crops contributes nitrogen, organic matter and other plant nutrients to the soil, and helps restore phosphorous and potassium extracted by crops these legumes (Lynam & Herdt 1989; Phiri et al. 2001), they are the source of nitrous oxide (N_2O). However, this study did not quantify the contribution of legume crops to fertility enhancement and greenhouse gas (GHG) emissions.

Table 6.3: Area under different crops in the study area of Dhanusha district, Nepal

Farm attributes	HIS	MIS	LIS	SAS
Average area under cereal crops cultivation (%)	40	39	37	54
Average area under irrigated paddy (%)	5	0.5	1.5	2
Average area under rain-fed paddy (%)	17	16	15	23
Average area under legume crops cultivation (%)	11	5	3	1
Average area under sugarcane cultivation (%)	20	24	17	27
Average area under vegetable cultivation (%)	4	5	7	8

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

Variation was also found in cropping intensity (CI), field crop diversification (CD) and mixed cropping (MC) (Table 6.4). Cropping intensity (CI) in the highly integrated agroforestry system (2.0) was found to be higher than in the other three systems, and even higher than the national average cropping intensity of 1.83. The CI has increased from 1.4 in the subsistence agriculture to 2.0 in the highly integrated system (Table 6.4). The higher cropping intensity in the highly integrated system is attributed mainly to the practice of mixed-cropping of pulses with wheat and mustard and allocation of higher proportion (10%) of farm area to forest crop compared to other two trees-based farming systems because the introduction of tree crops may force farmers towards more intensive cultivation mainly to offset the productivity loss caused by the decrease in cropped area and shedding effects of the tree crops to the field crops.

In terms of crop diversification, the highly integrated system was found to be superior compared to other three systems. The degree of diversification, which is less than 20, falls under very high diversification, that which is between 20.1 and 25.4 falls under high diversification and that which is between 25.5 to 40.5 falls under little diversification (Bhatia 1965). The higher degree of cropping diversification in the HIS system supports efficient use of different types of nutrients available in soil and also supports to increase agro-biodiversity and reduces the risk of crop failure, thereby making farms less vulnerable to food shortage (Frison et al. 2011). However, the farm input, particularly the application of chemical fertilizers, is associated with higher degree of crop diversification and hence are of prime importance because the chemical fertilizer is a source of GHG emissions. The rate of fertilizer application is negatively correlated (r = -0.99) with the degree of diversification. This study finding reinforced this argument because the rate of fertilizer application (321.5kg ha^{-1} $year^{-1}$) was much higher in the highly integrated system and differed significantly ($p < 0.05$).

Table 6.4: Cropping intensity, crop diversification and mixed cropping

	Index values			
	HIS	MIS	LIS	SAS
Cropping intensity[a]	2.0	1.6	1.5	1.5
Crop diversification[b]	17.6	20.9	24.4	25.5
Mixed cropping[c]	0.10	0.04	0.02	0.0

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

[a] The higher the index value, the higher the intensity.

[b] The lower the index value, the higher the diversity.

[c] The higher the index value, the higher the mixed cropping.

6.3. Economic performance of agroforestry-based farming systems without carbon value - Base case scenario

6.3.1. Total labour input per hectare

The labour inputs (man-days ha^{-1}) for a rotation of thirty years were lower in the highly integrated systems than in the other three farming systems (Table 6.5). The trend of labour input had decreased gradually from the subsistence agricultural system to highly integrated agroforestry system. The HIS system required more than 50% less man-days (ha^{-1}) than the SAS system. Two other systems MIS and LIS were less labour intensive also as compared to the SAS. The MIS and LIS systems required 41% and 26% less man-days than the SAS. This sort of high variation is due to the fact that the three systems HIS, MIS and LIS allocated a considerable area of the farm under tree crop planting as horticulture and agroforest (Table 6.1), which is less labour intensive than the field crops cultivation.

The total labour inputs varied considerably among the three tree-based farming systems as well (Table 6.5). This is due to the fact that the majority of the farmers in the highly integrated system used farm machineries (tractor and thresher) during land preparation and post harvesting, which reduced the labour demand considerably. The difference of average labour inputs (man-days ha^{-1} yr^{-1}) was statistically significant between these four farming systems ($p < 0.05$).

6.3.2. Total production cost per hectare

The production costs included labour costs and non-labour costs. The non-labour costs included costs of seed/seedlings, pesticides, fertilizers, livestock, livestock rearing and farm tools and tools maintenance. Labour inputs alone covered more than 50% of the total costs in these systems. Compared to SAS, the three tree-based systems HIS, MIS and LIS invested 40%, 34% and 30% less costs on production, respectively, in a 30-year period (Table 6.5). Similarly, these tree-based systems invested 50%, 39% and 24% less costs on labour-hiring compared to the SAS. The total cost has increased with a decrease in integration level. The cost (ha^{-1}) was negatively correlated ($r = -0.54$) with the farm size (Figure 6.1). Increased farm size has reduced the cost of production per hectare.

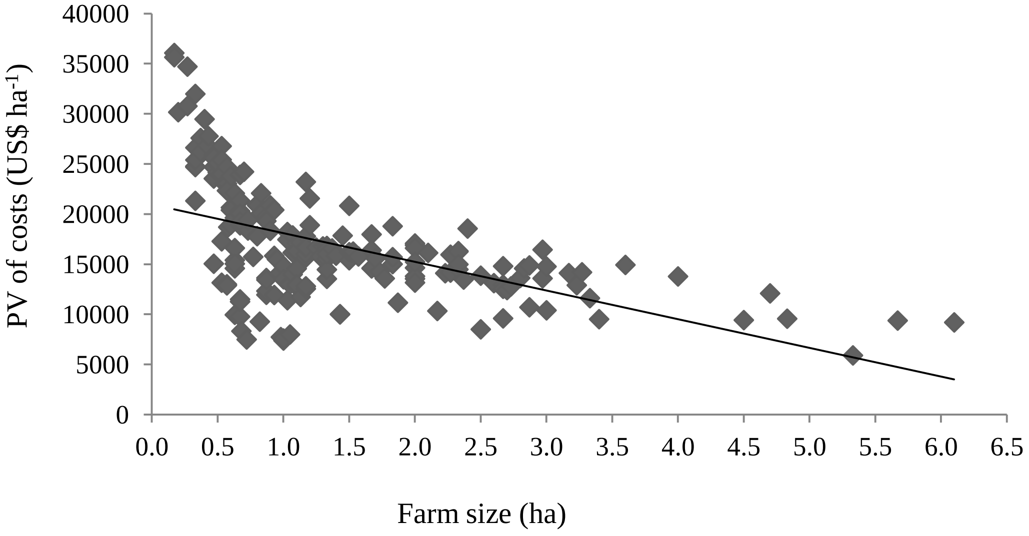

Figure 6.1: Relationship of cost of production (ha^{-1}) and farm size

6.3.3. Return-to-labour and return-to-land

The analysis of NPV revealed that all four farming systems were financially attractive farm enterprises but the HIS gave the highest economic return compared to other three systems and 38% more benefits than the subsistence agricultural system (Table 6.5). The discounted cash flow (DCF) of these farming systems is given in the Appendix D, table D.5. The other three farming systems were more competitive. This is due to the fact that the MIS and the LIS were less diversified and less intensified and the crops were less mixed in these two systems compared to the highly integrated system (Table 6.4). The NPV of farm enterprise has increased with increase in farm size (Figure 6.2). This is mainly due to the fact that the larger farms adopted much more diversified farming with higher crop intensity that helped to maximise farm productivity (ha^{-1}) (Tables 6.4 and 6.5) and reduce the cost of production (ha^{-1}) (Figure 6.1). This proved the *hypothesis-3* that HIS generates higher economic return (ha^{-1}) compared to other three farming systems.

Figure 6.2: Relationship between NPV (US$ ha^{-1}) and farm size

The cost-benefit analysis also revealed that all four farming enterprises are profitable. A big limitation of the B–C ratio, particularly in the context of small farming as in the case of the study area, is that it does not reflect the actual amount of benefit that farmers derive from the investments they have made. Small farm holders' decisions regarding what kind of land use they will adopt depend not on the input–output ratio, but largely on the net amount of income that they earn (Thapa & Weber 1994). The NPV analysis revealed that the NPV of HIS was much higher than that of other three farming systems (Table 6.5), reflecting that the HIS was the most attractive farming practice financially. However, the question arises as to why farmers are practicing the other three farming systems - less attractive ones despite higher benefits from the highly integrated agroforestry system. Its causes (factors) are explained in the Chapter 5.

Return-to-labour, as opposed to land, may be a more appropriate indicator of financial attractiveness to farmers, especially in areas where labour is relatively scarcer than land (Kwesiga et al. 1999). In an area such as the study district where land as well as labour is scarce, return-to-land (NPV) and return-to-labour are most appropriate criteria while evaluating farm enterprises. An examination of the returns-to-labour showed that the agroforestry-based farming systems, be it highly integrated or less, were more attractive than the SAS. In terms of labour inputs (man-days ha^{-1}), the three tree-based farming systems were less labour intensive compared to the SAS (Table 6.5).The return-to-labour was higher in all farming systems compared to the prevailing wage of US$ 2.62 man-day^{-1} in the study area but higher return was achieved from the tree-based farming enterprises compared to the SAS. The return-to-labour from a highly integrated agroforestry system was a respectable US$ 6.67 man-day^{-1}, which was 62% above that from subsistence agricultural system. The returns from the MIS and LIS were 30% and 24% higher than that from the SAS (Table 6.5). The analysis revealed that the highly integrated agroforestry system was more efficient in terms of labour use, return-to-land and return-to-labour compared to the other three farming systems.

Table 6.5: Economic performance of agroforestry-based farming systems for a 30-year time horizon with a discount rate of 0.12

	HIS	MIS	LIS	SAS	Compared to SAS =100		
					HIS	MIS	LIS
Net present value (NPV) (US$/ha)	7243.5	5572.5	5353.6	5232.4	138	106	102
Total labour inputs (Man-days/ha)	8883.3	10818.0	13603.1	18270.0	49	59	74
Average labour inputs (Man-days/ha /year)	296.1	360.6	453.4	609.0	-	-	-
Return to labour (US$/man-day)	6.67	5.36	5.10	4.11	162	130	124
Agricultural wage (US$/man-day)	2.62	2.62	2.62	2.62	-	-	-
B-C ratio	1.56	1.39	1.35	1.24	125	112	109

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

* 1 US $ = NRs.76.26

6.4. Economic evaluation of agroforestry-based farming systems under alternative scenarios: sensitivity analysis

In the Chapter 5, several factors that could affect the farmers' decisions with regards to the adoption of multiple technologies such as an agroforestry-based farming system in the study area were discussed. Factors were analysed through a multiple regression analysis. However, farmers' decisions were also influenced by the profitability and risk associated with any new technologies compared to other alternatives available. Therefore, in this chapter an attempt was made to evaluate the agroforestry-based farming system against the conventional agriculture in the study area. The results of this study revealed that the highly integrated agroforestry-based farming system (HIS) appeared to be performing better in terms of NPV, B-C ratio and 'return-to-labour' based on the current conditions and assumptions.

An agroforestry system by its very nature, i.e. being a long-term enterprise compared to annual agriculture and also the results of this study are based on the *ex-ante* approach of project appraisal, there involves varieties of risks and uncertainties. While making decisions on the adoption of new technologies, including land use systems, farmers are not only concerned about costs and benefits, but also about such risks and uncertainties associated with them. Therefore, a sensitivity analysis was conducted to assess the effect of variation in selected variables such as prices of inputs and outputs on the profitability since future values of a project's costs and benefits are unknown.

In this study, sensitivity of NPV to the variation in seven key variables was tested. The variables considered were (1) discount rate, (2) fertiliser cost, (3) seed/seedling cost, (4) labour price (wage), (5) yield of agroforestry (AF) crops (tree crop and horticultural crops), (6) yield of field crops and (7) AF products (AF crops and field crops). All variables except the discount rate were varied by ±25% to compare which variable would affect the NPV most. Discount rate was changed only ±9% because it was unreasonable to assume the local discount (interest) rate would change hugely (such as 25%). Sensitivity analysis was conducted for seven major variables by varying one at a time (Table 6.7).

In the study area, where the market for agroforestry produces such as timber, fuelwood and fruits, other support services such as extension services, and infrastructure viz. irrigation facilities, are not well-developed, varieties of risks and uncertainties may involve if farmers decide to shift from agriculture to the highly integrated an agroforestry-based farming system. The yields of different components of agroforestry are prone to be adversely affected by natural hazards such as pest and disease attack, winds, drought and hailstones and at the same time the weather (rainfall and temperature) could be favourable and that would support to higher yield. Moreover, the farmers may attach high value on present income and discount the future income at a much higher rate due to poverty and other socio-political situations. In view of such possibilities, the evaluation of agroforestry-based farming systems and agriculture were done by changing the key variable as described above.

6.4.1. Return-to-land under different discount rate scenarios

Two discount rates (3% - social discount rate and 21% - private discount rate) were applied to see the sensitivity of net return-to-land (Net economic benefits) to change in discount rates. As pointed out by Current et al. (1995), the farmers' actual discount rates may vary according to their level of savings, alternative income sources, risks associated with new technologies, degree of tenure security, access to formal and informal credits, market mechanisms and so forth. From social perspectives agroforestry is considered an environmentally friendly technology as it supports to enhance biodiversity, conserve water resources, control soil erosion, and supports to climate change mitigation through carbon sequestration. Hence, the society's actual discount rate would be definitely lower than the farmers'. Therefore, for this study the sensitivity was analysed at 3%, and 21% with 12% as a reference situation (Table 6.6).

Table 6.6: Return to land from four farming systems under different discount rates

Farming types	Discount rate (%)		
	3	12	21
Highly integrated agroforestry-based farming System	21839.6	7243.5	3579.3
Medium integrated agroforestry-based farming System	17724.1	5572.5	2590.0
Less integrated agroforestry-based farming system	17618.8	5353.6	2368.4
Subsistence based agriculture system	16556.8	5232.4	2254.7

The results showed that even at the higher discount rate of 21%, the HIS performed better than the other three farming systems in terms of NPV and B-C ratio and return-to-labour. It is expected that tree-based systems are financially less attractive than agriculture with higher discount rate because benefits from tree components are heavily discounted compared to costs. Even though the three agroforestry-based farming systems, i.e. HIS, MIS, and LIS, are tree-based farming systems, the contribution of the tree components (AF and horticultural tree products) in NPV was less than 35% and more than 65% came from field crops and livestock. Because of higher cropping intensity and more diversified cropping in agroforestry-based farming systems than in the subsistence agriculture system, the NPVs from field crops, although slightly higher in SAS, did not vary greatly among these four farming systems. These might be the reasons why agroforestry-based farming systems were still performing better even in higher discount rate. This is not surprising because similar results were found with 20% discount in the majority of agroforestry projects implemented in Central America and the Caribbean (Current et al. 1995).

6.4.2. Comparison of NPVs and return-to-labour of four farming systems with respect to change in field crop yield while other parameters remain constant

The biological relationships among system components (trees and field crops) under the agroforestry system are competitive as well as complementary and supplementary (Filius 1982; Hoekstra 1987). Competition is more pronounced between system components when the resources, i.e. nutrients, water and light, are limited and that results in reduced yield (Hoekstra 1987; Wannawong et al. 1991). Beyond this competitive interaction, the tree component of the system also contributes to soil fertility enhancement through addition of leaf litter into the soil and nitrogen fixation.

The result showed that the variable ‘field crop yield’ was most sensitive out of the five variables (Table 6.7). With a change in field crop yield (±25%), the range of NPV was largest in all farming systems. SAS was most affected by this change in field crop yield. This is because 89% of total NPV came from field crops in the case of SAS but field crop contribution is 64%, 65% and 63% of the NPV in HIS, MIS and LIS, respectively.

6.4.3. Comparison of NPVs and return-to-labour of four farming systems with respect to change in tree and horticultural crops (AF crops) yield while other parameters remain constant

The yields of tree crop (timber/fuelwood and poles) and horticultural crops (fruits) are prone to be adversely affected by natural hazards such as pest and disease attack and unfavourable weather conditions such as drought and extreme wind (Rasul & Thapa 2006). In the study area as well, *D. sissoo*, the second dominant tree species after *E. camaldulensis*, is more susceptible to disease and farmers have faced a considerable loss because of an unidentified disease in the *sissoo* tree in the past (Joshi et al. 2005). Similarly, *E. camaldulensis* is susceptible to pest and insect attack (Lanfranco & Dungey 2001). However, the impact is not as severe in the case of *E. camaldulensis* as in *D. sissoo* in the study area. The horticultural crop particularly the mango, the most dominant fruit tree in the study area, is adversely affected by high speed wind and draught during flowering season, i.e. March and April. Also the favourable weather conditions would support in increased production. Keeping all these possible effects on overall tree and horticultural crop yields in mind, it was assumed that the production would be affected by ±25%.

The result revealed that even with a 25% yield decrease, the HIS was found to be superior in terms of both return-to-land and return-to-labour. The other two systems, MIS and LIS, while not performing better as SAS in terms of NPV, were more attractive than SAS in terms of return-to-labour (Table 6.8). Interestingly, the Net present value (NPV) as an indicator for the economic attractiveness is not very sensitive to changes in AF crop yields. A 25%-change in these variables leads to a variation of about 10% only (Table 6.7). This is because the contribution of AF crops in total NPV is less than 35% for all tree-based farming system.

Table 6.7: NPV sensitivity of the four farming systems to the change of an input variable

Parameters	Return- to- land (NPV- US $ ha^{-1})				Return- to- labour (US $/man-day)			
	HIS	MIS	LIS	SAS	HIS	MIS	LIS	SAS
Reference situation	7243.5	5572.5	5353.6	5232.4	6.67	5.36	5.10	4.11
AF crops yield								
Decrease by 25%	6656.6 (-8.1)	5105.6 (-8.4)	4838.7 (-9.6)	5232.4	6.40	5.05	4.82	4.11
Increase by 25%	7841.2 (8.8)	6062.0 (8.3)	5895.3 (10.1)	5232.4	7.13	5.67	5.38	4.11
Input costs								
Fertilizer								
Decrease by 25%	7510.1 (3.7)	5819.8 (4.4)	5510.3 (2.9)	5377.8 (2.8)				
Increase by 25%	6976.9 (-3.7)	5325.3 (-4.4)	5197.0 (-2.9)	5087.1 (-2.8)	6.56	5.27	5.10	4.08
Seeds								
Decrease by 25%	7600.9 (4.9)	5961.4 (7.0)	5635.6 (5.3)	5703.5 (9.4)				
Increase by 25%	6886.1 (-4.9)	5183.7 (-7.0)	5071.6 (-5.3)	4741.4 (-9.4)	6.51	5.22	5.10	4.01
Labour								
Decrease by 25%	8844.3 (22.1)	7518.7(34.9)	7792.6 (45.6)	8448.8 (61.5)				
Increase by 25%	5642.7 (-22.1)	3626.4 (-34.9)	2914.6 (-45.6)	2016.1 (-61.5)	6.67	5.36	5.10	4.11
Field crops yield								
Decrease by 25%	3880.1 (46.6)	2440.9 (56.2)	2374.2 (55.7)	943.5 (82.0)	6.10	4.93	4.77	4.11
Increase by 25%	10620.9 (46.6)	8704.2 (56.2)	8333.1 (55.7)	9521.4 (82.0)	8.09	6.44	5.91	4.99
AF products (Field crops and AF crops) yield								
Decrease by 25%	3293.2 (-54.5)	1974.0 (-64.6)	1859.3 (-65.3)	943.0 (-82.0)				
Increase by 25%	11218.6 (54.9)	9193.7 (65.0)	8874.8 (65.8)	9521.0 (82.0)				

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system. Figures in parentheses are percentage changes from the reference situation

6.4.4. Comparison of NPVs and return-to-labour of four farming systems with respect to change in inputs price while other parameters remain constant

Labour, fertilizer and seeds/seedlings are the major farm inputs in the study area. Fertilizer and seed/seedlings are responsible for about 4% and 5% of the total cost, respectively. The result revealed that the change in fertilizer and seed costs was less sensitive to the NPVs of all farming systems as compared to change in labour cost. Change in seedling and fertilizer costs change (±25%) did not fluctuate the NPV much compared with other variables in all farming systems. Labour price changes (±25%) affected the NPV of the HIS, MIS, LIS and SAS differently, causing a large change in the NPV of SAS while causing very little in the NPV of HIS. This is because the SAS farming system is the most labour intensive practice of the four systems studied. Increase in labour cost (25%) has affected the NPV of LIS and SAS significantly. The NPV has dropped by 45% and 61%, respectively. Even though the NPV of HIS system was affected by increase in labour cost, the decrease in NPV was less than half of SAS and LIS (Table 6.7).

6.5. Assessment of economic performance of agroforestry-based farming systems with carbon values

In the first section of this chapter, four different farming systems were evaluated based on the tangible benefits that farmers achieved from the system components. In this section, these systems are further evaluated with greenhouse gas (GHG) value (carbon value). A sensitivity analysis is performed with a different carbon price to see its effects on NPVs of these farming systems. To achieve this goal, first the total emission and sequestration of GHG is estimated for each farming system and then NPV is recalculated including the GHG values.

6.5.1. Integrated evaluation of GHG (CO_2, CH_4 and N_2O) emissions from four farming systems

One of the objectives of this study was to assess the profitability of four farming systems including carbon value. To meet this objective it is necessary to determine and discuss the aggregate GHG emissions from four different farming systems and carbon sequestered by the agroforestry-based farming systems first. Therefore in the following sections, the amount of GHG emissions from different sources and carbon sequestered by tree component of the agroforestry-based practices are discussed first and then followed by the profitability of these farming systems.

Fossil fuels and synthetic fertilizer use

Diesel is the only fossil fuel that is used in the study area for farming purpose. Thresher and tractor both run on diesel engines and are used for agricultural activities. The thresher is used during post-harvest of wheat and paddy while the tractor is used for land preparation. The mean amount of diesel fuel consumed at farms HIS, MIS, LIS and SAS was 87.1, 70.4, 37.8 and 36.2 litres ha^{-1} $year^{-1}$, respectively. The greater consumption rate observed for HIS was not only due to the larger area of farmed soils (Table 6.1), but also to greater consumption per hectare

(Table 6.8) owing to the more intensive soil management because of higher cropping intensity of farm HIS (Table 6.2).

A similar trend was observed in the case of fertiliser application as in the case of diesel consumption. The mean amount of fertiliser applied at farms HIS, MIS and LIS was 321.5, 284.2, 174.8 and 166.5Kg ha^{-1} $year^{-1}$, respectively. The greater application rate observed for HIS was not only due to the larger area of farmed soils, but also to the greater application rate per hectare (Table 6.8) owing to the more intensive soil management because of higher cropping intensity (Table 6.2) and smaller number of livestock. Because of bigger number of livestock in SAS, some amount of fertilisers required for cultivation is compensated by the farm yard manure (FYM). The reason for higher livestock (herd) size in SAS might be the distance from home to national forest, which is only an average of 4.8 km and that allows farmers easy access to the forest and forest resources while the average distance of HIS, MIS and LIS was 12.6, 7.4 and 5.7 km, respectively (Chapter 4, Table 4.9). There is a strong negative correlation (r = -0.45) between distance and the herd size.

Fuelwood and crop residue burning

Fuelwood and crop residues are still the source of energy used for cooking and heating purposes in the study area despite some affluent households using alternative energy sources such as biogas, liquefied petroleum gas (LPG) and electricity. Both the fuelwood and crop residue consumption rate was higher in SAS than in other three farming systems. The consumption rate has decreased with the increase in the farm integration level (Table 6.8). The SAS farmers consumed 4.6 times more fuelwood than the HIS farmers. The requirement of energy sources largely depends on the family and number of livestock. Both the family size and livestock number were much higher in SAS than in other three farming systems (Tables 6.8 and 6.9).

Table 6.8: Annual consumption of farm inputs by four farming systems

Farm attributes	HIS	MIS	LIS	SAS
Diesel consumption (litre ha^{-1} yr^{-1})	87.1(225.3)	70.4(107.2)	37.8 (28.4)	36.2 (26.6)
Fertiliser application (kg ha^{-1} yr^{-1})	321.5 (631.5)	284.2 (433.0)	174.8 (131.3)	166.5 (91.9)
Urea	123.5	90.7	62.4	61.4
DAP	124.8	117.6	82.0	80.1
Muriate of Potash	20.2	23.1	15.0	14.3
Zinc	15.9	19.6	10.3	10.7
Ammonium sulphate	37.1	33.2	5.1	0.0

HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

Figures in the parenthesis indicate the mean amount of inputs –diesel (litre/household/year) and fertiliser (kg $household^{-1}$ $year^{-1}$)

Table 6.9: Fuelwood and crop residue burning across four farming systems in the study area

Sources of energy	HIS	MIS	LIS	SAS
Amount of fuelwood (t ha^{-1} yr^{-1})	1.43	2.75	4.16	6.69
Amount of crop residue (t ha^{-1} yr^{-1})	0.37	0.43	0.44	0.69
Paddy	0.14 (4)	0.15 (7)	0.17 (8)	0.28 (8)
Wheat	0.11(15)	0.18 (18)	0.19 (20)	0.26 (20)
Maize	0.12 (60)	0.10 (60)	0.08 (65)	0.15 (63)
Population density (number ha^{-1})	2.7	4.7	9.7	13.3

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

Figures in the parenthesis indicate the percentage of crop residue burnt.

Total GHG emissions from the four farming systems

Table 6.10 summarizes the results of the integrated evaluation of GHG emissions from the four farming systems for a 30-year time horizon. It provides insights into the main sources of GHG emissions and shows their contribution to the total atmospheric loading, expressed as aggregate CO_2 equivalent (CO_2e). The total emissions (tCO_2e ha^{-1}) from the four farming systems varied greatly. The emissions of CO_2e were approximately three times higher for farm SAS (17.85t ha^{-1} yr^{-1}) than for farm HIS (6.47t ha^{-1} yr^{-1}). The CO_2e for farm SAS were two and 1.7 times higher than MIS (8.62t ha^{-1} yr^{-1}) and LIS (10.75t ha^{-1} yr^{-1}) respectively (Table 6.10). This proved the *hypothesis-2* that agroforestry based farming systems releases lower amounts of GHG compared to agriculture-based farming systems. The relative contribution of the various sources to the total GHG emission was similar in three tree-based farming systems but slightly different in the case of farm SAS (Figures 6.3, 6.4, 6.5 and 6.6).

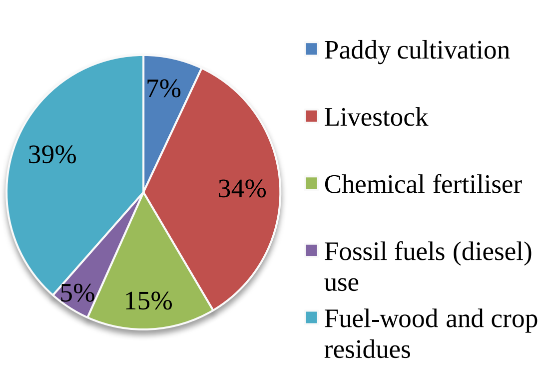

Figure 6.3: Relative contribution of emission sources in HIS

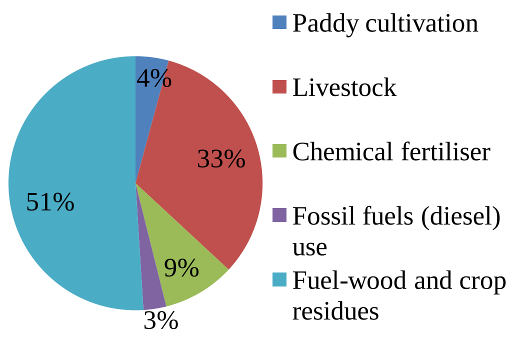

Figure 6.4: Relative contribution of emission sources in MIS

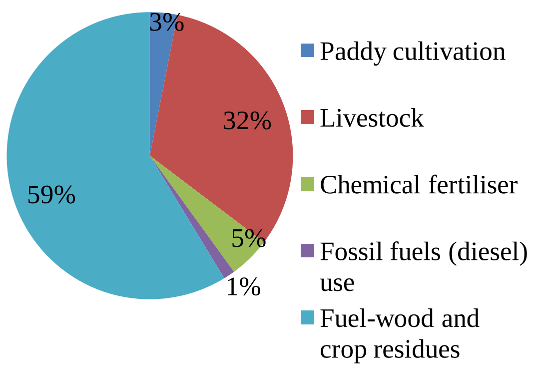

Figure 6.5: Relative contribution of emission sources in LIS

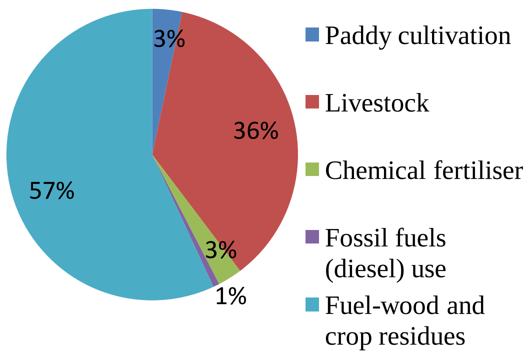

Figure 6.6: Relative contribution of emission sources in SAS

Emissions from biomass burning (fuelwood and crop residue combined) contributed the major part of emissions (39% farm HIS, 51% farm MIS, 59% farm LIS and 57% farm SAS), livestock production and storage of livestock manure made up approximately one-third, and fossil fuel consumption and fertilizer production together contributed 20% (farm HIS) and 12% (farm MIS), 6% (farm LIS) and 4% (farm SAS). Except for the source 'livestock', the amount of other sources was assumed to be constant for the entire 30-year period. Because of annual variation in number of livestock across the farming systems in that period, a slight fluctuation in yearly total emissions from these farming systems can be observed (Figure 6.7).

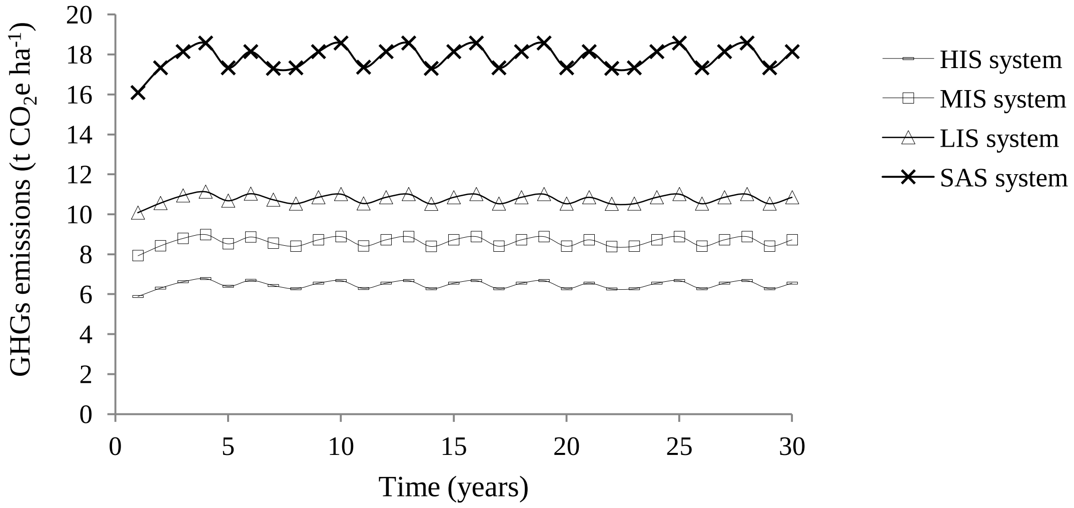

Figure 6.7: Yearly GHG emissions from four farming systems in a 30-year time horizon

There were other sources of GHG emission from these systems. The other sources mainly cover LPG and Biogas (Chapter 4). A huge amount of CO_2 is released during combustion of LPG (Kennedy et al. 2010; Smith 1994). Zhang et al. (2000) reported that one kilogram of LPG produced 3.09kg of CO_2 and 0.54g of CH_4. In the study area, the percentage of households using LPG was higher in HIS compared to other farming systems. However, the annual consumption of this gas (household^{-1}) is very low. One cylinder (14kg/33 liter) lasts longer than one year. Farmers use LPG in emergencies only such as rainy season when fuelwood is wet and difficult to burn easily without smoldering. If the annual consumption intensity of LPG was higher in HIS, the total emissions presented in the Table 6.10 would be definitely higher for HIS. Given the trend of low intensity of LPG use across all farming systems, even including the LPG related emissions would not alter the emission potential of these systems and also the profitability of these farming systems. Therefore, emissions from LPG were not included in this study. The same applies in the case of biogas use, which is insignificant in the study area. The total livestock manure was therefore assumed to be applied in the farms and emissions were estimated accordingly (Table 6.10).

Table 6.10: Total and per hectare emissions of GHG (CO_2e) from farming systems under different managements in a 30-year time horizon

	GHG emissions (CO_2e)							
	HIS		MIS		LIS		SAS	
Emission sources	Total emissions (t ha^{-1})	Average emissions (t ha^{-1} yr^{-1})	Total emissions (t ha^{-1})	Average emissions (t ha^{-1} yr^{-1})	Total emissions (t ha^{-1})	Average emissions (t ha^{-1} yr^{-1})	Total emissions (t ha^{-1})	Average emissions (t ha^{-1} yr^{-1})
Paddy cultivation	13.6	0.45	10.8	0.36	9.9	0.33	17.7	0.59
Livestock	*67.0*	*2.23*	*84.6*	*2.82*	*103.8*	*3.46*	*194.7*	*6.49*
Enteric fermentation	47.9	1.60	60.4	2.0	75.0	2.5	139.2	4.64
Manure management	9.3	0.31	11.6	0.39	13.6	0.45	27.1	0.90
Emission from soil due to use of manure	9.8	0.32	12.6	0.42	15.2	0.51	28.4	0.95
Chemical fertiliser	*29.4*	*0.98*	*23.9*	*0.80*	*15.2*	*0.51*	*14.6*	*0.49*
Production to transportation	14.1	0.47	11.6	0.39	7.4	0.25	7.1	0.24
Emission from soil due to use of fertilizer	15.3	0.51	12.3	0.41	7.8	0.26	7.5	0.25
Fossil fuels (diesel) use	9.4	0.31	7.6	0.25	4.1	0.14	3.9	0.13
Biomass (fuelwood and crop residue) burning*	74.7	2.49	131.8	4.39	189.6	6.32	304.5	10.15
Total	194.1	6.47	258.7	8.62	322.6	10.75	535.4	17.85

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

* includes CO_2 emissions from crop residue burning

Total GHG emission (excluding biomass burning) from the four farming systems

The emission results in the previous section are slightly overestimated because the CO_2 emission during crop residue burning has been taken into consideration while calculating total emission from each farming system. Generally it is assumed the CO_2 emissions to be zero. Further, use of biomass as an energy source is considered a better option than any other alternative sources of energy such as fossil fuels. Therefore, in the following section, an attempt has been made to evaluate these farming systems excluding the emissions caused by biomass burning.

The status of all farming systems remained the same in terms of GHG emission potential. The emission of CO_2 equivalents were approximately two times higher for farm SAS (7.70t ha^{-1} yr^{-1}) than farm HIS (3.98t ha^{-1} yr^{-1}), farm MIS (4.23t ha^{-1} yr^{-1}) and farm LIS (4.43t ha^{-1} yr^{-1}). The relative contribution of the various sources to the total GHG emission was similar in three tree-based farming systems but slightly different in the case of farm SAS (Table 6.10). Emissions from livestock production and storage and application of livestock manure contributed the major part (56% farm HIS, 67% farm MIS, 78% farm LIS and 84% farm SAS), and fossil fuel consumption and fertilizer use together contributed 32% (farm HIS) and 25% (farm MIS), 16% (farm LIS) and 8% (farm SAS).

Exclusion and inclusion of some emission causing activities resulted into either underestimate or overestimate. For example, inclusion of CO_2 emissions from residue burning resulted into overestimation of emission potential of each farming systems, and exclusion of N_2O emissions from the soils under legume crops and from indirect emissions induced by NO_3^- leaching and NH_3 volatilization during livestock manure handling underestimated the total emission from these farming systems. If the legume-induced N_2O were to be considered, the emission potential of the farm HIS would be higher than the total values expressed in the Table 6.10 because more than 10% of the HIS farm area is under legume crop each year. Similarly, if indirect N_2O emission were to be considered, the emission potential of SAS would be considerably higher than the total values expressed in the Table 6.10 because the number of livestock $ha^{-1}$of the farm SAS was much higher than the farm HIS.

Evaluation of GHG emissions based on farm yield from four farming systems

The emission rate expressed in a hectare basis sometimes could be misleading because some sources of emission are not area-dependant but family-size dependant. For example, emission from biomass burning largely depends on the family size of the individual household. If we apply this rule to re-evaluate the emission from biomass burning in Table 6.10, the emission scenario appeared completely different. The farm HIS, which was responsible for the lowest emission from biomass burning in a hectare basis, appeared a higher emitter in per head basis. A single person on farm HIS and MIS was responsible for emission of approximately 1t CO_2e yr^{-1} while the highest emitter, farm SAS, was responsible for emission of approximately 0.76t CO_2e yr^{-1} only.

Farm yield is another important reference unit for comparison of GHG emissions from any farm production systems (Flessa et al. 2002). However, comparison of yield-related emissions was difficult in this study, since it was difficult to measure the farm outputs of the system components in the same unit such as kilogram or mega-gram. To avoid this difficulty, the total present value of benefits (farm outputs) over a 30-year time span was considered as farm yield for each farm. The result showed that the farm HIS was required to emit 7.8 kg CO_2e to earn US$ 100.00 (Net present value of farm outputs) while the farm SAS was required to emit 136.9 kg CO_2e to earn the same benefit i.e. US$ 100.00, which is 17, 11 and 4 times higher than HIS, MIS (12.5 kg CO_2e) and LIS (30.7 kg CO_2e), respectively.

6.5.2. Tree biomass and carbon sequestration potential of three agroforestry-based farming system

6.5.2.1. Current practice of tree management in the study area

Out of 37 tree species including horticultural trees (Chapter 4, Table 4.2), five trees as mentioned in Table 6.1 are more common in three tree-based farming systems HIS, MIS and LIS. Out of five trees, *E. camalulensis* was the most extensively cultivated in all three systems, constituting more than 65% of the total trees (Table 6.1). *E. camaldulensis* is grown primarily for the production of poles and to some extent for small size timber and fuelwood. The small size timber is called bole, commonly known as *'KORO'* in local dialect.

Besides poles and fuelwood production, about 25% of the eucalypt trees at age ten produce such boles (*KORO*), which are used for house construction. The bole is sold for NRs 100.00 (US$ 1.31) each. The number of boles increases with the increase in harvest age. According to farmers, about 35% and 40% of the eucalypt trees produces boles at age eleven and twelve, respectively. These figures were used to estimate the revenue (benefits) from this tree species. Likewise, the purpose of growing *D. sissso* is to produce timber and to some extent fulfil the need of fodder for the livestock. *M. azedarach* had dual purposes: timber and fodder. *G. arborea* served multiple purposes; timber, fodder and fuelwood. *A. chinensis* is grown for the production of both timber and fuelwood.

The harvest cycle of these tree species varies with objectives and growth pattern of individual tree species. The current practice of harvest is described in Table 6.12 below. *D. sissoo* and *G. arborea* are harvested at age fifteen, which is a slightly longer harvest cycle than the other three trees species that are harvested at age ten, while fruit trees are replaced with new ones after thirty years of plantation. These harvest ages are based on farmers' practice, not the empirical estimates. For this study, the current practice (i.e. 30 years) that the famers from the study area have adopted was used. In a 30-year period, *E. camaldulensis*, *M. azedarach* and *A. chinensis* are planted and harvested three times while *D. sissoo* and *G. arborea* are planted and harvested twice. For example, a total (ha^{-1}) of 474 *E. camaldulensis*, 52 of *D. sissoo*, 24 of *G. arborea*, 48 of *M. azedarach* and 18 of *A. chinensis* trees are grown in the farm HIS in a 30-year time horizon.

Even though the harvest cycle of the tree crop is ten and fifteen, farmers start harvesting earlier (Table 6.11). For example, thinning of *E. camaldulenis* is done at age seven. Basically thinning is performed when farmers realise that the tree has attained the required size for pole production. The extraction rate also varies with tree species each year after harvest has started. According to farmers, 77% of the *E. camaldulensis* are harvested and sold and the remaining 23% are considered as a loss because of death caused by livestock attack, shading effect, disease and pest attack and unfavourable soil ecology (Table 6.11).

6.5.2.2. Current market mechanism of forest products in the study area

Pricing mechanism

At the time of data collection in 2010, there existed a market for poles, timber and fuelwood. The market was controlled by the local contractors. The contractor negotiated with farmers about the price of the forest products i.e. pole and timber. The contractor fixed the price of the products by size and species. The detail of price is given in Appendix B, Table B.3. For example, if the DBH of a *sissoo* log was above 35 cm, the contactor would buy the log on per cubic feet (volume) or per cubic meter basis but when the log was below 35 cm, it would be purchased on a per kilogram (weight) basis. This 35 cm benchmark varied with tree species, which is described in the Appendix B, Table B.3. According to this pricing rule, farmers are now selling their products on a per kilogram weight basis except for *E. camaldulensis* because not a single tree species could attain the required size of DBH (Figure 6.8) to be eligible for their products (timber) to be sold on a cubic feet or cubic meter basis.

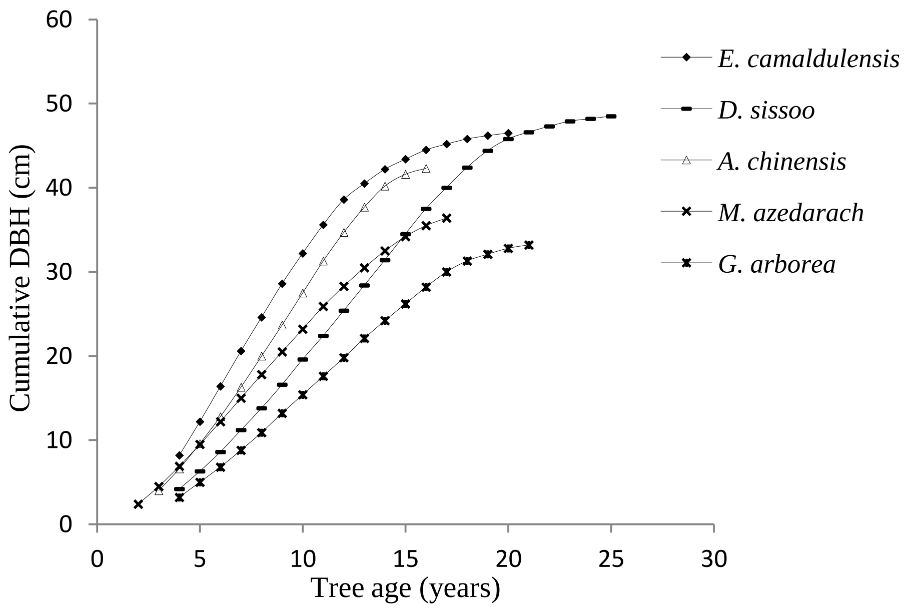

Figure 6.8: DBH growth curves of five agroforestry tree species

Table 6.11: Harvest cycle and harvest schedule of five tree species in the study area

Tree species	Rotation (years)	Harvest schedule (age) and extraction rate (%)									Survival (%)	Loss (%)
		7	8	9	10	11	12	13	14	15		
E. camaldulensis	10	10	27	30	10	-	-	-	-	-	77	23
D. sissoo	15	-	-	-	-	-	5	10	10	45	70	30
G. arborea	15	-	-	-	-	-	5	15	20	35	75	25
M. azedarach	10	-	20	45	15	-	-	-	-	-	80	20
A. chinensis	10	5	30	30	10	-	-	-	-	-	75	25

However, in the case of *E. camaldulensis* which is mainly cultivated for poles, the pricing mechanism is different. Volume and weight are not considered, the contractor judges the individual eucalypt tree determining if it has reached the pole size. The costs involved after harvest of the forest products such as transportation and other transaction costs are incurred by the contractor himself. The price, therefore, used here for analysis is the farm-gate price.

Partition of felled trees into merchantable timber, fuelwood and wastage

According to the farmers of the study area, the whole tree is divided into three components for pricing purpose; merchantable timber, fuelwood and wastage including leaves, twigs and small branches. The proportion of each component varies with tree species. For example, in the case of the *sissoo* tree, about 45% of the total above-ground biomass is considered as merchantable timber, another 45% as fuelwood and the rest (10%) as wastage. Details are given in Appendix B, Table B.3.

6.5.2.3.Growth performance of five tree species

Out of the five agroforestry tree species, *E. camaldulensis* showed the greatest growth potential with the mean annual increment in DBH (MAIDBH) of 3.22 cm yr^{-1} at age ten, which is almost double what *G. arborea* (1.74 cm yr^{-1}) could attain in age fifteen (Figure 6.10). The harvest age of *E. camaldulensis*, *A. chinensis* and *M. azedarach* was ten years while *D. sissoo* and *G. arborea* were harvested at age fifteen (Table 6.11). The MAIs of these tree species were in an order as follows; *E. camaldulensis* > *A. chinensis* > *M. azedarach* > *D. sissoo* > *G. arborea*. At the time of harvest (rotation age) the mean diameter at breast height (DBH) of *E. camaldulensis*, *A. chinensis*, *M. azedarach*, *D. sissoo* and G. *arborea* were 32.2 cm, 27.3 cm, 23.1 cm, 34.5 cm and 26.1 cm, respectively (Figure 6.8). The DBH of *E. camaldulensis* at age ten was almost equal to the DBH of *D. sissoo* at age fifteen. Likewise, *A. chinensis* attained a DBH of 27.3 cm at age ten, which is higher than the DBH attained by *G. arborea* at age fifteen.

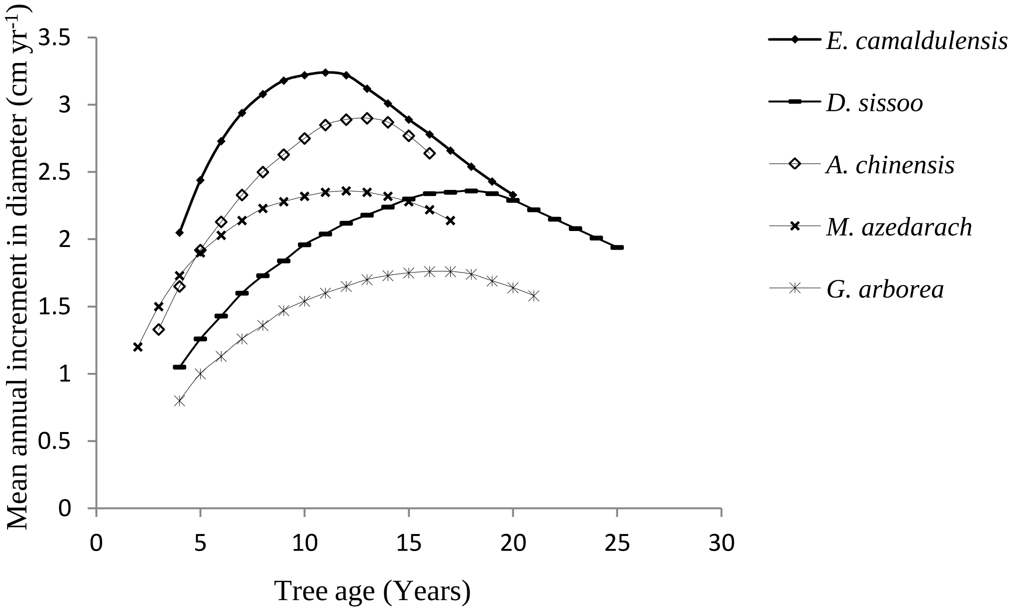

Figure 6.9: MAI curves of five agroforestry tree species

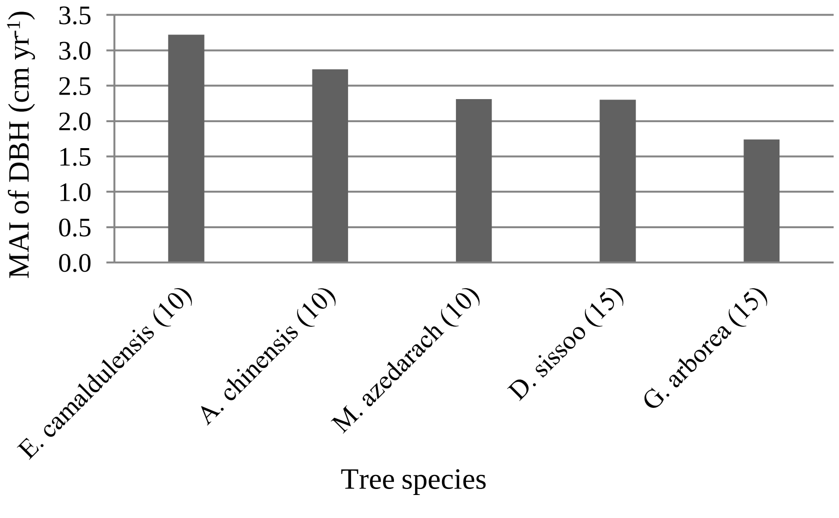

Figure 6.10: MAI of five agroforestry tree species at rotation age

Crown density of three agroforestry based farming systems

The crown density varied with farming systems (Table 6.12). It was found that the crown density was highest in HIS while MIS had the lowest. Among several factors such as type of tree species, tree density, age of the tree, and spacing that could affect the crown density, the growth characteristics of individual tree species such as branching is more important in determining the crown cover (Donoghue et al. 2007). The reason behind higher crown density of LIS than that of MIS can be attributed to the higher density and bigger crown coverage of horticultural trees in LIS. The individual tree crown diameter is given in the Appendix F. The result showed that the agroforestry based faming systems in the study area had the potential of crown density as low as 19 and as high as 24%.

The crown density is of high importance because it is the major criteria to define any land use as forest or non-forest (FAO 2010). In the present context when agroforestry is being considered as GHG mitigation strategy and small holder farmers can be financially benefited through carbon trading under CDM and REDD+ mechanisms, It is largely dependent whether any agroforestry intervention comes under the CDM mechanism on what definition that an individual country has adopted to define a forest. According to CDM forest definition, a forest is a land use having minimum crown coverage of 10 to 30%. However, FAO (2010) has defined a forest in a different way even though the basic components of definition i.e. height, area and crown density are same. According to FAO (2010), a forest is an area more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use. FAO (2010) has classified agroforestry and horticultural gardens as other land with tree cover and according to this definition any agricultural land use that has more than 10% crown cover is not considered as forest.

If CDM forest definition is followed, the result in the Table 6.12 below showed that all agroforestry based farming systems can be considered as forest as they meet the basic criteria of a forest. However, the government of Nepal has adopted the FAO definition to define a forest (DFRS 2010; FAO 2009b) and that clearly exclude agroforestry from being a forest.

6.12: Tree crown density under three different agroforestry based farming systems

Farming systems	Crown coverage (m^2 ha^{-1})	Crown cover (%)
Highly integrated agroforestry based farming system (HIS)	2439.2	24.4
Medium integrated agroforestry based farming system (MIS)	1897.2	19.0
Less integrated agroforestry based farming system (LIS)	2206.8	22.1

Total biomass production and carbon sequestration by three farming systems under the current practice of tree harvest

Even though all the major agroforestry tree species including three horticultural tree species were present in these three farming systems, the species-specific density varied greatly with farming systems (Table 6.13). Given the highest density of *E camaldulensis* in farm HIS and the largest MAIDBH, the farm HIS has the highest carbon sequestration potential of the three farms studied. In a 30-year time span, the HIS could generate a total of 149.6t C ha^{-1}, which is 1.5 and 1.4 times higher than that of MIS and LIS, respectively. This proved the *hypothesis-1* that HIS uptakes the higher amounts of carbon compared to other agroforestry based farming systems.

Total biomass and carbon sequestration by five agroforestry tree species under alternative practice based on maximum mean annual increment in diameter (MAIDBH)

From Figure 6.9 and Table 6.14, it was obvious that farmers in the study area harvested all agroforestry tree species before trees reached their maximum yield potential because the yield is maximized when a tree attains the highest mean annual increment (MAI), which is termed as technical rotation. Results showed that the current practice was below the optimal level of production. For example, a eucalypt tree, when harvested at age ten, would produce a total of 0.689t of biomass when the same tree would give a total of 0.883t of biomass when harvested one year later i.e. at age eleven, almost 200kg more biomass than the previous year (Table 6.14). However, in the case of *E. camaldulensis*, the overall financial return would not be that different when choosing either ten or eleven because the poles are not valued by volume and weight. The only difference would be the number of boles production and carbon. Further economic analysis is required of whether the increased boles and carbon would offset the loss in NPV because of a one year delay in the harvest of the crop.

For the rest of the agroforestry species, the DBH under the current practice was below the threshold (Table 6.14 and Appendix B, Table B.3.) i.e. the minimum DBH above which the tree logs are sold in volumetric basis. But the average DBH of each species at harvest age under the alternative practice was above the given threshold, i.e. tree logs are sold in volumetric basis. Even though the total biomass that a tree can accumulate would definitely be higher under the alternative practice than with the current practice (Table 6.14), it is necessary to assess which rotations are financially attractive. Let's take an example of a *Sissoo* tree harvested at age fifteen (current practice) and at age eighteen (alternative practice). The total above-ground biomass of a *Sissoo* tree at age fifteen with average DBH of 34.5 cm (Table 6.14) was 179.4kg, out of which 80.7kg was merchantable timber (US\$ 0.095 kg^{-1}), 80.kg fuelwood (US\$ 0.032 kg^{-1}) and the rest 17.9 kg was a wastage. The below-ground biomass was about 48.4kg (US\$ 0.032 kg^{-1}). The total revenue that a fifteen year old *Sissoo* tree could earn was US \$ 11.7.

If a *Sissoo* tree were to be harvested at age eighteen, the total above-ground biomass with average DBH of 42.4 cm (Table 6.14) would be 212.9kg, out of which the merchantable timber volume would be 0.122 m^3 (US\$ 370.3 m^{-3}), fuelwood weight would be 95.8kg (US\$ 0.032 kg^{-1}) and the wastage would be 21.3kg. The below-ground biomass weight would be 57.5kg (US\$ 0.032 kg^{-1}). The total revenue that an eighteen year old *Sissoo* tree could earn would be US \$ 50.00, which is four times as high as the revenue earned from the current practice. Even though the cost of production under the alternative practice would be slightly higher since comparatively more labour is required during harvesting and handling of the forest products, this would not affect the net revenue.

Table 6.13: Mean annual increment in diameter (MAIDBH), mean annual increment of weight (MAIW) and carbon sequestration rate of three farming systems in a 30-year time horizon by agroforestry and horticultural tree species in Dhanusha district, Nepal

	Density at harvest (ha^{-1})	MAI DBH ($cm\ yr^{-1}$)	MAIW ($t\ ha^{-1}\ yr^{-1}$)	Harvest cycles	Total biomass ($t\ ha^{-1}$)	Total carbon ($t\ C\ ha^{-1}$)	Carbon sequestration rate ($t\ C\ ha^{-1}\ yr^{-1}$)
Highly integrated system							
E. camaldulensis	121	3.22	8.34	3	250.11	125.05	4.17
M. azedarach	13	2.31	0.53	3	15.93	7.96	0.27
A. chinensis	4	2.73	0.19	3	5.76	2.88	0.10
G. arborea	9	1.74	0.28	2	8.27	4.13	0.14
D. sissoo	18	2.30	0.27	2	8.20	4.10	0.14
M. indica	16	1.17	0.31	1	9.33	4.66	0.16
A. heterophyllus	1	1.85	0.05	1	1.60	0.80	0.03
L. chinensis	<1	0.87	-	1	-	-	-
Total MAIW($t\ ha^{-1}\ yr^{-1}$)			9.97				
Total carbon ($t\ C\ ha^{-1}$)						149.60	
Carbon sequestration rate ($t\ C\ ha^{-1}\ yr^{-1}$)							4.99
Medium integrated system							
E. camaldulensis	79	3.22	5.44	3	163.29	81.65	2.72
M. azedarach	10	2.31	0.41	3	12.25	6.13	0.20
A. chinensis	7	2.73	0.34	3	10.09	5.04	0.17
G. arborea	2	1.74	0.06	2	1.84	0.92	0.03
D. sissoo	7	2.30	0.11	2	3.19	1.59	0.05
M. indica	15	1.17	0.29	1	8.74	4.37	0.15
A. heterophyllus	2	1.85	0.11	1	3.20	1.60	0.05
L. chinensis	<1	0.87	-	1	-	-	-
Total MAIW($t\ ha^{-1}\ yr^{-1}$)			6.75				
Total carbon ($t\ C\ ha^{-1}$)						101.30	
Carbon sequestration rate ($t\ C\ ha^{-1}\ yr^{-1}$)							3.38
Less integrated system							

E. camaldulensis	84	3.22	5.79	3	173.63	86.81	2.89
M. azedarach	9	2.31	0.37	3	11.03	5.51	0.18
A. chinensis	4	2.73	0.19	3	5.76	2.88	0.10
G. arborea	3	1.74	0.09	2	2.76	1.38	0.05
D. sissoo	3	2.30	0.05	2	1.37	0.68	0.02
M. indica	20	1.17	0.39	1	11.66	5.83	0.19
A. heterophyllus	3	1.85	0.16	1	4.8	2.40	0.08
L. chinensis	<1	0.87	-	1	-	-	-
Total MAIW(t ha^{-1} yr^{-1})			7.03				
Total carbon (t C ha^{-1})						105.50	
Carbon sequestration rate (t C ha^{-1} yr^{-1})							3.52

Table 6.14: Comparison of biomass production (m^3 $tree^{-1}$) under the current and alternative practice

Species	Current practice					Alternative practice based on MAIDBH				
	Harvest age	DBH (cm)	Biomass (t $tree^{-1}$)	Carbon (t C $tree^{-1}$)	Volume* (m^3 $tree^{-1}$)	Harvest age	DBH (cm)	Biomass (t $tree^{-1}$)	Carbon (t C $tree^{-1}$)	Volume* (m^3 $tree^{-1}$)
E. camaldulensis	10	32.2	0.689	0.345	0.98	11	35.6	0.883	0.442	1.25
M. azedarach	10	23.1	0.408	0.204	0.82	12	28.3	0.692	0.346	1.38
A. chinensis	10	27.3	0.480	0.240	1.20	13	37.7	1.100	0.550	2.75
G. arborea	15	26.1	0.459	0.230	1.07	17	30.0	0.659	0.330	1.53
D. sissoo	15	34.5	0.227	0.114	0.28	18	42.4	0.270	0.135	0.34

*Volume (m^3) = biomass (kg)/wood density (kg/m^3). Species specific wood densities: *E. camaldulensis*(705 kg/m^3), *M. azedarach* (500 kg/m^3), *A. chinensis* (400 kg/m^3), *G. arborea* (430 kg/m^3) and *D. sissoo* (801 kg/m^3).

6.5.3. Re-evaluating farming systems with carbon value

6.5.3.1. GHG emissions and carbon uptake

Sources of emissions cover farm inputs, fossil fuels, rice paddy, livestock and biomass burning. The farm inputs cover chemical fertilizer and farm yard manure (FYM) while the livestock covers manure management and enteric fermentation. The biomass burning covers crop residue and fuelwood. Fossil fuels related emissions are caused from use of tractors and threshers. Over thirty years, the total amount of GHG emissions due to the use of farm inputs in SAS, LIS, MIS and HIS were 43.0tCO_2e, 30.4tCO_2e, 36.5tCO_2e and 40.1tCO_2e, respectively, with HIS being the highest (Table 6.10). Similarly, livestock related emissions in SAS, LIS, MIS and HIS were 166.3tCO_2e, 88.6tCO_2e, 72.0tCO_2e and 57.2tCO_2e, respectively, with SAS being the highest. In terms of emission from biomass burning, SAS, LIS, MIS and HIS emitted 304.5tCO_2e, 189.6tCO_2e, 131.8tCO_2e and 74.7tCO_2e, respectively, with SAS again being the highest. The total amount of GHG emissions due to these sources in SAS in thirty years was around three times higher than HIS, two times higher than MIS and 1.6 times higher than LIS.

Carbon uptake covers tree biomass, above- and below-ground, and agricultural soil. The tree covers agroforestry tree species (Table 6.1), fodder tree species naturally grown in the farm and horticultural species (Table 6.13) raised as an orchard. Soil organic carbon (SOC) and carbon in fodder tree species are not considered here. Therefore, in terms of carbon uptake, SAS had zero potential. Over thirty years, the total amount of carbon stored by above- and below-ground biomass of agroforestry and horticultural trees in HIS, MIS, and LIS were 149.6tC (549.03tCO_2e), 101.30tC (371.77tCO_2e) and 105.50tC (387.16tCO_2e), respectively (Table 6.13). Excluding horticultural species, the amount of carbon sequestered in HIS, MIS, and LIS were 144.14tC (528.99tCO_2e), 97.33tC (357.20tCO_2e) and 95.07tC (348.91tCO_2e), respectively. Compared with emission from each farming system, the carbon uptake was three times higher in HIS and slightly higher in both MIS (1.5 times) and LIS (1.25 times). However, carbon stored in biomass is temporary; not a permanent removal from the atmosphere (Cacho et al. 2003), because the carbon once stored releases back to the atmosphere after harvest through burning and biological processes including decaying.

6.5.3.2. Comparison of net present value from four farming systems

Comparative results showed that the HIS, MIS, LIS and SAS returned \$7243.3 ha^{-1}, \$5572.5 ha^{-1}, \$5353.6 ha^{-1} and \$5232.4 ha^{-1} of net present values respectively in thirty years without including carbon values. Even excluding carbon value, the NPV of HIS was 1.4 times as high as SAS and other two agroforestry systems were more competitive with SAS (Table 6.15). Even though tree is the sink of carbon, all three agroforestry-based farming systems appeared to be sources of emissions because of the fact that the other components of the system, i.e. livestock, rice paddy cultivation, and associated farm activities such as use of farm inputs and biomass burning, were the sources of emissions. However, the total net present values lost from GHG emissions from these three agroforestry systems were lower than SAS. The loss in NPV from emission in SAS was 2.7 times higher than HIS, 2.1 times higher than MIS and 1.6 times higher than LIS (Table 6.15).

If carbon value is included, overall NPV of all farming systems will decrease but the degree of decrease varied with farming systems. NPV from SAS has decreased by 27.2%, which is four times higher than HIS. NPV from HIS was the least influenced by the carbon value among the four farming systems, only 6.6% decrease in NPV. While the other two farming systems, i.e. MIS and LIS, were more competitive in a 'no carbon scenario', the SAS appeared to be financially less attractive than MIS and LIS when carbon value was included. The NPVs of HIS, MIS and LIS were 1.7 times, 1.3 times and 1.2 times as high as SAS. Further, if SAS famers are motivated to adopting the agroforestry-based farming systems, the carbon benefit of converting SAS into other agroforestry systems would be US$ 595.00- 941.00 (Table 6.15).

Table 6.15: Net present value (NPV in US$ ha^{-1}) from four farming systems in thirty years

Farming systems	Agriculture	Agroforestry	GHG emission	GHG uptake	Net carbon value	Total NPV
Highly integrated agroforestry-based farming system (HIS)	0	7243.5	- 518.2	+ 35.9	- 482.3	6761.2
Medium integrated agroforestry-based farming system (MIS)	0	5572.5	- 690.9	+ 30.9	- 660.0	4912.5
Less integrated agroforestry-based farming system (LIS)	0	5353.6	- 863.7	+ 35.7	- 828.0	4525.6
Subsistence based agriculture system (SAS)	5232.4	0	- 1423.5	+ 0.0	- 1423.5	3808.9

6.5.3.3. Comparison of net present values from four farming systems with respect to different carbon prices

Even though there is a decreasing trend of carbon prices in international markets in recent years, it is likely that the price may increase in the future as more and more industrialized countries are obliged to neutralize their industrial carbon emissions by purchasing forest-based carbon credits. Therefore, a range of carbon prices were used to see the effects of those prices in NPV of four farming systems (Table 6.16).

As the SAS resulted in the highest GHG emissions (Table 6.10) into the atmosphere, among the farming systems studied, the NPV of this farming system was highly influenced by the changes in carbon prices. With increase in carbon price from \$10.00 t^{-1} CO_2e (base case price) to \$30.00 t^{-1} CO_2e, the drop in NPV for SAS was significant. With 200% (\$30.00) increase in carbon price, the NPV for SAS has decreased by 73% while it was only 14% for HIS, 27% for MIS and 36% for LIS (Table 6.16). The drop in NPV for SAS was about three times higher than that of HIS. Given the negative carbon revenues from all farming systems, an increase in carbon price would not be a financially attractive option for farmers. However, there is still some scope for increasing carbon revenues from these tree-based farming systems as the carbon stored in fodder tree species and in the soil as SOC was not taken into consideration while estimating these carbon credits. This addition, however, would not have considerably affected in reducing NPV loss from GHG emissions. Therefore, such an insignificant amount of carbon revenue (Table 6.15) from small-scale forestry with short rotation like that of the study area (Table 6.11) could not be a lucrative incentive for the farmers currently not adopting such practice to establish plantations on their farms as a component of farming system.

If the plantation (agroforest or woodlot) were to be considered as a separate land use like agriculture and forestry rather than just a component of a whole agroforestry-based farming system as in this study, the addition of carbon value with timber would definitely favour plantations over other competitive land uses: cultivation and pasture (Maraseni & Cockfield 2011b) because plantation as a separate land use is a sink of carbon while other land uses (pasture and cultivation) are source of GHG emission. Therefore, an increase in carbon price would generate more carbon revenue from the plantation while this would generate negative carbon revenues in the case of cultivation and pasture (Maraseni & Cockfield 2011b).

Table 6.16: Net present values from four farming systems with respect to different carbon prices

Farming	Carbon prices (\$ t^{-1} CO_2e)					
systems	\$5.00	\$10.00	\$15.00	\$20.00	\$25.00	\$30.00
HIS	7002.4	6761.2	6520.1	6278.9	6037.8	5796.7
MIS	5242.5	4912.5	4582.5	4255.5	3922.5	3592.5
LIS	4939.6	4525.6	4111.6	3697.6	3283.7	2869.7
SAS	4520.64	3808.9	3097.1	2385.4	1673.6	961.8

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

6.5.3.4. Role of agroforestry-based famring systems in GHG enission reduction: an alternative scenario

Without agroforestry intervention, the total amount of GHG emission in thirty years would be substantially higher (535.4tCO_2e ha^{-1}) (Table 6.10). The intervention of agroforestry has reduced emissions greatly (Table 6.10). This reduction in emission is a net gain of adopting agroforestry-based farming systems. Therefore, in the following section an attempt has been made to see the impact on overall NPV when this reduction was considered as a source of revenue of these agroforestry-based farming systems.

Compared to SAS, the HIS, MIS and LIS would reduce emissions in thirty years by 341.3tCO_2e, 276.7tCO_2e and 212.8tCO_2e, respectively (Table 6.10). With this reduction, HIS and MIS would return \$423.0 ha^{-1} and \$72.5 ha^{-1} of net present values from carbon uptake (Table 6.17) in the thirty-year period while net carbon value (revenue from GHG trade) for LIS and SAS would be negative. The total net present value lost from GHG in SAS (\$1423.5 ha^{-1}) was five times that of LIS (\$268.2 ha^{-1}). In contrast, total net present value gain from GHG in HIS (\$423.0 ha^{-1}) was 5.8 times that of MIS (\$72.5 ha^{-1}) (Table 6.17). After inclusion of GHG reduction as a carbon benefit, HIS remained the best option as it was without carbon value and SAS remained the worst as it was without carbon value. This proved the *hypothesis-4* that NPVs of all agroforestry based farming systems are greater than that of SAS when GHG values are included.

Table 6.18 summarises the NPV sensitivity to the change of carbon price when reduction was considered as net carbon benefits of the farming system. Results showed that LIS would not benefit even with the higher carbon price. NPV of HIS has increased by about 3% at \$5.00 t^{-1} CO_2e and 17% at \$30.00 t^{-1} CO_2e. In the case of MIS, change in NPV did not vary greatly (0.6% at \$5.00 t^{-1} CO_2e and about 4% at \$30.00 t^{-1} CO_2e) with respect to the reference situation (Table 6.7).

Table 6.17: Net present value (NPV in US\$ ha^{-1}) from four farming systems in thirty years including GHG emission reduction value at \$10.00 t^{-1} CO_2e

Farming systems	Agriculture	Agroforestry	GHG emission	GHG uptake	GHG reduction	Net carbon value	Total NPV
HIS	0.0	7243.5	- 518.2	+ 35.9	+905.3	+423.0	7666.5
MIS	0.0	5572.5	- 690.9	+ 30.9	+732.5	+72.5	5645.0
LIS	0.0	5353.6	- 863.7	+ 35.7	+559.8	-268.2	5085.4
SAS	5232.4	0.0	- 1423.5	+ 0.0	+0.0	-1423.5	3808.9

HIS = highly integrated agroforestry-based farming system; MIS = medium integrated agroforestry-based farming system; LIS = less integrated agroforestry-based farming system and SAS = subsistence based agriculture system

Table 6.18: NPV sensitivity to the change of carbon price including GHG reduction as revenue

Farming systems	Carbon prices ($ t^{-1} CO_2e)					
	$5.00	$10.00	$15.00	$20.00	$25.00	$30.00
HIS	7455.1	7666.5	7878.1	8089.5	8301.1	8512.6
MIS	5608.8	5645.0	5681.3	5720.6	5753.9	5790.1
LIS	5219.5	5085.4	4951.4	4817.3	4683.3	4549.3
SAS	4520.6	3808.9	3097.1	2385.4	1673.6	961.8

HIS = highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

6.6. Discussion

6.6.1. Agroforestry tree species selection and productivity: economic and ecological implications

The agroforestry-based farming system, which became more visible only after the late 90's in the study area, is a new technology in the study area, gradually evolving over time (Chapter 4). Adoption of any new technologies is influenced by several factors, which are discussed at length in Chapter 5. Besides those discussed earlier, a farmer's decision of adoption is largely influenced by the profitability and risk associated with such a new technology over other alternatives available (Cockfield 2005; Franzel et al. 2001). The finding of this study clearly indicates that integrating trees (both agroforestry and horticultural) with agriculture and livestock would perform better in terms of NPV, B-C ratio and return-to-labour than the subsistence agriculture.

Similar findings were documented by several researchers (Anane & Twumasi-Ankrah 1998; Garforth et al. 1999; Jain & Singh 2000; Kurtz et al. 1991; Neupane & Thapa 2001). The farm profitability is determined by overall farm productivity and cost of production. Not only from a profitability point of view but also from ecological perspectives, an agroforestry is considered a more sustainable land use than agriculture (Alam et al. 2010; Montagnini & Nair 2004; Nair 1997; Sanchez 1995). However, selection of agroforestry tree species plays a vital role in achieving these dual goals (economic as well as ecological) (Montagnini 2006). Some of ecological benefits include improved nutrient cycling, soil conservation, carbon sequestration and recovery of biodiversity.

In the study area, five agroforestry tree species are major species (Table 6.1). Farmers selected these species based on criteria, which is described in detail in Chapter 4. Under the current farming practice in the study area, *E. camaldulensis*, an exotic species, is the most dominant tree species followed by *D. sissoo*, a legume species (Table 6.1). High preference to *E. camaldulensis* by the farmers is attributed to its fast growth rate (3.22 cm yr^{-1}) and a quick and high financial return. A eucalypt tree reaches a merchantable size in as early as seven years (first thinning) while it takes twelve years for *D. sissoo* and *G. arborea to reach* first thinning (Table 6.11). Farmers can generate revenue of US$ 13.11 from the sale of a single eucalypt pole in a seven-year period while *A. chinensis* (second highest growth rate) can make only US$ 9.48 from its timber sale during the same time period. Further, if cost of production is taken into consideration, raising a eucalypt tree is much more profitable than any of the other four tree species because harvesting of a eucalypt tree is less costly as the eucalypt tree is not required to be converted into logs, which reduces labour cost.

There is a possibility of farmers in the future shifting to a monoculture plantation of *E. camaldulensis* from the current practice of a mixed plantation because monoculture plantations are more profitable than mixed plantations (Henry et al. 2009) and this study also reinforces this argument. This shift would be more costly in the long run both at farm as well as landscape level from an ecological perspective. Even though the financial attractiveness of such Eucalyptus-based agroforestry is an opportunity for improving the livelihood of the rural communities, the ongoing strong debate concerning the ecological impacts of the species are issues of concern among the farmers and agricultural experts. Biodiversity could potentially be adversely impacted through the establishment of such large, even-aged monoculture plantations that can fix massive amounts of carbon and generate comparatively higher revenue but contribute little to landscape diversity (Schoeneberger 2009).

E. camaldulensis, being the larger sized trees morphologically and having higher growth rate, could be a right choice for carbon sequestration projects (Henry et al. 2009). However, the effect on soil ecology because of eucalyptus plantation is detrimental. Several studies highlighted the negative effects of eucalyptus on soil ecology (Duguma 2013). Duguma and Hager (2011) reported that farmers' perceive such eucalyptus-based woodlots have serious impact on soil moisture and on nearby crop yields. Sanchez (1995) reported that Eucalyptus spp. can devastate cereal crops growing close to them when resources become scarce, because of their extensive root systems and can decimate crop yields several meters away. Basically the eucalypt tree is a high water-demander and that would definitely result in diminishing production of field crops. Therefore, choosing *E. camaldulensis* as an agroforestry tree species in a dry area is not a rational selection.

Even in the study area, although characterised as high rainfall area, given the soil properties, i.e. low water holding capacity and high percolation rate, the extensive plantations of *E. camaldulensis* as seen in the study area (more than 60% of the total trees on the farm) would definitely contribute to further drying of the farm land. It is obvious that the competition for water resource between field crops and tree crop would result in reduced farm yield in the long run. Even during the focus group discussion, some farmers shared with the author that they have witnessed the negative impacts this trees species was having on their farm land. According to farmers, a distance of six meters (three meters each side of the stump) when grown in rows, is almost crop-less during low rainfall period of the year (January to May), the maize planting and harvesting season. Nonetheless, the absence of alternative fast growing species that could supply wood products for the farm households and generate substantial income is still forcing farmers to continue growing this species despite the constraints.

Another negative impact of this tree species would be an increased pressure on natural forest because *E. camaldulensis* can only fulfil the demand of poles and household need of fuelwood to some extent but other household needs mainly fodder and timber (house construction and furniture making) are not met and that would result in forest deforestation and degradation. The *terai* region which has witnessed a rapid forest deforestation and forest degradation already would face further destruction if such mono-specific plantation were promoted. The fundamental goal of having trees on the farm is to increase farm income while fulfilling the basic household needs of food, fuelwood, fodder, leaf litter and timber and also support in achieving some environmental co-benefits such as soil and water conservation, biodiversity conservation and climate change mitigation through carbon sequestration (Alavalapati et al. 2004; Jose 2009; Long & Nair 1999).

Monoculture eucalypt plantations could be economically more attractive than multiclonal (mixed) plantations as discussed above but long-term productivity may increase with species richness due to an increased capacity to buffer physical disturbances (Henry et al. 2009). Therefore, some policy intervention is deemed necessary to stop farmers from growing monoclonal plantation (eucalyptus plantation) and encourage them towards adopting mixed plantation that would enhance biodiversity and fulfil other environmental co-benefits as well.

6.6.2. Farm size, labour, land quality and farm productivity

Farm productivity is of prime importance as it is associated with farmers' livelihoods globally. It is generally measured either as yields per land unit or gross output value per land unit, which does not consider the input value (cost) associated with the farm production. However, this farm productivity, although being a partial productivity, is found widely used in the literature (Bardhan 1973; Bhalla 1988; Bhalla & Roy 1988; Chayanov 1966; Newell et al. 1997; Sampath 1992; Sen 1966). Use of this partial productivity is misleading because net profit might be lower even in high productivity. For example, the Net return-to-land (NPV) from SAS, which is characterised as a small size farm, is lower than those of three tree-based farming systems (Table 6.5). Therefore, the total factor productivity (TFP), output to input ratio, proposed by Norsworthy and Jang (1992), which is more an economic ratio rather than just a physical ratio, could reflect more precisely the farm productivity. However, in this study, gross margin (difference between output value and input value) was used. The gross margin is more similar to the TFP to assess the overall farm productivity of the farms studied.

The overall farm productivity depends on farm size, farm type, labor, capital, land quality and technology (Bhalla 1988; Bhalla & Roy 1988; Chand et al. 2011). However, the relationship between farm size and farm productivity per unit land was found to be negative, i.e. the bigger the farm size, the lower the farm productivity, which is known as negative relationship (NR). This relationship is much debated and discussed in the literature. After Sen (1962), several researchers have re-examined the validity of this negative relationship in developing countries and the results are mixed. A large number of studies during 1960s and1970s provided convincing evidence that crop productivity per unit of land declined with increase in farm size (Bardhan 1973; Berry 1972; Mazumdar 1965; Rao 1966; Saini 1971; Sen 1964) which provided strong support for land reforms, land ceiling and various other policies to support smallholders on grounds of efficiency and growth. Subsequently, various analysts started exploring reasons or factors for higher productivity of smallholders (Berry & Cline 1979; Binswanger & Rosenzweig 1986; Dong & Dow 1993; Frisvold 1994; Jha et al. 2000) and some of them even questioned the negative relationship between farm size and productivity.

Bhalla and Roy (1988) observed that the inverse relation between farm size and productivity weakened and disappeared when soil quality was included in their study. Chadha (1978) analysing farm level data for three agro-climatic regions in Punjab for 1969-70, reported that the negative relationship had ceased to hold in more dynamic zones. Ghose (1979) argued that an essential precondition for the existence of the negative relationship phenomenon is technical backwardness implying that with advances in technology the negative relationship will vanish. Similar to this, Deolalikar (1981) observed that the inverse size-productivity relationship cannot be rejected at low levels of agricultural technology in India, but can be rejected at higher levels. Rudra (1968) concluded that “there is no scope for propounding a general law regarding farm size and productivity relationship”.

One recent study done by Bhandari (2006) in Nepal’s *terai* showed a positive relationship between farm size and productivity, rejecting the argument that in Nepal, small farms appear to be more efficient and productive than large farms. Therefore, the NR once considered as ‘stylized fact’ is not 100% stylized fact. The result of this study also contradicts this stylized fact. The finding suggests that large farms are more productive than the small ones (Figure 6.11). Similar results were found from the studies carried out both in developed and developing countries (Bhalla 1988; Hooper et al. 2002; Knopke et al. 1995). In the following section is discussed several factors influencing farm productivity and why and how the finding of this research contradicts the farm size-productivity relationships.

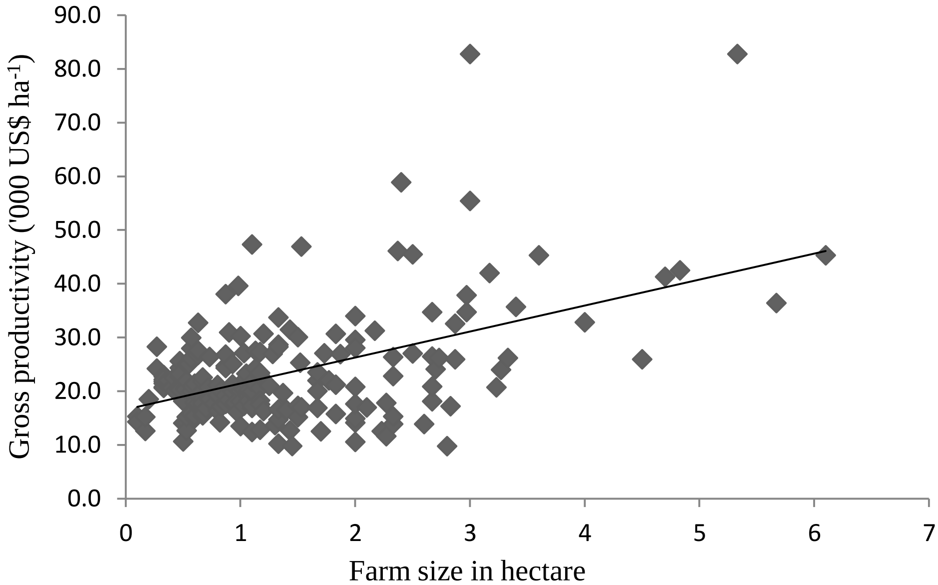

Figure 6.11: Relationship between gross productivity and farm size

6.6.2.1.Farm productivity, labour inputs and land-use intensity

Small farms are more productive than large farms because of intensive use of labour by small farmholders as they largely depend on family labour. Family workers supply more efforts in farm production as compared to large farmers who depend mostly on hired labour which is considered less efficient than family labour (Bardhan 1973; Eswaran & Kotwal 1986; Feder 1985; Sen 1962). Therefore, labour per unit of land is negatively correlated with farm size (Cornia 1985), which results into increased labour productivity with increased farm size. The finding of this study also agrees with this negative relationship between farm productivity and labour inputs as there exists a strong negative correlation (r = -0.82) between farm size and labour inputs and more than 65% of the total cost of production is accrued by labour inputs in the case of small size farm, i.e. subsistence agriculture system (SAS). This is because large farmholders are encouraged to substitute capital equipment for labour (Cornia 1985) as mechanization has economies of scale and therefore more efficient if applied to large farm units (Cornia 1985).

In the study area, large farmers are more inclined to use tractors for land preparation and thresher for post-harvest of rice and wheat. The strong positive correlation (r = 0.55) between farm size and use of fuels (a proxy for mechanization) justifies this argument. However, mechanization only is not the reason for lower demand of labour in large farm management. Allocation of a certain area of the farm to less labour intensive farm activity, i.e. tree planting (both horticulture and agroforestry) is another reason for lower demand of labour. The tree density has increased with increase in farm size; there is a strong positive correlation (r = 0.65) between tree planting and farm size.

Even though the data on labour was not disaggregated as family and hired, it can be said from the data that availability of family labour is higher in small farms because population density (ha^{-1}) is higher in small size farm than in medium and large farms. Even with the higher family labour inputs, the small size farms are less productive than large ones, which contradict the previous findings. The negative relationship of farm size and labour inputs exists not because small farms are more intensively used than large farms but because large farms preferred to adopting new technology, i.e. tree planting which is less labour intensive than agriculture.

The supporters of NR hypothesis often urged that even though the labour productivity is lower in small farms, the gross productivity is higher because the small farms are intensively used due to higher cropping intensity (Cornia 1985). The finding of this study contradicts this argument also because this study gave a completely opposite result, i.e. large farms are intensively used with lower labour inputs because of semi-mechanized mode of production. The cropping intensity is higher in large farms than in small farm (Table 6.4) and there exists a strong positive correlation (r = 0.56) between farm size and cropping intensity. This is attributed to the farmers' risk minimizing strategy because there would be a considerable loss in farm productivity until the tree crop started giving economic return seven years after investment.

To conclude that the tree planting strategy of farmers led to the greater crop intensity could be misleading because cropping intensity is largely determined by irrigation facilities (Sampath 1992). Since there is no exogenous irrigation infrastructure developed in the study area, such as water canals, big water ponds etc., the possibility of small farmholders using higher amount of water per hectare as urged by Sampath (1992) is almost zero. Endogenous irrigation facilities such as a motor is the only source of irrigation in the study area and for small farmholders, it is not affordable and cost effective either. The positive correction (r = 0.59) between hours of irrigation per hectare and farm size supports this argument.

6.6.2.2. Farm productivity and land quality

Several authors suggest that the observed negative relationship between farm size and productivity may be due simply to differences in land quality between small and large farms, with small farms having better quality land (Bhalla 1988; Bhalla & Roy 1988; Newell et al. 1997; Sampath 1992). The major drawbacks of these studies are that the findings are based on national level aggregated data (pooled data), that did not control the variations in land quality, cropping intensity, cropping pattern and other regional variations that could affect the farm productivity such as drought, rainfall etc. Theoretically, areas with higher quality land might attract a higher population density, leading to pressures to subdivide farms and resulting in smaller-sized landholdings than in areas with lower quality land. Using Indian data, researchers have found that controlling for village-specific effects reduces the observed effect of farm size on productivity, i.e. while villages with smaller farms tend to have higher output per unit of land; there is no negative relationship within villages (Bhalla & Roy 1988; Newell et al. 1997). Furthermore, when farm-level land-quality variables are included in the analysis, the negative relationship significantly weakens and in some cases disappears (Bhalla & Roy 1988; Sampath 1992).

In the study area the land quality is controlled by two factors: exogenous and endogenous. Exogenous includes chemical fertilisers and farmyard manure (FYM) while endogenous includes soil properties such as soil depth, colour, texture, and types, moisture content and water holding capacity. With the study area being very small in term of area coverage with no altitudinal variations among the sample farm households, no variations in drought and rainfall pattern can be expected and basic soil properties do not vary greatly. However, the rate of fertiliser and farm yard manure application may vary from one to another farm household. In terms of FYM, the application rate is higher in small farms. There exists a strong negative correlation (r = -0.75) between FYM and farm size because of higher livestock density in small farms than in large farms. But in the case of chemical fertiliser, the scenario is quite opposite; the application rate is positively correlated (r = 0.68) with farm size. It can be concluded that there is no variation in land quality across farm households be it small or large. Because of no variations in land quality between small and large farms, this study rejects the ‘stylised fact’, the negative relationship that small farms are more productive because they maintain high quality soil. The study findings are in agreement with some previous findings (Bhalla & Roy 1988; Sampath 1992).

So far it is discussed about gross productivity and was found that large farms were more productive than small farms as opposed to the ‘conventional wisdom’, i.e. small farms are more productive. Even high gross productivity could be less attractive for farmers if the cost of production is higher because farmers of developing countries such as Nepal cannot afford high cost farm technology and therefore any farm technology should be evaluated not only by gross productivity but by cost effectiveness of the technology and profitability (gross margin per hectare). In terms of these two variables, the large farm enterprises are more profitable and cost effective than the small farm enterprises. Figure 6.1 suggests there is a negative relationship between farm size and cost of production per hectare. Similarly, there exists a positive relationship between gross margin and farm size (Figure 6.2).

Similar results were observed in Australian Broadacre agriculture (Hooper et al. 2002; Knopke et al. 1995).

Two explanations have typically been offered to explain the positive correlation between farm size and productivity. One is the presence of increasing returns to scale and the other is ‘economies of size’ (Knopke et al. 1995). The first explanation is not relevant here as it was not measured in this study and also many research findings indicate that agriculture may not experience increasing returns to scale in the long run (Chand et al. 2011). The second explanation is quite relevant and fits the context of the study area because emerging technologies have favoured farms with a relatively large operating size, leading to greater scope for input substitution and improved access to capital for financing developments in management and farming practices (Hooper et al. 2002; Knopke et al. 1995). Forest tree planting is a new farm technology in the study area and any new farm technology adoption is greatly influenced by farm size (Chapter 5). Because of tree planting, farmers adopted more intensive land-use practice with semi-mechanization which heavily reduced the labour inputs resulting in greater scope of input substitution. Also, tree planting is less labour intensive than agriculture.

In addition to the aforementioned productivity enhancing variables (land quality, cropping intensity and irrigation), there are several other variables responsible for overall farm performance. Adoption of high yielding varieties (HYVs), choice of field crops, yield potential of various crops, adoption of high value cash crops, and differences in cropping pattern also influence the overall farm productivity (Bhalla & Roy 1988; Chand et al. 2011). However, the relationships of these variables with farm size are both positive and negative. Chand et al. (2011) observed that the adoption rate of high yielding varieties is higher in small farms than in large farms and the cropping pattern follows a declining trend with an increase in size of holding. However, Bhalla and Roy (1988) urged that large farms have better access to the credit necessary to purchase yield increasing inputs and that operators of large farm holdings are generally less averse to the adoption of new technologies. In the study area, farmers have adopted high yielding varieties of maize, wheat and rice but the adoption rate is not known due to lack of data. However, as urged by Chand et al. (2011) that adoption of HYV is strongly associated with irrigation, it can be presumed that the adoption rate is higher in large farms in the study area as there is a positive correlation between farm size and hours of irrigation (Figure 6.12). As opposed to what Chand et al. (2011) urged, this study revealed that the cropping pattern (mixed cropping and crop diversification) followed an increasing trend with an increase in size of holding (Table 6.4).

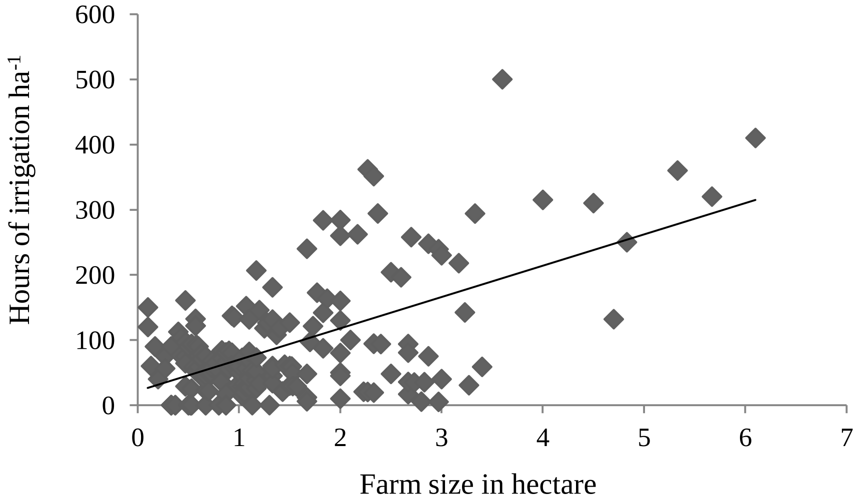

Figure 6.12: Relationship between irrigation and farm size

6.6.3. Carbon sequestration, current practice of tree management and farm profitability

In the study area, carbon sequestration is not the goal of the agroforestry-based farming system that farmers have adopted. Primarily they introduced trees on their fields to maximise profits from the sale of timber and poles. Carbon sequestration is a co-benefit for which a global market is emerging and gradually growing and farmers in the developing countries such as Nepal could benefit from carbon trade in the future because agroforestry is widely recognized as climate change mitigation and adaptation strategy.

Farm profitability is determined by production cost (inputs) and output values. Famers always aim to maximise profit by reducing production cost and increasing outputs by selecting high-yielding and high value crops as far as possible. In the study area, the large farmholders made higher profit than the smallholders who have adopted MIS, LIS and SAS type of farming enterprises (Table 6.5). This variation is mainly attributed to less labour use (reduction in labour cost) because of larger area under-tree crops and adoption of mixed, diversified and intensive cropping by the large farmers (Tables 6.4 and 6.5).

Unlike agriculture, agroforestry is a perennial farm enterprise, taking more than one year horizon to complete one production cycle which is determined by the harvest cycle (rotation age) of the trees of the system. Therefore, determination of harvest cycle of the tree species is more important because it determines the possible benefits (profits) that farmers can achieve from the tree harvest and thus from the whole farming system. Selection of other field crops also affects the farmer’s profits from the system and that has already been discussed in the previous section. Therefore, this is not the point of discussion for now. The focus of the discussion would definitely be towards the current practice of tree management, whether this practice is a right choice from a profit maximising point of view and if not, why farmers are forced to adopt such a wrong practice which has deprived them from fetching the maximum possible benefits.

The optimality of the current practice was judged against two criteria; biologically optimum rotation (maximum sustained yield (MSY) rotation) and financial rotation (Fautsmann rotation). The growth pattern of the species clearly indicated that the age at which they attained maximum mean annual increment (MAI) was higher than the existing rotation age that farmers have adopted (Tables 6.11 and 6.14 and Figures 6.8, 6.9 and 6.10). Clearly farmers are producing and selling quite below the optimum yield. If the revenue generated by these trees under the current practice is to be compared with the revenue that these trees could generate under alternative practice (biologically optimum rotation), the revenue would be quite higher in the latter case, as discussed in the result section with an example of *D. sissoo* under the sub-section "*Total biomass and carbon sequestration by five agroforestry tree species under alternative practice based on maximum mean annual increment in diameter (MAIDBH)".*

The reasons for low revenue generation under the current practice can be attributed to the obviously lower physical output (yield) because of the fact that the trees were harvested before maturity, i.e. harvesting at the age when trees were at strong increment (Figures 6.8 and 6.9) and the two different pricing mechanisms based on the size of the timber. Under the current practice not a single tree is eligible to be sold on a volume basis given that the size is below the required size. Results showed that there was a high variation in tree value between sold on a volume basis and on a weight basis. However, in the case of *E. camaldulensis*, both the pricing mechanisms do not apply; farmers sell eucalypt trees when they reach pole size irrespective of volume and weight.

Comparing the current practice with the financial rotation, the second criteria, would be quite problematic because the growth patterns (Figure 6.8) are based on chronosequence, not on the time series data from the permanent plots. Empirical studies suggest that the biological rotation age of these tree species should be higher than what is shown in the Table 6.14. For example; *D. sissoo* attains its maximum MAI between twenty-eight and thirty-five years of age depending on site quality but this study showed that it is at age eighteen that D. *sissoo* reached its maximum MAI, which is quite less. The reasons behind such an unexpected result can be attributed to the use of chronosequence data as discussed earlier and selection of agroforest (woodlots) as a representative of all types of tree planting to measure the growth of agroforestry tree species.

Table 6.2 clearly indicates that agroforestry trees are grown both as belt, such as alley and boundary, and as plantation (woodlots). Studies have shown that the growth pattern of the same species varied with mode of tree planting (Dhakal 2008). In a study carried out in the same area where this PhD research was conducted, it was found that *D. sissoo, E. camaldulensis*, and *G. arborea* performed better in belt planting than in the blocks. The mean DBH of *D. sissoo* at age fifteen was found to be higher by 19% in belt planting than in the wood-lots. Similarly, *E. camaldulensis* and *G. arborea* exhibited 18% and 10% higher growth respectively in mean DBH compared to woodlots (Dhakal 2008). Similar results were witnessed in other studies carried out elsewhere. For example, Paul et al. (2013) and Henskens et al. (2001) in

Australia found that compared to planting in blocks, the belt planting could increase stem volume by 20-29% due to decreased intra-specific competition for light, water and nutrients. Given the time constraints it was not feasible to select sample trees from all types of plantations to measure the growth variables, i.e. height and diameter, for this study. Further, since the objective of this study was to see the potential of carbon sequestration at system level, less attention was given to the likely variation in growth and overall harvest cycles of the trees under study.

Theoretically, the financial rotation is shorter than biological rotation. However, the former is largely determined by the discount rate and price of timber. When the timber price and discount rate increase, financial rotation shortens and vice-versa (Kula & Gunalay 2012; Maraseni & Cockfield 2011b; Olschewski et al. 2010). If carbon sequestration is to be included as financial benefit from agroforestry, the management regime would be definitely longer than the timber, only rotation (Fautsmann rotation), but still shorter than biological rotation (Huang & Kronrad 2001; Kula & Gunalay 2012; Maraseni & Cockfield 2011b; Romero et al. 1998; Van Kooten et al. 1995). Unlike timber price, rise in carbon price results in longer rotation (Asante et al. 2011; Cao et al. 2010). These are just theoretical perspectives on how the objectives of tree raising (timber production, timber plus carbon sequestration) bring change in the management regime of an agroforestry system. Ironically, the crucial question, "What would be the optimum rotation age of the agroforestry tree species in the case of timber only and timber plus carbon and what effect would be there in rotation age when both timber and carbon price increased?" remained unanswered. However, it can be concluded that the present practice of tree management is neither biologically nor economically optimum. Further study is required to answer this unanswered question through time series data collected from permanent plots.

Now the question arises why farmers are adopting such an inefficient practice of harvesting, i.e. sub-optimum level, depriving them from getting the actual benefits from their investment in tree crops. One major reason is risk of disease outbreak. *D. sissoo*, the second dominant and main timber species in the study area, is more susceptible to disease as it matures and therefore farmers prefer to harvest this tree species before maturity so that they can be safe from the complete crop failure because of disease outbreak. Since there is no provision of insurance so far as in the Indian state, Uttar Pradesh (Jain & Singh 2000) that shares boarder with the study area, farmers are reluctant to keep this tree species longer than current harvest cycle i.e. fifteen years. Another reason for early harvesting might be the initial higher cost associated with tree planting and no cash flow realized for at least seven years for most tree species in the study area. During this seven-year period the outcome from tree planting is limited to grasses for animal feed and fuelwood, which contribute less to the overall cash flow. Therefore, as the rotation age increases, the duration of no cash flow also increases.

6.6.4. Farmers objectives, farm policies and adoption of agroforestry-based farming systems

The finding of this research clearly indicates that the agroforestry-based farming systems are more productive than conventional agriculture, which is a subsistence type. Further, having trees on a farm of any density (as tree density varied with agroforestry types in the study area) has supported to offset emissions caused by the agriculture component of the system through reduction in cropped area (ha^{-1}) and sequestration of carbon by tree biomass above- and below-ground and also through enhancing organic carbon in the soil. Even though this research did not study the soil carbon dynamics, previous studies have proved that the soil carbon accumulation rate is higher in agroforestry systems than in agriculture (Jose 2009; Nair et al. 2009).

Not only in terms of gross productivity, but in terms of gross margin as well, agroforestry-based farming systems proved to be more profitable than agriculture (Table 6.5). The finding of this study reinforces the argument that the agroforestry-based farming system is an economically viable and environmentally sustainable land-use practice. A study from Nepal's mid-hills (Neupane & Thapa 2001) showed that agroforestry intervention nearly doubled the farm income per hectare and greatly supported in soil fertility enhancement. In the Chittagong Hill Tracts of Bangladesh also, practice of agroforestry on the degraded agricultural lands improved economic returns (Rasul & Thapa 2006). However, adoption of such a promising land use system is not widespread and globally several agroforestry projects have failed. In Chapter 5, the factors that influenced farmers' decisions about adopting an agroforestry system (an amalgam of multiple farm technologies) were discussed. The result suggested that farm size was the most limiting factor influencing the farmers' decisions as more than 60% variation in adoption decisions is explained by the farm size alone (Chapter 5). At landscape level, as discussed in Chapter 4, the technology development and transfer and infrastructure (opening up of the east-west highway) development played a crucial role in the evolution of an agroforestry-based farming system in the study district but these variables were non-significant at farm level, showing no influence in farmers' decisions regarding the adoption of an agroforestry-based farming system. Finding of this study reinforces the argument that technology development is a necessary but not sufficient condition for the widespread adoption of most agroforestry innovations (Sanchez 1995).

Besides individual farmers' characteristics (age, education, experience, and gender), biophysical, social, and economic factors that affect the adoption decision, farmers' choice of farm technology is by large dependent on its profitability, which is discussed elsewhere in this chapter. While these factors are usually important, they are never sufficient to guarantee the adoption of agroforestry systems. This implies that the policy and institutional context should play a significant role in the development of agroforestry. In addition, due to its long-term nature, adoption may not take place in a policy vacuum, as it often has to be facilitated by a conducive policy and by national and local institutional arrangements. Even though agroforestry-based land use is not as wide as it would be because of its economic and environmental sustainability, in the study area this farming system, which has recently evolved through a project intervention by a national NGO, appeared to be a successful intervention because out of two hundred households sampled for this study, 87.5% had adopted this agroforestry-based farming system. However, there is a high variation in degree of adoption from less to highly integrated. Now the question arises, "Would the farmers who have adopted this system continue in the future also because several studies showed that farmers, once adopters, have become non-adopters?" (Adesina & Chianu 2002; Chianu & Tsujii 2005). Studies show that sustained adoption is a combination of field efforts and by several policies beyond the field (Ajayi & Kwesiga 2003; Buck 1995; Hazell & Wood 2000; Place & Dewees 1999; Syampungani et al. 2009).

The finding of this study strongly suggests that the type of agroforestry, which is now widely practiced, should continue for both private (farm level) and social benefits as it is more productive and can generate higher NPV and B-C ratio. One favorable condition for farmers moving to highly integrated agroforestry systems is the labor shortage in the study area following the trend of youth going abroad for work as the highly integrated system is less labor-intensive. However, given the trend (the discontinuity), the possibility of farmers, who have practiced subsistence agriculture (12.5%), less integrated agroforestry (32.5%) and medium integrated agroforestry (32.5%), shifting to highly integrated agroforestry (22.5%) which is more productive and profitable than the three farming systems, is questionable because farmland is the most limiting factor for farmers in the study area and farm size largely influences the farmers' decisions with regards to adoption (Chapter 5). Therefore, the bottleneck that stops farmers from moving to more productive farm enterprise should be addressed through some policy intervention which could favor agroforestry promotion in Nepal. In the following section some such issues that can be addressed through policy intervention are discussed with particular reference to the study area.

6.6.4.1. Size of land holding and land and tree tenure

The size of land holding is a major issue in the adoption of an agroforestry-based farming system in the study area as adoption is size-dependent. Even though large farms appeared to be more productive, given the gradual increase in population and the culture of family split in Nepalese society, it has been a big challenge for the large farmholders to maintain their farms as large as before. Elsewhere around the globe, the issue of land and tree tenure is more prominent than size issue because farmers are reluctant to plant trees, which is a long-term investment, when their land rights are not secured and they are not free to harvest tree crops as per their wishes (Sanchez 1995).

In the study area, the land tenure insecurity is not relevant since farmers own their land. However, tree tenure security is quite ambiguous by the prevailing forest policy of the country. According to the Forest Act-1993 of Nepal, farmers can plant trees on their farms but are not allowed to harvest trees without permission from the forest authority. In practice, farmers do not ask for permission when they harvest trees for their own use. This sort of restriction on the cutting of trees leads to great uncertainty, onerous official permission requirements, and sometimes bribes. However, when the purpose of harvest is to sell their forest products, i.e. timber, poles, fuelwood etc., farmers have to complete the legal formalities as described by the policy. Since the policy has complex, tedious and demanding permit procedures for the harvesting and transport of timber produced on farms, farmers sell their products to the middlemen (contractors) to avoid those complexities. As a result, farmers are deprived of getting the actual price of their forest commodities (Regmi & Garforth 2010). There is, however, a legal provision that farmers can register their trees as private forest under the Forest Act - 1993. Unlike agricultural commodities, once the trees are registered, farmers have to pay value added tax (VAT) to the government.

The effect of tenure on agroforestry is particularly strong relative to other factors due to the often longer-term benefits from trees as discussed earlier. The land tenure issue is not a prominent issue in the study area; the major issue is the size of land holdings available, because the type of agroforestry that has evolved in the study area is unfavourable on small holdings.

6.6.4.2. The time lag and uncertain markets

While the agroforestry-based farming system in the study area is promising from both an economic as well as an environmental point of view, the fact that farmers realize its benefits only after certain years of investment has hindered the wide adoption of this promising farming system on small holdings. In the study area, farmers get return from their investment on both agroforestry and horticultural trees, after seven and six years of investment, respectively. This implies that, unlike conventional agriculture, farmers may have to bear initial net losses before benefitting from their investment. However, the large farmholders who have adopted agroforestry-based farming systems have intensified their farmland through crop diversification, mixed cropping and intensive crop cultivation (Table 6.4) so as to compensate the initial loss resulting from the tree planting. Whether such intensification fully compensated the loss would be a topic of further study. This intensification, however, was possible because of farmer’s capacity for investing in irrigation. In contrast, the smallholder farmers, comparatively resource poor, are more risk-averse than the large farmholders (Gray et al. 2004), and they discount future value heavily (Rasul & Thapa 2006). Therefore, interventions to help farmers endure this difficult period before the tree exert their profitability and ecological function is a major issue in agroforestry adoption and promotion in the study area.

Another issue with respect to agroforestry promotion in the study area is the prevailing market mechanism for the forest products. As discussed in the result section of this chapter, the market of forest products is not well-established; it is a contractor-based market mechanism where producers (farmers) have to negotiate a price for their commodities with contractors. There prevails a high uncertainty in the market of forest products that farmers are not sure about the future price of their products unlike the price for agricultural commodities. Amid such unfavourable conditions for the adoption, tax is another issue, discussed under the sub-heading “Size of land holding, and land and tree tenure” that hinders smallholders from adopting tree based farming system.

6.6.4.3. Valuation of environmental externalities

Agroforestry generates significant public ecosystem services, such as watershed protection, soil and biodiversity conservation, carbon sequestration and avoided emissions, as well as minimizing climatic and financial risks. The finding of this study suggests that having trees on farms reduces GHG emissions annually by 64% compared with the subsistence agricultural system SAS (Table 6.10). In terms of carbon, the three-tree based systems namely HIS, MIS and LIS have the potential of sequestering 4.99t C ha^{-1} yr^{-1}, 3.38t C ha^{-1} yr^{-1} and 3.52t C ha^{-1} yr^{-1}, respectively (Table 6.13) while this sequestration potential is almost zero in subsistence agriculture since soil carbon is not considered here. Both the externalities-negative (emissions) and positive including carbon sequestration- affect the society as a whole.

Most of the environmental goods and services that an agroforestry provides to the society are not valued by the market except for the carbon for which a market is emerging internationally. Under the existing management regime of agroforestry systems in the study area, the financial incentive that farmers can realise from the carbon credit is very insignificant (less than 0.5% contribution to the NPV generated from the sale of timber, fuelwood and poles). This contribution would be slightly higher if soil organic carbon and the carbon stored in fodder trees were considered. Being insignificant, only the carbon benefits cannot be a tempting incentive to motivate farmers towards adopting an agroforestry-based farming system. Therefore, some other environmental externalities such as biodiversity conservation, soil erosion control, nutrient cycling, should be valued like other tangible benefits through the mechanism of payments for environmental services (PES). This can be done only through some policy intervention. Any kind of financial and technical support to farmers who are introducing trees onto their fields can be considered a form of payment for environmental services (PES).

6.6.5. Farm productivity and sensitivity analysis

One of the most important decisions a farmer makes is the farming system in which to invest his scarce resources. Investment in one of the farming systems is usually mutually exclusive because land holdings are small. As has been seen, all systems are acceptable and profitable at the chosen discount rates and can be ranked in decreasing order of profitability as, HIS, MIS, LIS and SAS. This study revealed “the more integrated the farm enterprise is, the more the profit”. Having trees, both AF trees and horticultural trees, with varying density, has affected the overall farm productivity and thus the profitability of the three agroforestry-based farming systems in the study area.

Most farmers in the study area believe that tree planting is a risky farm enterprise and not profitable in the long run for mainly two reasons; trees are susceptible to disease outbreak as witnessed in *D. sissoo* in the recent past and unpredictable weather pattern such as wind and draught during flowering season of horticultural crops. As opposed to the generally held belief of farmers, the sensitivity analysis of farm performance (NPV) with 25% decrease in agroforestry crops revealed that the HIS still performed better and appeared to be financially more attractive in terms of NPV and return-to-labour than conventional agriculture. Two other agroforestry-based farming systems i.e. MIS and LIS, however, appeared to be less attractive as they generated lower NPV than SAS. This is because of lower tree density in these two farm enterprises. Using only return-to-land (NPV) as a decision criterion would be misleading when labour is a scarce resource (Kwesiga et al. 1999). In the study area, following the increased trend of youth moving out of the country for jobs (Joshi et al. 2012), farmers would be faced with severe labour shortage in the near future.

The shortage of labour would more adversely affect the SAS famers than the farmers adopting less labour intensive farm enterprises, i.e. HIS, MIS and LIS. Even if the NPVs of MIS and LIS are lower than that of SAS, adoption of any kind of agroforestry-based farming systems would be more attractive in the changed socio-economic context of the study area because profitability may not always be the first consideration in the adoption process; other factor such as labour availability might be the more important factor in the adoption (Takimoto et al. 2010). However, for smallholder farmers moving to adopting agroforestry-based farming systems is heavily constrained by the land availability (farm size) (Chapter 5).

Sensitivity of NPV was further tested with ±25% change in field crop yields. Results revealed that all farming systems were greatly influenced by change in this variable indicating that field crop yield was the most determining variable in overall farm profitability. However, SAS was most sensitive to change in field crops yield as compared to other tree-based farming systems. Even with 25% decrease in field crops SAS realized 82% decrease in NPV while it was only 46.6, 56.2 and 55.7 for HIS, MIS and LIS, respectively. When NPV was tested with 25% increase, similar results were obtained; i.e. 82% increase in NPV of SAS and appeared to be performing better than MIS and LIS while HIS still appeared to be generating higher NPV than the SAS. Even in the case of 25% decrease in both field crops and AF crop (AF products) yields, HIS was still a financially more attractive farm enterprise, which indicates feasibility of the agroforestry-based farming system even in the case where the yields of any one of its products falls by up to 25%, provided farmers become able to make a better combination of system components because the other two agroforestry-based farming systems were less attractive than SAS in the case of 25% decrease in AF products yield.

The viability of these four farming systems was sensitive to change in labor wage. The variable ‘labor cost’ was the second most influencing variable to overall farm performance (NPV). SAS was again influenced most by the change in labor price. An increase of 25% in labor price, however, did not yield negative NPV for all farming systems but this increase greatly reduced (61.5%) the NPV of SAS and comparatively, other tree-based farming systems were less affected (45.6% in LIS, 34.9% in MIS and 22.1% in HIS). This is because SAS is a labour-intensive farm enterprise. About 609 man-days $ha^{-1}year^{-1}$ was required for SAS while this figure was quite lower for the other three tree-based farming systems (Table 6.5). When labor price was dropped by 25%, SAS appeared to be more competitive to HIS and more attractive financially than the other two farming systems. But given the current trend of young going abroad as discussed earlier, there is less possibility of labor being cheap in the future. Rather, labor will become scarcer than at present, which would definitely affect the performance of all farming systems but more severely the SAS farming system. If labor price were increased by 50%, the SAS would yield a negative NPV while other agroforestry-based farming systems would still be yielding positive NPVs.

Another sensitivity analysis indicates that if the cost of all inputs (fertilizer, seeds/seedlings and labor) were to increase by 25% simultaneously, the NPVs of HIS, MIS, LIS and SAS would decrease by 30.7%, 46.3%, 53.8% and 73.6%, respectively. Despite this increase the NPVs remained positive. However, SAS was affected most by this increase as compared to the other three tree-based farming systems. This situation, more probable than a simultaneous increase in AF products yields (Dube et al. 2002), shows that agroforestry-based farming systems remain economically more viable than conventional agriculture.

Carbon price was another variable used to test the sensitivity of NPVs of the four farming systems. Three scenarios with varying prices of carbon from \$ 5.00 t^{-1} CO_2e to \$ 30.00 t^{-1} CO_2e with \$ 10.00 t^{-1} CO_2e as a base, were analysed to see the effect of carbon price on total NPVs generated by these farming systems (Tables 6.16 and 6.18). In the scenario when only carbon uptake was considered, carbon sale undoubtedly seemed to increase the NPVs of three tree-based farming systems while there was no effect on SAS's NPV. Therefore, comparatively, the farmers who have adopted tree-based farming systems would be benefited from this additional income from carbon sale. However, the amount of C payment per hectare was too little; it would not be attractive for farmers to participate the C sale program. The contribution of income from C sale to the total NPVs of three agroforestry-based farming systems was less than 0.5%, which is an insignificant amount. Nonetheless, if farmers can gain this small carbon payment without any extra financial burden resulting from participating in carbon trade, there is no reason for farmers not to participate the C sale program.

Under the second scenario where both the GHG emissions and carbon uptake were taken into consideration, even the highly integrated agroforestry-based farming system appeared to be the source of GHG emissions. Therefore, if these farming systems are to be evaluated from carbon financing point of view, they would not be preferred by farmers because the net carbon balance of these systems were negative, which results in reduced NPVs with an increase in carbon price. In the third scenario where in addition to carbon uptake by tree component, GHG emission reduction by the system considered as a carbon uptake was taken into consideration, two farming systems out of four, i.e. HIS and MIS, would benefit from the C sale program because in comparison to LIS and SAS, these two farming systems have contributed to GHG emission reduction significantly. If farmers had not adopted the highly integrated agroforestry, 323.9t more CO_2e would have been released into the atmosphere from their farms in thirty years. Therefore, this reduced emission was considered as carbon benefit, like saved time in collection of fuelwood and fodder was considered as income of fodder bank and live fence (Takimoto et al. 2010). With this reduction included, HIS and MIS farmers would be getting their NPVs increased by 5% and about 1%, respectively (Table 6.17). However, the LIS, although a tree based farming system, could not benefit from this reduction scheme because of higher livestock and lower tree (AF tree) density.

This study revealed that relatively rich farmers (having large land holdings) were the ones who adopted agroforestry-based farming systems and succeeded to some extent. For them, carbon credit might not be a motivating factor for such technology adoption. In contrast, for the relatively poor farmers (having small land holdings) who were constrained by limited land resources to adopt the economically viable and environmentally sustainable land management technology, such carbon credits could be of prime importance. Therefore, in order to achieve poverty alleviation through C credit sale, it is important that the poorest of the poor of the study area adopt the technology. Involving farmers with little resources needs, naturally, extra support. Since C sale is not likely to provide much income under current conditions, even under the GHG emission reduction scheme, covering the cost of assistance, and transaction costs for C trade, would be a large financial burden. Institutions such as international NGOs or national/local governments will have to be encouraged to bear these costs. Further, carbon credits could be more attractive if carbon stored in fodder trees, horticultural trees and soil, which is not considered in this study, were taken into consideration and that would motivate small farmers moving towards an agroforestry-based farming system.

6.7. Conclusions

It can be concluded from this study that all farming systems were economically viable at a given discount rate. Comparatively, the performance of agroforestry-based farming systems were better than subsistence-based agriculture in terms of NPV and B-C ratio and this is attributed to mainly higher crop diversification and intensity, reduced labour resulting from use of tractors and threshers, substitutes for labour and obviously introduction of horticultural and agroforestry crops that also supported the reduction of production cost in long run because tree planting is less labour intensive that agriculture. Sensitivity analysis further reinforces that the subsistence agriculture system (SAS) was most sensitive to the change in production inputs compared to agroforestry-based farming systems.

Variations of ± 25% of field crop yields of SAS significantly affected the sensitivity analysis, closely followed by variations of prices of labour. The agroforestry-based farming systems appeared to be less sensitive to a simultaneous decrease of 25% in AF products (field crops and tree crops yield) than the SAS. Inclusion of carbon value further decreased the NPV of SAS while there was an increase in NPVs of agroforestry-based farming systems. The livelihoods of small holder farmers who have adopted subsistence agriculture, already vulnerable, would be further vulnerable given the labour constraints and environmentally unsustainable land-use practice.

Even if small holder farmers wish to shift to more integrated farming practice, they are unable to do so, given the land constraints. Adoption of integrated farming is largely dependent on farm size (Chapter 5). On the other hand, even the large farmers who have adopted agroforestry systems are at risk given the population growth and family split culture in Nepalese society that makes it difficult for them to keep their farm land as large as before. Decrease in farm size results in decreased profitability and decreased farm productivity. Therefore, there seems a visible challenge for policy makers, natural resource managers and even farmers regarding how to deal with such a paradoxical situation so that large farmholders can keep their farm land intact and at the same time small farmholders can have a favourable condition to adopt agroforestry.

Possibility of agroforestry being a good source of income from carbon trade cannot be ignored. However, individual countries have their own definition of a forest that might not match with the definition of existing international carbon trading mechanism such as CDM and REDD+. For example, Nepal has adopted FAO definition, according to which agroforestry does not come under forest; it is categorized as other land with tree cover. But, by the CDM forest definition, agroforestry systems in the study area are eligible to participate in CDM projects as these systems meet the minimum threshold of crown cover to be considered as forest. Therefore, using FAO definition is depriving smallholder farmers of getting benefits from the C trade. Using FAO definition needs to be reviewed for the benefits of small holder farmers.

To view agroforestry as a panacea for farm land degradation resulting into low productivity and low profitability would be a stereotypic analysis and somewhat biased. This study revealed that farmers in the study are more inclined to monoclonal plantation of *E. camaldulensis* given the short rotation and comparatively higher economic gain. Even the government-sponsored program has emphasized the promotion of this tree in the study area with a slogan, “Eucalypt farming: panacea for poverty”. However, several studies suggest that having *E. camaldulensis* on the farm land would be detrimental in the long run both from an environmental and economic point of view because it is considered to be responsible for drying land as it absorbs a lot of water from the soil. On the other hand, under the current practice of agroforestry management regime, farmers are deprived from getting the actual return from the tree crop harvest. The current practice of tree harvest is quite below the optimum level. These are some issues that need to be addressed for better promotion of an agroforestry-based farming system in the region. Some policy interventions are deemed necessary in this regard. This is discussed under Chapter 7 ‘Summary, Conclusions and Recommendations.

Chapter 7

Summary, Conclusions and Recommendations

7.1. Introduction

This study attempted to address some research issues related to agroforestry intervention in developing countries through a comprehensive and an integrated evaluation of system performance taking a case of two farming systems, i.e. subsistence agriculture system (SAS), and agroforestry-based farming system (less integrated, medium integrated and highly integrated) of Dhanusha District, Nepal. Compared to other studies in this field, this study is more comprehensive not just because it detailed the history of the agroforestry-based farming system development at landscape level and more specifically the adoption potential of such a system at farm level but because it attempted to cover both tangible as well as GHG benefits while evaluating these farming systems. Previous studies failed to study the system performance more holistically; rather they focused on sequestration potential of farming systems ignoring a large amount of GHG gases, i.e. Methane, Nitrous Oxide and Carbon Dioxide emissions from the system in the atmosphere. Therefore, this study would provide a more comprehensive and convincing backstop to the resources managers while designing agroforestry and policy makers while formulating polices with regards to agroforestry intervention.

This chapter provides the major findings of this study and then puts forward research contributions, future research issues and some policy recommendations.

7.2. Summary of major findings

Broadly the objective of this study was to examine the adoption potential of agroforestry intervention and the feasibility of such intervention from a profitability point of view. The first part of the objective was addressed through assessing the factors that determined farmers' decisions on whether or not to adopt an agroforestry-based farming system. The second part of the objective was addressed through a comparison of four different farming systems in terms of profitability with and without GHG values by using three financial indicators NPV, B-C ratio and return-to-labour. The detailed results followed by discussions were discussed in Chapters 4, 5 and 6. Here only a few major findings that the authors thought might have a long term implications in designing, adopting and implementing agroforestry intervention in developing countries are summarised.

7.2.1. Development of the agroforestry-based farming system

Farming system in the study area has evolved gradually over time from very simple mono-cropping to multi-cropping, and to a more integrated agroforestry-based farming system. This had occurred as a result of several factors, not just population growth. The present day farming practice, the agroforestry-based farming, was the result of several factors that contributed to land-use change in different time periods of farming history of the study area. The finding of this study clearly demonstrated that the institutional support has been the major driver of change in each period of farming history and infrastructure development was equally contributing to land-use change in the study area. The institutional support included skills and information transfer, material support, secured market, follow up support and extension services while infrastructure included road and road networks and irrigation facility.

Another major driver of change in farming practice was deforestation due to agricultural expansion that resulted in scarcity of forest resources such as timber, fuelwood, fodder and leaf litter, which are an integral part of the Nepalese farming system. This scarcity led farmers towards crop diversification and integrating more and more trees with field crops on their farms. However, the degree of integration varied between farm households because all farmers are not at the same stage of adoption, which resulted in four different and distinct farming systems in the study area, subsistence based agricultural system (SAS), less integrated agroforestry-based farming system (LIS), medium integrated agroforestry-based farming system (MIS) and highly integrated agroforestry-based farming system (HIS). These farming systems clearly showed variations in some fundamental features of a farming system. These features are summarised in the following section.

7.2.2. Distinguishing features of four farming systems

Several farm characteristics were different. Only a few features which were directly related to farm profitability and GHG dynamics are summarized here. The tree density (agroforestry as well as horticultural tree) is of prime importance as this would affect the carbon sequestration potential of a farming system. In terms of biomass carbon, the SAS had a zero potential of sequestration since soil carbon was not considered in this study. Even within three agroforestry-based farming systems, the density (number of tree ha^{-1}) was found to be increasing with the increase in integration level indicating that the highly integrated system had higher density of trees on their farms.

Not only tree density, the composition of trees also influences the carbon sequestration. *Eucalyptus camaldulensis* that possesses the fastest growth rate was the most dominant tree species in all three farming systems. However, the density of this species was higher in HIS than in MIS and LIS indicating that the HIS had higher sequestration potential than the other two. In terms of tree distribution within farm, the HIS grew more trees as agro-forest (wood-lot or plantation) than alley and boundary plantation while the MIS and LIS raised more trees on alley and farm boundary. This is because of farm size. The HIS having a larger farm size than that of MIS and LIS could allocate more land for tree plantation. Therefore, for successful agroforestry intervention, one should take into account the farm size.

Cropping intensity (CI), crop diversification (CD) and mixed cropping were some fundamental features in the study area directly affecting the farm productivity and GHG dynamics. The result showed that HIS had the highest CI and SAS had the lowest, indicating that the HIS farm was most intensively cropped. The higher cropping intensity resulted in higher amounts of farm inputs such as fertilisers, hours of irrigation and hours of farm machineries use. The HIS had the highest farm inputs and the SAS had the lowest. MIS and LIS placed second and third respectively, in terms of farm input use. Therefore, the GHG emissions associated with these farm inputs was higher in HIS than in the other three farming systems. Similarly, the HIS was highly diversified and mixed cropping was more frequently practiced in HIS than the other three farming systems.

Two very important farm features of these farming systems were farm size and livestock number since they are closely related to farm productivity and GHG dynamics. The conventional wisdom regarding farm size, productivity relationship, is that there exists a negative relationship (NR). However, this study showed that farm size and productivity were positively correlated, i.e. the larger the farm size, the higher the productivity. The average land holding of these farming systems were significantly different. The productivity of SAS was quite below the productivity of HIS. It can be concluded that agroforestry intervention increases the farm productivity as the farm size increases.

In terms of livestock density, the SAS possessed the highest density of livestock (ha^{-1}) among the four farming system studied while it was the HIS that kept smallest number of livestock. This study showed that the number of livestock was closely associated with the distance of home to the national forest. The farmers living in the vicinity of the forest possessed more livestock than those living farther from the forest. There exists a strong negative correlation between livestock size and distance. This has negative environmental externalities. Firstly, farmers close to forest are reluctant to plant trees on their farm and that would create pressure on the forest and obviously accelerate deforestation and forest degradation. Deforestation and forest degradation is the source of Carbon Dioxide (CO_2) emissions. Secondly, livestock and associated activities such as manure storage and application in the field are main the sources of GHG emissions mainly Methane (CH_4) and Nitrous Oxide (N_2O). The results of this study showed that the SAS was the highest emitter on a hectare basis among the four systems studied.

7.2.3. Factors affecting the adoption decision by farmers

Several factors play role in the adoption decision by farmers. The adoption model identified eight variables significantly influencing farmers' decisions regarding adoption of an agroforestry-based farming system in the study area. The eight variables were: 'farm size', 'availability of irrigation', 'education of household heads', 'extension service', 'household's experience in agroforestry', 'agricultural labour force', 'home-to-government forest distance' and 'expenditure on farm inputs'. About 60% variation was explained by the variable 'farm size' alone out of 0.75 explanatory power (R^2) of the model. Four variables, i.e. 'farm size', 'irrigation water', 'education of household head', and 'agricultural labour force' combined, explained more than 92% of the total variation (0.75) explained by the model.

7.2.4. Biomass carbon and GHG emissions

Tree biomass (above- and below-ground) is the only component considered to estimate the carbon sequestration potential of agroforestry-based farming systems in the study area. However, it was not possible to estimate the biomass carbon at the 30th year (completion of an agroforestry cycle) because of the different rotation age of five agroforestry tree species. For example *Eucalyptus camaldulensis*, *Melia azedarach* and *Anthocephalus chinensis* are harvested every ten year and therefore there are three harvest cycles of these tree species in a 30-year time horizon while *Dalbergia sissoo* and *Gmelina arborea* are harvested every fifteen year and have two harvest cycles for these two species. Chapter 6 showed that on average, the HIS had the highest sequestration potential among the three agroforestry-based farming systems. The sequestration rate of HIS (5.0t C ha^{-1} yr^{-1}) was 1.5 and 1.4 times higher than that of MIS (3.4t C ha^{-1} yr^{-1}) and LIS (3.5t C ha^{-1} yr^{-1}), respectively.

Sources of GHG emissions for all four farming systems cover paddy cultivation, livestock and manure management, farm inputs (farmyard manure and chemical fertilisers), use of fuels and biomass burning (fuelwood and crop residue). Chapter 6 showed that the total emissions (t CO_2e ha^{-1}) in thirty years from the four farming systems varied greatly. The total amount of CO_2e emissions was approximately three times higher for farm SAS (17.85t ha^{-1} yr^{-1}) than farm HIS (6.47t ha^{-1} yr^{-1}). The CO_2e emissions for the farm SAS were two and 1.7 times higher than MIS (8.62 t ha^{-1} yr^{-1}) and LIS (10.75t ha^{-1} yr^{-1}), respectively. If compared in terms of emissions from farm inputs, the amount of emissions in SAS (43.0t CO_2 ha^{-1}) was slightly higher than in HIS (39.2t CO_2 ha^{-1}) and 1.2 and 1.4 times higher than in MIS (36.5t CO_2 ha^{-1}) and LIS (30.4t CO_2 ha^{-1}), respectively.

Even though emissions from the use of chemical fertiliser alone was highest in HIS (29.4) and lowest in SAS (14.6), because of bigger number of livestock in SAS the overall emissions from farm inputs was higher in SAS compared to the other three agroforestry-based farming systems. The reason for the highest emissions in HIS from chemical fertilizer is related to the higher amount of fertiliser (ha^{-1}) application in HIS due to the higher cropping intensity and the very diversified farming system. Similarly, the amount of emissions from fossils fuels in HIS (9.4t CO_2 ha^{-1}) was 2.4 times higher than in SAS (3.9t CO_2 ha^{-1}) because larger farms are more dependent on tractors and threshers for land preparation and harvest and post-harvest activities, respectively.

7.2.5. Crown density, definition of a forest, REDD+ and CDM

Crown density is one of the criteria adopted widely while delineating forest from other land uses such as shrub land, agricultural land, agroforestry and horticultural garden. The crown density of the three agroforestry based farming systems in the study area ranged from 19 to 25%. As discussed earlier, according to CDM forest definition, these agroforestry practices came under forest. However, FAO definition excludes these practices and includes as other land with tree cover. Since the government of Nepal has adopted FAO definition, the chance of small holder farmers benefiting from participating in C trade is not possible unless the definition is reviewed.

The successful implementation of REDD+ is questionable unless agricultural sector is included because agricultural expansion is the major driver of deforestation and forest degradation in developing countries such as Nepal. Unless strategy that could stop further deforestation and forest degradation is not developed, the goal of REDD+ is not achievable. This study showed that agroforestry could be one possible strategy to create harmony between agriculture and forestry sector because agroforestry-based farming systems proved to be performing better in terms of NPV, return-to-labour and B-C ratio and reserved the potential of carbon sequestration, carbon conservation and GHG reduction.

Further, agroforestry based farming systems appeared to be more intensive, which resulted into higher productivity. And this (intensification) is very important to stop deforestation and forest degradation. However, the intensification of agricultural land had a negative implication too. This study showed that intensive land required more farm inputs such as fertilizer which is the source of GHG emissions. At the same time irrigation was another farm input responsible for land intensification in the study area and irrigation is not considered as source of GHG emissions since irrigation was operated by electricity run by hydro-power in the study area. Therefore, agroforestry could be one possible intervention in developing countries as it can meet the aspirations of both farmers and the society, the global community.

7.2.6. Comparison of return-to-land (NPV- US \$ ha^{-1}) and return-to-labour (US \$ manday^{-1}) from four farming systems

This research first compared four farming systems based on NPV from traditional benefits (i.e. benefits from filed crops, crop residues, livestock and timber and fuelwood) and return-to-labour, and later these systems were compared with the GHG values. The first comparison showed that integrating trees with field crops with any tree density, be it highly integrated or less, appeared to be financially more attractive than SAS. Among the four farming systems, the HIS was found to be the most attractive farm enterprise, followed by MIS, LIS and SAS. Even with 25% decrease in yield of agroforestry crops, the HIS generated higher NPV than SAS. However, this 25% increase would result in two agroforestry farming systems (i.e. LIS and MIS) being less attractive than SAS. While in terms of return-to-labour, all farming systems appeared to be attractive. However, the HIS was found to be the most attractive farm enterprise followed by MIS, LIS and SAS. Even with 25% decrease in yield of agroforestry crops, return-to-labour of MIS and LIS were higher than that of SAS.

Even though agroforestry-based farming systems (i.e. LIS, MIS, and HIS) sequestered carbon in tree biomass (above- and below-ground), they were responsible for emissions of GHG as well. Chapter 6 showed that incorporating the GHG value did not enhance NPV of agroforestry-based farming systems because carbon loss was higher than carbon gain in these systems. However, SAS lost a greater amount of NPV compared to the other three farming systems because SAS is the highest emitter with zero potential of carbon sequestration. Even if only the carbon gain is considered, there was an insignificant contribution of income from carbon sale in overall NPV of agroforestry-based farming systems. Income from carbon sale (US \$ 10 $t^{-1}CO_2e$) would only add less than 0.5% to the overall NPV of these agroforestry-based farming systems.

The result showed that agroforestry intervention heavily reduced the amount of GHG emissions compared to the SAS. The amount of GHG emission could reach as high as 535.4t CO_2e ha^{-1} in thirty years. After intervention of agroforestry, this figure reduced to 194.4t CO_2e ha^{-1} (HIS), 258.7t CO_2e ha^{-1} (MIS) and 322.6t CO_2e ha^{-1} (LIS). The amount of GHG emissions could be reduced by 40% to 64% in thirty years if SAS was replaced with an agroforestry-based farming system. Incorporating this reduction as carbon gain, the result showed that NPV of HIS increased significantly from 7243.5 to 7666.5 US\$ ha^{-1}, a 6% increase, while MIS realised a slight increase in its NPV. There is a reasonable chance of land-use transformation from SAS, LIS and MIS to HIS if carbon markets for the reduced emissions become reality in agroforestry sector.

7.2.7. Hypotheses tested

Four hypotheses were formulated and tested in this study. They were:

H1: The highly integrated agroforestry-based farming system (HIS) sequesters higher amounts of carbon compared to the medium integrated agroforestry-based farming system (MIS) and less integrated agroforestry-based farming system (LIS)

The carbon sequestration potential of any system is dependent on tree density and tree species. The result of this study showed that the HIS had higher density of tree including horticultural tree species and therefore higher amount of carbon sequestration as compared to other tree-based farming systems.

H2: The HIS agroforestry releases the lower amount of GHGs emissions compared to other three farming systems (MIS, LIS and SAS)

Larger portion of farm land was allocated to tree planting in HIS than in MIS and LIS and this led to lower level of emissions from HIS. Further, the livestock density (ha^{-1}) was lower in HIS than in any other farming systems. Livestock was the major sources of emissions in the study area. Therefore, due to higher tree density followed by lower livestock density, HIS appeared to lowest GHG releaser among the four farming systems studied.

H3: HIS agroforestry generates higher farm profitability than any other faming systems i.e. MIS, LIS and subsistence-based agriculture (SAS).

As discussed earlier, HIS allocated a larger portion of farm land for tree planting and tree planting was less labour intensive than agricultural activities. The study showed that more than 50% costs goes to labour hiring. Because of lower demand of labour for tree-based farming systems, the profitability of these farming systems appeared to be higher than subsistence-based farming system.

H4: The NPVs of all agroforestry-based farming systems (HIS, MIS and LIS) are greater than SAS when GHGs values are included.

Agroforestry based farming systems had the potential of carbon sequestration while SAS had zero potential. Further, SAS appeared to the highest in terms of total GHG emissions in a 30-year period among the four farming systems studied. Therefore, inclusion of GHG values in NPV estimation caused higher loss in NPV in case of SAS compared to other farming systems. This proved the hypothesis no. 4.

7.2.8. Current practice of tree management

Farmers in the study area adopted two harvest cycles: 10 years for *E. camaldulensis, M. azedarach* and *A. chinensis* and 15 years for *D. sissoo* and *G. arborea*. However, the growth curve of these species showed that the trees were being harvested when they were at rapid growth i.e. before reaching maximum MAI. A comparative analysis of NPVs from two rotations i.e. current practice and biological rotation (Maximum MAI) showed that current practice of tree harvest generated lower NPV than the biological rotation. Therefore, it can be concluded that current practice of tree management is not economically optimal.

7.3. Research contributions

The overall objective of this study was to assess the adoption and feasibility of agroforestry intervention in developing countries from both environmental as well as economic perspectives. This research contributes new knowledge in the following areas.

- Adoption is a continuous process and therefore dividing farmers into two categories as adopters versus non-adopters for assessing the factors influencing farmers' decisions on adoption cannot reflect a real adoption potential of agroforestry-based farming systems, which is by its very nature a mix of many practices. For single technology adoption such as adoption of improved maize, farmers can be easily divided into two categories: adopters and non-adopters. However, in the case of agroforestry where farmers integrate many technologies/practices together, one practice might be absent in one farmer's field while the same practice might be adopting by other farmers. Therefore, it is not practical and scientific to follow the binary choice method in adoption studies, particularly in agroforestry-related studies. Therefore, this study developed a simple, practical and more reliable science-based method on how adoption as a dependant variable can be quantified. The adoption index developed in this way can capture every farmer's level (stage) in adoption scale and avoid the chances of biasness in defining farmers as adopters, pseudo-adopters, and non-adopters.

- This study developed an adoption model based on the method described above. The model has a strong explanatory power as it explains 75% variation of adoption decision. The model has identified eight variables influencing farmers' decision significantly. For any new agroforestry intervention in Nepal and other developing countries having similar biophysical, socio-economic and climatic settings, this model could be a guiding model.

- Studies with regards to types of agroforestry are more focused on the tropical and temperate regions. There are agroforestry practices in extra-tropical regions (sub-tropical) such as Nepal. This study documented some prominent agroforestry practices prevalent in the study area. A simple method which was based on an integration level was developed to identify the prevailing agroforestry systems in the study area. Therefore, both the types of agroforestry and the method used are the new knowledge in the existing literatures on agroforestry.

- In developing economies where there is not much technological advancement in agriculture, there exists a negative relationship (NR) between farm size and farm productivity. Previous studies are based on the production of some major cereal crops such as rice, wheat and maize. However, the agriculture in the study area is so complex that farmers grow thirteen different field crops, raise timber and fodder-tree species, cultivate many horticultural crops and keep livestock. This study is more comprehensive because all components are considered in productivity analysis. Therefore, the finding of this study could be more valid than the previous ones. The finding showed that larger farms are more productive than the smaller ones, which is opposite to the prevailing hypothesis. A simple agroforestry intervention could change this ‘stylised fact’.

- Studies so far with regards to agroforestry’s role in mitigating climate change were focused on carbon sequestration by trees (above- and below-ground) and the soil. Agroforestry is not just trees but it is a mix of trees, field crops and livestock. Consequently, there are several sources of GHG emissions in an agroforestry system. This study covers both sink and sources of GHG and compares its potentiality with other land use, i.e. agriculture in terms of climate change mitigation. In that sense, this study is more comprehensive.

7.4. Research implications

Agroforestry is a long-term investment and therefore cannot flourish and continue in a policy vacuum. Here some research implications are made based on this study’s findings for better adoption of the agroforestry-based farming system in developing countries.

7.4.1. Policy level

This study showed that agroforestry is an environmentally as well as economically viable land-use practice. Nonetheless, agroforestry is not considered as separate land use unlike forestry and agriculture. Part of agroforestry, i.e. tree components, comes under forest policy and other part of the system, i.e. field crops and livestock, comes under agriculture policy. This has been a huge hurdle for farmers because if farmers wish to plant trees on their farm, they have to get permission from the forest authority and register as private forest and they have to follow a rigorous administrative procedure to get all this done. Farmers have to pay value added tax (VAT) for the forest product they sell. These sorts of hurdles should be addressed through a separate agroforestry policy. A first step towards it would be that agroforestry be recognized as a separate land use system.

There is no doubt that agroforestry provides both private and social benefits. Therefore, some incentive mechanism to motivate farmers towards agroforestry adoption can be developed. For example, the farm products can be certified as agroforestry products and comparatively higher price of the agroforestry products than that of non-agroforestry products can be fixed.

Use of forest definition proposed by FAO has deprived small holder farmers from getting extra financial income from the C trade. A considerable amount of NPVs can be generated from C sale by adopting agroforestry based farming system. Non-adopter now might be motivated to adopting agroforestry in future because of benefits they realise from such farming system. Therefore, government of Nepal needs to review the criteria for any land use to be considered as forest to get the benefits from the emerging carbon market internationally.

Farmers are profit oriented. This study showed that *E. camaldulensis* was the most dominant agroforestry tree species in the study area irrespective of agroforestry type. That clearly indicates that in future farmers will move to mono-clonal plantation of this species, which could be an environmentally unsustainable choice in the long run as discussed in Chapter 6. Such trends cannot be checked without policy intervention. Therefore, some policy that favours the multi-species plantations should be formulated to make agroforestry socially acceptable.

The study revealed that farm size is the most important factor determining whether or not to adopt the agroforestry-based farming system. Farm size was found to be positively correlated with adoption. Due to agroforestry intervention, larger farms appeared to more productive than smaller ones. Therefore, fragmented farming (division of farmland into small patches) should be discouraged. A joint farming policy should be formulated to enhance farmers' livelihoods through agroforestry intervention. Farming through cooperative approach may increase the chance of farmers participating in international carbon trade through compliance markets such as CDM, REDD+ and voluntary markets. Collectively, a huge amount of carbon could be traded following the cooperative approach to farming. The joint farming practice is emerging as a successful intervention in many developed countries such as Australia.

As summarised above, the current practice of tree harvesting is neither economically nor biologically optimum, thus affecting both private and social benefits that could be achieved through tree planting. The main reasons for this can be attributed to poverty and risks of disease outbreak in *D. sissoo*. Therefore, some policy that could guarantee the insurance in case of crop failure could motivate farmers to keep the longer rotation which is economically optimal.

7.4.2. Implementation level

Adoption of agroforestry-based land management practice was significantly influenced by a range of factors. The regression model revealed that adoption of AFLMP was significantly influenced by farm size, education, expenditure in farm input, availability of irrigation water, agricultural labour force, frequency of visits by extension workers, household's experience in agroforestry, and distance of home to the government forest. Therefore, prior to any agroforestry intervention, these eight variables should be taken into account for the successful adoption of an agroforestry-based farming system. It is strongly recommended to use this model because the model would enhance efficiency of future adoption related research work and thus save time and money.

It appears that the knowledge base of the farmers greatly influenced the adoption decision. Therefore, efforts should be directed towards educating farmers about agroforestry-based farming systems so that farmers would be able to analyse risks and uncertainty associated with any new technologies. Similarly, the adoption model identified extension service as one of the factors influencing adoption. Therefore, focus should be on interaction between farmers and extension workers so that farmers could get access to information regarding new farming technology and this sort of interaction would help farmers alleviate their doubts if any regarding the new technology. Irrigation is another factor that positively influences adoption. Therefore, at farm level, focus should be laid on development of irrigation facilities to promote the agroforestry-based farming system.

7.5. Suggestions for further research

Even though this study attempted to evaluate the agroforestry-based farming system in terms of profitability with and without incorporating GHG values, there are still some areas that need to be addressed to make the future research more holistic. Agroforestry could support climate change mitigation in three ways; carbon sequestration in tree biomass and soil, carbon conservation through reducing pressure in natural forest and GHG emissions reduction. This study covered most of this. However, carbon conservation and soil organic carbon uptake are not considered. Therefore, these aspects need further investigation while comparing agroforestry systems with other competitive land uses: plantations and agriculture.

Another area of further research could be determining the agroforestry cycle that could degenerate maximum economic return. In this study a 30-year cycle was selected based on famers' experience. However, this study revealed that the current practice of agroforestry tree harvest was below the optimal level, meaning that farmers were adopting the inefficient rotation cycles for each agroforestry tree species. Because of the chronosequence data, it was not possible to determine the optimum rotation cycle through this study. Therefore, this could be one area of further research. For that, a time series data is necessary to capture annual variation in growth pattern of tree species under study. Permanent research plots need to be established to monitor the annual tree growth.

Similarly, in this study the NPV of four farming systems were estimated assuming the productivity would remain constant over thirty years. In the context of climate change, variation in temperature and the precipitation regime is quite certain. This variation would definitely affect the farm productivity. Therefore, it is recommended to consider this aspect of climate while estimating the farm productivity in future research.

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Appendices

Appendix A. Household survey questionnaire

Code no.

Name of the respondent (household head):
Age:
number: Education:
Family size:

Sample household
Gender:
AF type:

A. Farm characteristics

1. Farm related information

Type of tenure	Type of land	Area (ha)
Rented (R)	Upland	
	Lowland	
	Total area	
Private (P)	Upland	
	Lowland	
	Total area	
	Marginal land (M)	
	Farm size (P + M)	

2. System components integration within the farm

Sn	Components	Yes	No	Area (ha)	No. of trees
1	Agriculture				
	Vegetable				
	Field crops				
2	Horticulture				
3	Tree crops				
	Agroforest				
	Alley				
	Homestead				
	Boundary plantation				

3. Tree crops and horticulture related information

Sn	Tree species	Density (no of tree farm^{-1})	Harvest cycle (years)	Uses	
				Primary	Secondary
1	Horticulture				
	Mango				
	Lychee				
	Jackfruit				
	Guava				
	Citrus spp.				

	others				
2	Tree crops				

4. How far is your home from the natural forest?

Type of forest	**Distance (km)**
Government forest	
Community forest	

5. Where do you collect the following products from?

Sn	Forest products	Sources and amount (%)		
		National forest	Community Forest	Private source
1	Timber			
2	Fuelwood			
3	Fodder			

B. Biophysical characteristics

6. Physical attributes of the farm

Farm attributes	**Degree**				
	Very high	High	Medium	Low	Very low
Slope gradient					
Fertility gradient					
Erosion hazards					
Flood hazards					

7. Do you have Irrigation facility?

Yes () No ()

8. If yes, what is the irrigation facility used for?

C. Farmers' characteristics

9. Family size

Age	**Number**
< 15 years	
15 to 60 years (labour force)	
> 60 years	
Total family size	

10. Education

Years of schooling	**Number**
< 5 years	
0 year	
1 year	
2 years	
3 years	
4 years	
Sub-total	
5 to 10 years	
5 years	
6 years	
7 years	
8 years	
9 years	
10 years	
Sub-total	
12 years	
11 years	
12 years	
Sub-total	
> 12 years	
13 years	
14 years	
15 years	
16 years	
> 16 year	
Sub-total	
Total Family size	

11. Farmers risk bearing capacity – adopting new farming system (1 to 10 scale)

Low High

1 2 3 4 5 6 7 8 9 10

12. How long have you been involved with AF farming system (in years)?

13. How long has your family involved with this AF farming system (in years)?

14. Where do you put your existing farming system in the following complexity scale?

Less integrated AF system Highly integrated AF system

1 2 3 4 5 6 7 8 9 10

D. Institutional characteristics

15. Are you a member of any organization?

Yes () No ()

16. If yes, specify.

Type	**categories**					
	NGOs	**CBOs**	**Cooperative**	**Saving groups**	**Farmers' group**	**Others**
Formal						
Informal						

17. If any member of the family is associated with such organization?

Yes () No ()

18. If yes, specify.

Types	**No. of family members involved**
NGOs	
CBOs	
Cooperative	
Saving group	
Farmers' group	
Others	

19. Are there any development organizations (NGO and INGOs) in your area?

Yes () No ()

20. If yes, how far are they located from your home (in km)?

21. Are there any government offices (livestock, forest and agriculture) in your area?

Yes () No ()

22. If yes, how far are they located form your home (in km)?

Office	**Distance (in Km)**
Agriculture	
Forest	
Livestock	

E. Infrastructure

23. How far is your home from the highway (in km)?

24. How far is your home from the local market centre?

25. Do you have transport means of your own for AF products transport?

Yes () No ()

26. If yes, mention the types.

F. Farm production (consumed + sold)

27. Agro-crop production (Based on normal year production)

Crops	**Area (ha)**	**Irrigation**		**Yield (kg ha^{-1})**	**Price (kg^{-1})**	**Total value (NRs)**
		Yes	**No**			
Rice						
Winter						
Rainy						
Wheat						
Maize						
Winter						
Rainy						
Millet						
Mustard						
Lentil						

Gahat						
Sugarcane						
Wheat+ pea+ lentil						
Mustard+ lentil						
Mustard+ lentil+ pea						
Vegetable						
Any other						

28. Forest products production

Forest products	**Yield (*Bhari*)**	**Market price/unit**	**Total value (NRs)**
Fuelwood			
Fodder			

29. Livestock size

Live-stock	**Category**	**Sub-category**	**Number**	**Value livestock^{-1}**
Cattle (cow)	Improved	Dairy		
		Non-dairy		
		Calves		
	Local	Dairy		
		Non- dairy		
		Calves		
Buffalo	Improved	Dairy		
		Non- dairy		
		Calves		
	Local	Dairy		
		Non- dairy		
		Calves		
Sheep	Male			
	Female			
	Kids			
Goat	Male			
	Female			
	Kids			
Oxen				
Others				
Total				

30. Livestock (milk) production

Livestock products	**Quantity (litre day^{-1})**				**Price litre^{-1} (NRs)**	**No. of milking months**
	1st quarter	2nd quarter	3rd quarter	4th quarter		
Milk (buffalo)						
Milk (cow)						

31. Use of crop residues

Crops	**Use of crop residues (in percentage)**

	Burning	bedding	feed	Thatching	Others
Rice					
Wheat					
Maize					
Millet					
Soybean					
Cow pea					
Pigeon pea					
Lentil					
Mustard					
Others					

G. Energy related information

32. Annual fuelwood consumption (Seasonal calendar)

Seasons	**Winter**	**Rainy**	**Total**
Consumption (in BHARI*)			

* Some representative BHARI will be measured to estimate the mean weight of a BHARI (in kg).

33. Sources of fuelwood

Fuelwood source	**% of demand fulfilled**
Private sources	
Community forest	
Government forest	

34. What kind of stoves you use for burning?
    a. Traditional
    b. Improved
    c. Both

35. If you use both, what percentage of fuelwood is burnt by which stove?

Stove type	**% of fuelwood**
Traditional	
Improved	

36. Do you use other sources of energy for heating and cooking purpose?

Yes () No ()

37. If yes, what are they?
    a. Biogas
    b. LPG gas
    c. Cow dung
    d. Kerosene stoves

(H) Costs associated with field crops production

38. Cost associated with paddy cultivation

Activities	Paddy											
	Upland				Low land							
					Winter				Rainy			
	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)
Seeds	kg											
Land preparation												
Ploughing												
Pair of ox	No.											
Labour	MD											
Use of tractor												
Time required	Hrs											
Labour required	MD											
Land levelling	MD											
Planting	MD											
Fertilizer application												
Urea	kg											
DAP	kg											
Potash	kg											
Zinc	kg											
Ammonium sulphate	kg											
Labour for application	MD											
Weeding	MD											
NRrigation												
Time required	Hrs											

Energy consumed	Kwh											
Labour	MD											
Use of Pesticides												
Quantity used	Lit/kg											
Labour	MD											
Harvesting	MD											
Post harvesting												
By machine												
Operation time	Hrs											
Labour	MD											
Manual	MD											
Grand total cost												

39. Cost associated with Maize and wheat

Activities	Wheat				Maize							
					Winter				Rainy			
	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)
Seeds	kg											
Land preparation												
Ploughing												
Pair of ox	No.											
Labour	MD											
Use of tractor												
Time required	Hrs											
Labour required	MD											
Land levelling	MD											
Planting	MD											
Fertilizer application												
Urea	kg											
DAP	kg											
Potash	kg											
Zinc	kg											
Ammonium sulphate	kg											
Labour for application	MD											
Weeding	MD											
Irrigation												
Time required	Hrs											
Energy consumed	Kwh											
Labour	MD											
Use of Pesticides												

Quantity used	Lit/kg										
Labour	MD										
Harvesting	MD										
Post harvesting											
By machine											
Operation time	Hrs										
Labour	MD										
Manual	MD										
Grand total cost											

40. Cost associated with lentil, *gahat*, and vegetables

Activities	Lentil				*Gahat*				Vegetables			
	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)
Seeds	kg											
Land preparation												
Ploughing												
Pair of ox	No.											
Labour	MD											
Use of tractor												
Time required	Hrs											
Labour required	MD											
Land levelling	MD											
Planting	MD											
Fertilizer application												
Urea	kg											
DAP	kg											

Potash	kg											
Zinc	kg											
Ammonium sulphate	kg											
Labour for application	MD											
Weeding	MD											
Irrigation												
Time required	Hrs											
Energy consumed	Kwh											
Labour	MD											
Use of Pesticides												
Quantity used	Lit/kg											
Labour	MD											
Harvesting	MD											
Post harvesting												
By machine												
Operation time	Hrs											
Labour	MD											
Manual	MD											
Grand total cost												

41. Costs associated with Sugarcane, mustard and Millet

Activities	Sugarcane				Mustard				Millet			
	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)	Unit	Total units	Rate unit^{-1}	Total (NRs)
Seeds	kg											
Land preparation												
Ploughing												
Pair of ox	No.											

Labour	MD												
Use of tractor													
Time required	Hrs												
Labour required	MD												
Land levelling	MD												
Planting	MD												
Fertilizer application													
Urea	kg												
DAP	kg												
Potash	kg												
Zinc	kg												
Ammonium sulphate	kg												
Labour for application	MD												
Weeding	MD												
Irrigation													
Time required	Hrs												
Energy consumed	Kwh												
Labour	MD												
Use of Pesticides													
Quantity used	Lit/kg												
Labour	MD												
Harvesting	MD												
Post harvesting													
By machine													
Operation time	Hrs												
Labour	MD												
Manual	MD												
Grand total cost													

42. Livestock management cost (Annual)

Costs	Types of livestock							Total
	Cattle (cow & ox)		Buffalo		Calves	Goat	Sheep	
	Dairy	Non-dairy	Dairy	Non-dairy				
Veterinary and medicine								
Feeds								
Other								
Grand total								

43. Labour required for livestock keeping (annual)

Types	Days	Man-days	% of time for fuelwood collection	% of time for livestock look after
Free grazing (forest)				
Stall fed				

44. Income from draught service provided by ox

Total months:

Income:

45. Costs of farm accessories

Sn	Farm accessories	Unit	Rate unit^{-1}	Total number	Costs (NRs)	Average lifespan (yr)	Maintenance cost (NRs)
1.	Metal Plough	No.					
2	Wooden plough	No.					
2.	Spade	No.					
3.	*Foruwa*	No.					
4	*Naras*	No.					
5.	Yoke	No.					
6.	Axe	No.					
7.	Sickle	No.					
8.	Saw	No.					
9.	Khurpi	No.					
10.	*Khurpa*	No.					
11.	*Doko*	No.					
12.	*Namlo*	No.					
13.	*Dhakki*	No.					
14.	*Henga*	No.					
15.	Motor	No.					

Appendix B.

Table B.1: The selected tree age for Diameter at breast height (DBH) measurement of agroforestry tree species in Dhanusha district

Age	Tree species and DBH (cm)				
	E. camaldulensis	*D. sissoo*	*G. arborea*	*M. azedarach*	*A. chinensis*
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	4.5	4.0
4	8.2	4.2	3.2	6.9	6.6
5	-	-	-	9.5	-
6	16.4	8.6	-	-	12.8
7	-	-	8.8	-	-
8	24.6	13.8	-	-	20.0
9	-	-	13.2	20.5	-
10	**32.2***	-	-	**23.2***	**27.5***
11	-	-	17.6	-	-
12	38.6	25.4	-	28.3	34.7
13	-	-	22.1	-	-
14	-	-	-	-	40.2
15	-	**34.5***	**26.2***	34.2	-
16	44.5	-	-	-	42.3
17	-	-	30.0	36.4	-
18	-	-	-	-	-
19	-	44.4	32.1	-	-
20	46.5	-	-	-	-
21	-	-	33.2	-	-
22	-	47.3	-	-	-
23	-	-	-	-	-
24	-	-	-	-	-
25	-	48.5	-	-	-
26	-	-	-	-	-
27	-	49.5	-	-	-
28	-	-	-	-	-
29	-	-	-	-	-
30	-	50.2	-	-	-

* Farmers' selected rotation age

Table B.2: Tree measurement form

Name of the species	Age	DBH (cm)	Height (m)				Crown cover (m)		
			Top angle	Bottom angle	Eye height	Total height	Longest width	Shortest width	Avg. width

Table B.3: Timber (with bark) and poles price (US $) fixed by local contractors in the study area of Dhanusha district

Size (DBH) in cm	*E. camaldulensis*	*G. arborea*	*D. sissoo*	*M. azedarach*	*A. chinensis*
> 25		11.1*		3.3*	
≤ 25		0.10**		0.06**	
> 30					3.3*
≤ 30					0.06**
> 35			11.8*		
≤ 35			0.9**		
Pole size	13.1***				

* = $cuft^{-1}$, ** = kg^{-1} and *** = $pole^{-1}$

Table B.4: Percentage of merchantable timber, fuelwood and wastage for each agroforestry tree species

Sn	Species	Percentage		
		Merchantable timber	Fuelwood	Wastage
1	*Eucalyptus camaldulensis*	70	20	10
2	*Dalbergia sissoo*	45	45	10
3	*Gmelina arborea*	45	45	10
4	*Anthocephalus chinensis*	40	50	10
5	*Melia azedarach*	60	30	10

Appendix C.

Table C.1: Crop yield productivity (tonne ha^{-1}) of four farming systems

FS	Rice_rainy	Rice_winter	Wheat	Maize	Millet	Mustard	Lentil	*Gahat*	Sugarcane
HIS	4.05	5.60	2.33	2.10	1.70	0.80	0.60	0.98	54.50
MIS	3.90	5.20	2.30	2.00	1.50	------	0.50	0.93	48.80
LIS	3.95	5.60	2.35	2.00	1.35	------	------	1.01	49.20
SAS	3.60	5.50	2.05	2.50	1.80	0.75	------	-----	45.00

FS = Farming systems; HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

Table C2: Price (US$/100kg) of agricultural commodities in the study area of Dhanusha district

Sn	Commodities	Price
1	Paddy	23.9
2	Maize	25.6
3	Wheat	28.8
4	Millet	30.1
5	Pea	118.1
6	Lentil	69.5
7	*Gahat*	111.5
8	Sugarcane	5.0*
9	Mustard	72.1
10	*Rahari*	72.1
11	Sesame	118.1

* = Factory gate price

Table C.3: List of farm accessories used by farmers of the study area

Sn	Farm accessories	Unit	Rate unit^{-1} (US $)
1.	Iron mold board plough	No.	13.1
2	Wooden plough	No.	13.1
2.	Spade	No.	3.9
3.	Hoe	No.	3.9
4	*Naras*	No.	1.3
5.	Yoke	No.	3.9
6.	Axe	No.	13.1
7.	Sickle	No.	0.7
8.	Saw	No.	5.2
9.	Khurpi	No.	2.6
10.	*Khurpa*	No.	3.3
11.	*Doko*	No.	1.9
12.	*Namlo*	No.	0.7
13.	*Dhakki*	No.	3.9
14.	Wooden plank	No.	9.2
15.	Motor	No.	39.3

Appendix D.

Table D.1: Annual cost of field crops production (US $ ha^{-1}) for four farming systems in the study area

Farming systems	Cost items												
	Seed	Land Preparation	Levelling	Planting	Weeding	Fertilizer	Irrigation	Pesticides	Harvest	Post harvest	Transpor tation	Farm tools	Total
HIS	206.9	161.5	23.4	75.8	95.3	132.4	32.6	38.0	175.9	95.3	168.2	38.0	1243.4
MIS	227.8	164.6	25.8	78.9	105.3	121.6	27.3	39.6	183.2	74.3	174.1	35.1	1257.8
LIS	160.4	184.1	31.4	91.2	114.9	74.6	32.6	54.3	174.7	63.7	110.3	64.9	1157.1
SAS	272.8	218.0	38.4	118.3	145.2	130.9	24.9	98.3	234.3	109.1	198.6	63.1	1651.9

HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

Table D.2: Cost of and benefits from agroforestry tree crop production (US$ ha^{-1}) for three farming systems for a 30-year time horizon

FS	B/C	year																													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
HIS	Cost	37.7	7.7	8.7	1.8	16.5	16.5	50.9	93.9	98.9	44.0	44.6	24.7	30.1	25.4	45.6	24.2	52.0	95.1	98.9	44.1	30.0	6.6	5.7	1.8	16.5	16.5	54.3	101.8	107.8	73.2
	Benefits	0.0	0.0	0.0	0.0	26.1	29.9	491.1	1072.5	1134.4	392.9	13.6	34.4	83.6	97.3	306.6	29.9	491.1	1072.5	1134.4	379.3	0.0.	0.0	0.0	0.0	39.7	43.5	525.5	1156.1	1231.6	659.8
MIS	Cost	25.2	6.2	6.8	2.5	30.7	30.7	54.4	86.6	90.7	50.9	50.9	35.2	37.1	33.4	40.4	33.2	54.7	87.0	90.7	50.9	22.7	5.8	4.0	2.5	30.7	30.7	55.6	89.1	93.4	60.7
	Benefits	0.0	0.0	0.0	0.0	57.8	70.0	345.5	762.3	813.0	288.2	14.8	11.5	24.8	28.0	148.2	70.0	345.5	762.3	813.0	273.5	0.0	0.0	0.0	0.0	72.6	84.8	356.9	787.1	841.0	363.8
LIS	Cost	26.9	8.4	9.0	4.7	47.3	47.3	72.5	104.1	107.7	67.9	67.5	51.6	53.4	49.7	54.6	49.3	72.8	104.4	107.7	67.9	24.9	8.1	5.0	4.7	47.3	47.3	73.4	106.3	110.1	75.2
	Benefits	0.0	0.0	0.0	0.0	79.9	87.1	364.1	784.5	828.6	288.6	6.3	10.1	23.7	28.0	153.9	87.1	364.1	784.5	828.6	282.3	0.0	0.0	0.0	0.0	86.3	93.4	374.2	808.2	856.6	356.3

FS = Farming systems; HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system

Table D.3: Cost of and benefits from horticultural crop production (US$ ha^{-1}) for three farming systems for a 30-year time horizon

FS	B/C	year																													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
HIS	Cost	247.3	177.3	181.1	183.4	27.8	30.1	33.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	142.1
	Benefits	335.0	335.0	268.0	268.0	0.0	89.0	27.8	89.5	28.0	130.2	44.0	276.9	88.5	303.0	101.6	580.9	185.9	585.8	188.3	581.0	185.9	664.7	211.0	661.6	209.5	550.8	174.8	486.3	155.1	903.7
MIS	Cost	254.7	181.9	185.6	187.9	28.0	30.2	33.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	144.3
	Benefits	304.9	304.9	243.9	243.9	0.0	89.1	28.0	89.6	28.2	133.0	45.5	278.9	89.9	308.0	104.5	583.3	188.2	589.5	191.3	583.7	188.4	666.5	213.2	663.5	211.7	553.6	177.2	490.0	157.5	931.5
LIS	Cost	288.3	202.7	207.4	210.4	35.7	38.7	42.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	183.4
	Benefits	326.5	326.5	261.2	261.2	0.0	109.0	33.2	109.9	33.7	152.7	49.2	340.5	106.4	351.6	111.9	707.3	220.4	717.0	225.3	718.1	225.8	824.7	257.8	819.7	255.3	677.6	210.8	596.4	185.6	1186.8

FS = Farming systems; HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system

Table D.4: Cost of and benefits from livestock component (US$ ha^{-1}) for four farming systems for a 30-year time horizon

FS	B/C	year																													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
HIS	Cost	857.4	246.3	249.5	255.9	249.5	765.0	255.9	249.5	248.7	348.2	255.9	765.0	249.5	249.5	255.9	249.5	249.5	765.0	255.9	348.2	249.5	249.5	255.9	765.0	249.5	249.5	255.9	249.5	249.5	249.5
	Benefits	249.6	249.6	249.6	249.6	886.3	418.6	249.6	886.3	249.6	291.5	890.2	418.6	249.6	884.6	249.6	249.6	886.3	418.6	249.6	928.2	253.5	249.6	886.3	418.6	249.6	886.3	249.6	249.6	886.3	460.5
MIS	Cost	1135.7	373.1	376.5	383.2	376.5	990.2	383.2	376.5	376.5	528.5	383.2	990.2	376.5	376.5	383.2	376.5	376.5	990.2	383.2	528.7	376.5	376.5	383.2	990.2	376.5	376.5	383.2	376.5	376.5	376.5
	Benefits	353.5	353.5	353.5	353.5	1108.2	556.1	353.5	1108.2	353.5	413.9	1117.3	556.1	353.5	1108.2	353.5	353.5	1108.2	556.1	353.5	1168.6	362.5	353.5	1108.2	556.1	353.5	1108.2	353.5	353.5	1108.2	616.5
LIS	Cost	1412.0	492.5	493.5	495.4	493.5	1072.4	495.4	493.5	493.5	835.5	495.4	1072.4	493.5	493.5	495.4	493.5	493.5	1072.4	495.4	835.0	493.5	493.5	495.4	1072.4	493.5	493.5	495.4	493.5	493.5	493.5
	Benefits	482.2	482.2	482.2	482.2	1207.5	667.5	482.2	1207.5	482.2	624.0	1223.3	667.5	482.2	1207.5	482.2	482.2	1207.5	667.5	482.2	1349.3	498.0	482.2	1207.5	667.5	482.2	1207.5	482.2	482.2	1207.5	809.4
SAS	Cost	2532.9	810.0	813.2	819.5	813.2	2271.8	819.5	813.2	813.2	1080.7	819.5	2271.8	813.2	813.2	819.5	813.2	813.2	2271.8	819.5	1080.7	813.2	813.2	819.5	2271.8	813.2	813.2	819.5	813.2	813.2	813.2
	Benefits	707.0	707.0	707.0	707.0	2559.9	1163.1	707.0	2559.9	707.0	821.0	2570.2	1163.1	707.0	2559.9	707.0	707.0	2559.9	1163.1	707.0	2673.9	717.2	707.0	2559.9	1163.1	707.0	2559.9	707.0	707.0	2559.9	1277.1

FS = Farming systems; HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

Table D.5: Discounted cash flow (US$ ha^{-1}) of four farming systems in the study area

FS	Years																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
HIS	1.2	575.7	462.3	411.6	673.7	148.9	366.3	829.4	549.6	309.6	347.3	130.4	162.1	322.1	161.7	188	239.2	203.6	194.7	211.3	66.8	101.4	103.8	58.3	47	93.5	47.7	78.8	88.5	68.8
MIS	-282.1	434.1	339.8	300.4	665.5	52.7	258.4	717.9	396.1	219.5	340.9	69.4	115.5	303.5	111.6	169.1	222.2	144.5	145.7	194.4	55	89.7	102.1	44.5	39.4	93.3	35.8	60.4	75	58.3
LIS	-452.5	416.9	322.2	287.3	641.0	62.2	250.0	706.9	394.0	183.5	327.7	83.1	113.5	301.5	110.9	187.7	219.8	161.0	148.9	192.3	57.2	101.2	54.6	41.2	41.2	97.4	36.6	64.1	74.5	66.7
SAS	-1058.4	428.5	380.3	335.5	1354.6	-237.2	238.8	964.2	192.7	122.6	687.4	-120.2	122.4	488.5	96.5	87.2	347.7	-60.9	61.3	231.6	50.4	44.2	175.7	-30.8	31.4	125.4	24.8	22.4	89.2	36.9

FS = Farming systems; HIS = Highly integrated agroforestry-based farming system; MIS = Medium integrated agroforestry-based farming system; LIS = Less integrated agroforestry-based farming system and SAS = Subsistence based agriculture system

Appendix E.

Table E.1: Year-wise projection for a -30 year time horizon based on the number of milk cows and buffaloes at the time of data collection in the study area*

	Year-wise buffalo and cattle population									
Size	**Yr1_0to12_F**	**Yr1_0to12_M**	**Yr1_1to 3_F**	**Yr1_1to3_M**	**Yr1_Mil_catttle**	**Yr2_0to12_F**	**Yr2_0to12_M**	**Yr2_1to3_F**	**Yr2_1to3_M**	**Yr2_Mil_catttle**
1	1	0	0	0	1	0	1	1	0	1
2	2	0	0	0	2	0	2	2	0	2
3	3	0	0	0	3	0	3	3	0	3
5	5	0	0	0	5	0	5	5	0	5
Size	**Yr3_0to12_F**	**Yr3_0to12_M**	**Yr3_1to3_F**	**Yr3_1to3_M**	**Yr3_Mil_catttle**	**Yr4_0to12_F**	**Yr4_0to12_M**	**Yr4_1to3_F**	**Yr4_1to3_M**	**Yr4_Mil_catttle**
1	0	0	1	1	1	1	0	1	1	1
2	0	0	2	2	2	2	0	2	2	2
3	0	0	3	3	3	3	0	3	3	3
5	0	0	5	5	5	5	0	5	5	5
Size	**Yr5_0to12_F**	**Yr5_0to12_M**	**Yr5_1to3_F**	**Yr5_1to3_M**	**Yr5_Mil_catttle**	**Yr6_0to12_F**	**Yr6_0to12_M**	**Yr6_1to3_F**	**Yr6_1to3_M**	**Yr6_Mil_catttle**
1	0	1	1	0	1	0	0	1	1	1
2	0	2	2	0	2	0	0	2	2	2
3	0	3	3	0	3	0	0	3	3	3
5	0	5	5	0	5	0	0	5	5	5
Size	**Yr7_0to12_F**	**Yr7_0to12_M**	**Yr7_1to3_F**	**Yr7_1to3_M**	**Yr7_Mil_catttle**	**Yr8_0to12_F**	**Yr8_0to12_M**	**Yr8_1to3_F**	**Yr8_1to3_M**	**Yr8_Mil_catttle**
1	1	0	0	1	1	0	1	1	0	1
2	2	0	0	2	2	0	2	2	0	2
3	3	0	0	3	3	0	3	3	0	3
5	5	0	0	5	5	0	5	5	0	5
Size	**Yr9_0to12_F**	**Yr9_0to12_M**	**Yr9_1to3_F**	**Yr9_1to3_M**	**Yr9_Mil_catttle**	**Yr10_0to12_F**	**Yr10_0to12_M**	**Yr10_1to3_F**	**Yr10_1to3_M**	**Yr10_Mil_catttle**

	Year-wise buffalo and cattle population									
Size	**Yr1_0to12_F**	**Yr1_0to12_M**	**Yr1_1to 3_F**	**Yr1_1to3_M**	**Yr1_Mil_catttle**	**Yr2_0to12_F**	**Yr2_0to12_M**	**Yr2_1to3_F**	**Yr2_1to3_M**	**Yr2_Mil_catttle**
1	0	0	1	1	1	1	0	1	1	1
2	0	0	2	2	2	2	0	2	2	2
3	0	0	3	3	3	3	0	3	3	3
5	0	0	5	5	5	5	0	5	5	5
Size	**Yr11_0to12_F**	**Yr11_0to12_M**	**Yr11_1to3_F**	**Yr11_1to3_M**	**Yr11_Mil_catttle**	**Yr12_0to12_F**	**Yr12_0to12_M**	**Yr12_1to3_F**	**Yr12_1to3_M**	**Yr12_Mil_catttle**
1	1	0	1	0	1	0	0	1	1	1
2	2	0	2	0	2	0	0	2	2	2
3	3	0	3	0	3	0	0	3	3	3
5	5	0	5	0	5	0	0	5	5	5
Size	**Yr13_0to12_F**	**Yr13_0to12_M**	**Yr13_1to3_F**	**Yr13_1to3_M**	**Yr13_Mil_catttle**	**Yr14_0to12_F**	**Yr14_0to12_M**	**Yr14_1to3_F**	**Yr14_1to3_M**	**Yr14_Mil_catttle**
1	1	0	1	1	1	0	1	1	0	1
2	2	0	2	2	2	0	2	2	0	2
3	3	0	3	3	3	0	3	3	0	3
5	5	0	5	5	5	0	5	5	0	5
Size	**Yr15_0to12_F**	**Yr15_0to12_M**	**Yr15_1to3_F**	**Yr15_1to3_M**	**Yr15_Mil_catttle**	**Yr16_0to12_F**	**Yr16_0to12_M**	**Yr16_1to3_F**	**Yr16_1to3_M**	**Yr16_Mil_catttle**
1	0	0	1	1	1	1	0	1	1	1
2	0	0	2	2	2	2	0	2	2	2
3	0	0	3	3	3	3	0	3	3	3
5	0	0	5	5	5	5	0	5	5	5
Size	**Yr17_0to12_F**	**Yr17_0to12_M**	**Yr17_1to3_F**	**Yr17_1to3_M**	**Yr17_Mil_catttle**	**Yr18_0to12_F**	**Yr18_0to12_M**	**Yr18_1to3_F**	**Yr18_1to3_M**	**Yr18_Mil_catttle**
1	0	1	1	0	1	0	0	1	1	1
2	0	2	2	0	2	0	0	2	2	2
3	0	3	3	0	3	0	0	3	3	3
5	0	5	5	0	5	0	0	5	5	5

	Year-wise buffalo and cattle population									
Size	**Yr1_0to12_F**	**Yr1_0to12_M**	**Yr1_1to 3_F**	**Yr1_1to3_M**	**Yr1_Mil_catttle**	**Yr2_0to12_F**	**Yr2_0to12_M**	**Yr2_1to3_F**	**Yr2_1to3_M**	**Yr2_Mil_catttle**
Size	**Yr19_0to12_F**	**Yr19_0to12_M**	**Yr19_1to3_F**	**Yr19_1to3_M**	**Yr19_Mil_catttle**	**Yr20_0to12_F**	**Yr20_0to12_M**	**Yr20_1to3_F**	**Yr20_1to3_M**	**Yr20_Mil_catttle**
1	1	0	1	1	1	0	1	1	0	1
2	2	0	2	2	2	0	2	2	0	2
3	3	0	3	3	3	0	3	3	0	3
5	5	0	5	5	5	0	5	5	0	5
Size	**Yr21_0to12_F**	**Yr21_0to12_M**	**Yr21_1to3_F**	**Yr21_1to3_M**	**Yr21_Mil_catttle**	**Yr22_0to12_F**	**Yr22_0to12_M**	**Yr22_1to3_F**	**Yr22_1to3_M**	**Yr22_Mil_catttle**
1	0	0	1	1	1	1	0	0	1	1
2	0	0	2	2	2	2	0	0	2	2
3	0	0	3	3	3	3	0	0	3	3
5	0	0	5	5	5	5	0	0	5	5
Size	**Yr23_0to12_F**	**Yr23_0to12_M**	**Yr23_1to3_F**	**Yr23_1to3_M**	**Yr23_Mil_catttle**	**Yr24_0to12_F**	**Yr24_0to12_M**	**Yr24_1to3_F**	**Yr24_1to3_M**	**Yr24_Mil_catttle**
1	0	1	1	0	1	0	0	1	1	1
2	0	2	2	0	2	0	0	2	2	2
3										
5	0	5	5	0	5	0	0	5	5	5
Size	**Yr25_0to12_F**	**Yr25_0to12_M**	**Yr25_1to3_F**	**Yr25_1to3_M**	**Yr25_Mil_catttle**	**Yr26_0to12_F**	**Yr26_0to12_M**	**Yr26_1to3_F**	**Yr26_1to3_M**	**Yr26_Mil_catttle**
1	1	0	1	1	1	0	1	1	0	1
2	2	0	2	2	2	0	2	2	0	2
3	3	0	3	3	3	0	3	3	0	3
5	5	0	5	5	5	0	5	5	0	5
Size	**Yr27_0to12_F**	**Yr27_0to12_M**	**Yr27_1to3_F**	**Yr27_1to3_M**	**Yr27_Mil_catttle**	**Yr28_0to12_F**	**Yr28_0to12_M**	**Yr28_1to3_F**	**Yr28_1to3_M**	**Yr28_Mil_catttle**
1	0	0	1	1	1	1	0	1	1	1
2	0	0	2	2	2	2	0	2	2	2
3	0	0	3	3	3	3	0	3	3	3

	Year-wise buffalo and cattle population									
Size	**Yr1_0to12_F**	**Yr1_0to12_M**	**Yr1_1to 3_F**	**Yr1_1to3_M**	**Yr1_Mil_catttle**	**Yr2_0to12_F**	**Yr2_0to12_M**	**Yr2_1to3_F**	**Yr2_1to3_M**	**Yr2_Mil_catttle**
5	0	0	5	5	5	5	0	5	5	5
Size	**Yr29_0to12_F**	**Yr29_0to12_M**	**Yr29_1to3_F**	**Yr29_1to3_M**	**Yr29_Mil_catttle**	**Yr30_0to12_F**	**Yr30_0to12_M**	**Yr30_1to3_F**	**Yr30_1to3_M**	**Yr30_Mil_catttle**
1	0	1	1	0	1	0	0	1	1	1
2	0	2	2	0	2	0	0	2	2	2
3	0	3	3	0	3	0	0	3	3	3
5	0	5	5	0	5	0	0	5	5	5

* This table was used to predict the livestock size (buffalo and cattle) for each household surveyed.

Table E.2: Year-wise projection of goat population for a -30 year time horizon based on the number of milk goats at the time of data collection in the study area*

Milk goat	Year-wise goat population									
Size	**<1yr_1**	**>1yr_1**	**<1yr_2**	**>1yr_2**	**<1yr_3**	**>1yr_3**	**<1yr_4**	**>1yr_4**	**<1yr_5**	**>1yr_5**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5
Milk goat Size	**<1yr_6**	**>1yr_6**	**<1yr_7**	**>1yr_7**	**<1yr_8**	**>1yr_8**	**<1yr_9**	**>1yr_9**	**<1yr_10**	**>1yr_10**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5

Milk goat Size	Year-wise goat population									
	<1yr_1	**>1yr_1**	**<1yr_2**	**>1yr_2**	**<1yr_3**	**>1yr_3**	**<1yr_4**	**>1yr_4**	**<1yr_5**	**>1yr_5**
Milk goat Size	**<1yr_11**	**>1yr_11**	**<1yr_12**	**>1yr_12**	**<1yr_13**	**>1yr_13**	**<1yr_14**	**>1yr_14**	**<1yr_15**	**>1yr_15**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5
Milk goat Size	**<1yr_16**	**>1yr_16**	**<1yr_17**	**>1yr_17**	**<1yr_18**	**>1yr_18**	**<1yr_19**	**>1yr_19**	**<1yr_20**	**>1yr_20**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5
Milk goat Size	**<1yr_21**	**>1yr_21**	**<1yr_22**	**>1yr_22**	**<1yr_23**	**>1yr_23**	**<1yr_24**	**>1yr_24**	**<1yr_25**	**>1yr_25**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5
Milk goat Size	**<1yr_26**	**>1yr_26**	**<1yr_27**	**>1yr_27**	**<1yr_28**	**>1yr_28**	**<1yr_29**	**>1yr_29**	**<1yr_30**	**>1yr_30**
1	2	1	2	1	2	1	2	1	2	1
2	4	2	4	2	4	2	4	2	4	2
3	6	3	6	3	6	3	6	3	6	3

Milk goat	Year-wise goat population									
Size	**<1yr_1**	**>1yr_1**	**<1yr_2**	**>1yr_2**	**<1yr_3**	**>1yr_3**	**<1yr_4**	**>1yr_4**	**<1yr_5**	**>1yr_5**
4	8	4	8	4	8	4	8	4	8	4
5	10	5	10	5	10	5	10	5	10	5

*This table was used to predict the livestock size (goat) for each household surveyed

Appendix F.

Table F.1: Average crown diameter of individual tree species of the study area

Sn	Tree species	Average crown diameter (m)
1.	*E. camaldulensis*	2.6
2.	*D. sissoo*	3.6
3.	*G. arborea*	3.2
4.	*A. chinensis*	3.6
5.	*M. azedarach*	3.1
6.	*M. indica*	9.0
7.	*L. chinensis*	6.5
8.	*A. heterophyllus*	7.2