ECONOMIC AND ENVIRONMENTAL EFFECTS OF

LAND USE ON WATER YIELD AND SEDIMENT:

A CASE STUDY IN COLOMBIA

By

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PREFACE

This study was conducted to provide further knowledge and insight with regard to the economic and environmental effects of land allocation in the Rionegro watershed located in the state of Antioquia (Colombia). This project would not have been possible without the support of Colciencias, the Fulbright Commission, the University of Antioquia, the Blackland Research Center, and the Department of Agricultural Economics at Oklahoma State University. The data provided by Cornare, and the state secretary of Agriculture, both in Colombia, were determinant for the success of this project. It is hoped that the results of this research will contribute to the economic development of the region through a more sound policy making process.

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Special thanks to my father from whom I learned the value of science and who has been always a source of inspiration in my academic life. Without his support, ideas and encouragement this project would not have been possible. I also want to thank my mother (q.e.p.d), my brother and my sisters whose moral support and company were invaluable for these years far from home. I also wish to thank Jorge Hugo Barrientos for his assistance, support and dedication in collecting and analyzing the data. I also thank María Berrío and Gloria Cartagena, from Cornare, for their support and guidance in all matters related to ArcView and the digitized maps. I also want to express my gratitude to all people at the Blackland Research Center in Temple, Texas, for their kindness, and scientific support. Special thanks to Dr. Jeffrey Arnold, Nancy Sammons, Dr. Mauro Di Luzio, Dr. Paul Dyke, Dr. James Kiniry and Dr. Joaquin Zanabria. Thanks to all my good friends in Stillwater: Diego, Hitomi Kitagaki, Mohammad, Eric, John Buetner, and John

Dole, because they made this experience more enjoyable. I also want to thank my friend Edwar who has supported me to finish this research.

I dedicate this research to all the people who are working hard to make Colombia a better country to live, for us and for the generations to come.

“Si las actividades económicas no son sostenibles la situación social se vuelve insostenible”

Jairo Alviar R.

“La mejor compensación para el sufrimiento de las víctimas y de las comunidades, y el mayor reconocimiento a sus esfuerzos, es la transformación de nuestra sociedad en una sociedad que haga de los derechos humanos por los que ellos lucharon, una realidad viva. Esto es, en concreto lo que significa perdonar pero no olvidar”

Nelson Mandela

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table | Page

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER I

INTRODUCTION, BACKGROUND, AND OBJECTIVES

Introduction

This dissertation covers a set of watershed management problems faced by social planners in the eastern part of the province of Antioquia, Colombia. This dissertation aims to shed light on the land management problems in the Rionegro watershed of Antioquia by approaching different alternatives of land uses and their economic and environmental effects on water yield and soil erosion. According to the physical, climatic, and economic characteristics of the watershed, management prescriptions must provide the social planner with the tools to choose among the alternatives with the highest social net benefit from the activities developed in the watershed. Such activities (natural forests, shifting cultivation, and agroforestry) are meant to be within a sustainable[1] development context.

This dissertation intends to show that beyond the technicality of watershed management that the idea of putting nature and economic development together in a harmonious relationship must be the core of an integrated watershed management program. It is important to show that achieving economic growth through forest and agriculture activities is possible as long as all costs and benefits (including the environmental ones) are taken into account when calculating the net present value of social benefits derived from such activities. If producers have incentives to include the effects of land use on water yields and soil erosion, the decision making process will lead to a better allocation of resources as well as contributing to the sustainability of agriculture and forests. Many of the benefits of water resource development in the third world have been lost because of soil erosion, caused by an intense deforestation process in the highlands (Lal, 1995).

Economic development based on natural resources has been considered, for many economists, as part of the primitive stages of development and it has also been associated with poor agrarian and rural societies. However, natural resources can contribute to economic growth and development as long as they are managed in an efficient and sustainable fashion. It means allocating land to the use that generates the maximum welfare for the present and future generations. Renewable natural resources such as forests, soils, and water not only serve as a basis for capital accumulation and generation of surplus, but are also a source of foreign exchange through the international trade of commodities such as processed wood (timber products) or other agro-industrial commodities. At the same time, non-timber products (environmental services) such as runoff control, soil conservation, hydropower generation, carbon sequestration, ecotourism, and other environmental goods and services can generate foreign exchange, employment, and income for rural populations.

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[1] Sustainable development is a very controversial concept. Here, it is defined as the capability for future generations to enjoy a level of consumption at least equal to the level of consumption of the present

Although some studies have attempted to measure the environmental impacts of different land covers on water yield and sediment in tropical countries, this research attempts to measure such impacts by using the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1984) in a tropical environment characterized by high elevations, steep-sloping lands and abundant precipitation. The EPIC model overcomes the limitations of other methods since it can estimate environmental impacts at a watershed level and predict the impact of land management practices on water yield, sediment, organic carbon, and soil depth among other variables. Once the environmental effects of land use are estimated using the EPIC model, the goal is to estimate the impacts of those environmental effects on people's welfare through net social benefits derived from those land uses. Despite data limitations, the output obtained from EPIC is consistent with observed and measured values in the Rionegro watershed and also in the related literature (Cornare, 1998).

A multiple-use perspective is needed to achieve sustainable and integrated watershed management, particularly in developing countries, where rural populations depend upon a variety of resources produced in upland watersheds. It is also true that much of the farming, grazing and wood harvesting that takes place in tropical developing countries is leading to soil degradation through deforestation, and extensive livestock production. As a consequence, onsite and offsite effects of soil degradation, as well as loss of biodiversity, must be mitigated through different land use management alternatives such as agroforestry systems, improved fallows, and forest plantations (Barbier and Bishop, 1995).

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generation

Chapter 2 presents the literature review emphasizing watershed management in tropical countries. Chapter 3 describes the watershed in detail and the conditions that have dominated the land management practices in the region. Chapter 4 discusses the main results obtained from the simulations run in EPIC on the Rionegro watershed. Chapter 5 presents the economic valuation of onsite and offsite environmental costs for the Rionero watershed. A cost-benefit analysis approach is undertaken to illustrate the present value of net social benefits within the watershed. Chapter 6 presents the conclusions and a future research agenda.

Background

Colombia is a tropical country located in the Northwest corner of South America. Its population is about 42 million people out of which 70 percent live in urban areas. Colombia is politically divided into 32 provinces or states one of which is Antioquia, the state where the watershed subject of this study is located. The country of Colombia contains about 114 million hectares of which 49 percent is still covered by natural forest in the Amazon and Pacific regions. Colombia shares the Amazon region with Brazil, Peru, Ecuador and Venezuela. Colombia is the only country in South America that borders on both, the Caribbean and the Pacific oceans.

Tropical countries like Colombia are privileged in the sense that their geographical and climatic characteristics favor the formation of a great variety of ecosystems. Colombia shelters approximately 10 percent of the worldwide biodiversity (Ministry of Environment, 1997). The two main features of Colombia that should be the basis of any watershed management program are: 1) the great variety of elevations and 2) the abundant rainfall. According to these features, the country has been divided in five regions, Andean, Caribbean, Pacific, Orinoquia and the Amazon. The Andean mountain system, which crosses the country from South to North, is split in three branches: Western, Central and Eastern. These branches exhibit a great variety of geographical elevations, which range from the coastal basin up to 5700m (18,700 feet) above the sea level. The watershed in this study is located in the western branch of the Andean mountain system.

The average annual rainfall in Colombia is estimated to be 3000mm (9.8 feet), which represents about 30 thousand cubic meters (1,050,000 cu feet) per person per year (Ministry of Environment, 1994). The amount of rainfall that Colombia enjoys is one of the highest in the world (Table 1.1), giving the country a comparative advantage for generating hydropower, developing irrigation systems in some areas, and in providing drinkable water. However, the rainfall is not uniformly distributed. There are some

Table I-1. Freshwater availability per capita. Selected countries 1997

Country	Cubic Meters
Colombia	26722
France	3029
Germany	2084
Italy	2903
Japan	4338
Korea	1438
Netherlands	5767
Spain	398
Sweden	20340
Switzerland	7054
United Kingdom	1203
United States	9259
High Income Countries	9024
Latin America	27386

Note: Freshwater includes flows of rivers and groundwater from rainfall
Source: The World Bank. World Development Indicators. 1999

regions where precipitation reaches 12000mm (39.4 feet) and other regions where the rainfall is just 300mm (0.1 feet) per year.

The variety of elevations, the amount of precipitation, and the location of Colombia in the tropical zone are the determinants of the rich biodiversity that is represented by the following facts. Colombia is the habitat for 1,721 bird species, the largest number of birds in the world (Table 1.2). Some researchers believe that 55 or 60 species of birds are endemic. After Brazil, Colombia ranks second in the number of plant species with fifty thousand of them classified. Colombia has also 3500 species of orchids (*Orchidiaceae*), which represent about 15 percent of the total worldwide ("Alexander von Humboldt" Institute, 1998).

Antioquia is a region (province or state) located at the northwest corner of Colombia and also of South America (Figure 1.1). It has 6.3 million hectares or six percent of the nation's total area. Its population is approximately 5.2 million people (about twelve percent of the total Colombian population). The predominant forests in this region are classified as Lower Montane Moist Forest according to the Life Zones defined by Holdridge (1971). Thus, 28 percent of the state territory is composed of land areas located over 1500m (5000 feet) above the sea level (Figure 1.2). This highland, according to the Regional Secretary of Planning, is not really suited for crop agriculture or pasture, not only because of the quality of soil, but also because the slopes are quite steep. In addition, those areas represent the most valuable watersheds in the region as well as the habitat for many wood species. The Rionegro watershed is located between the range of 1900m and 2500m above sea level.

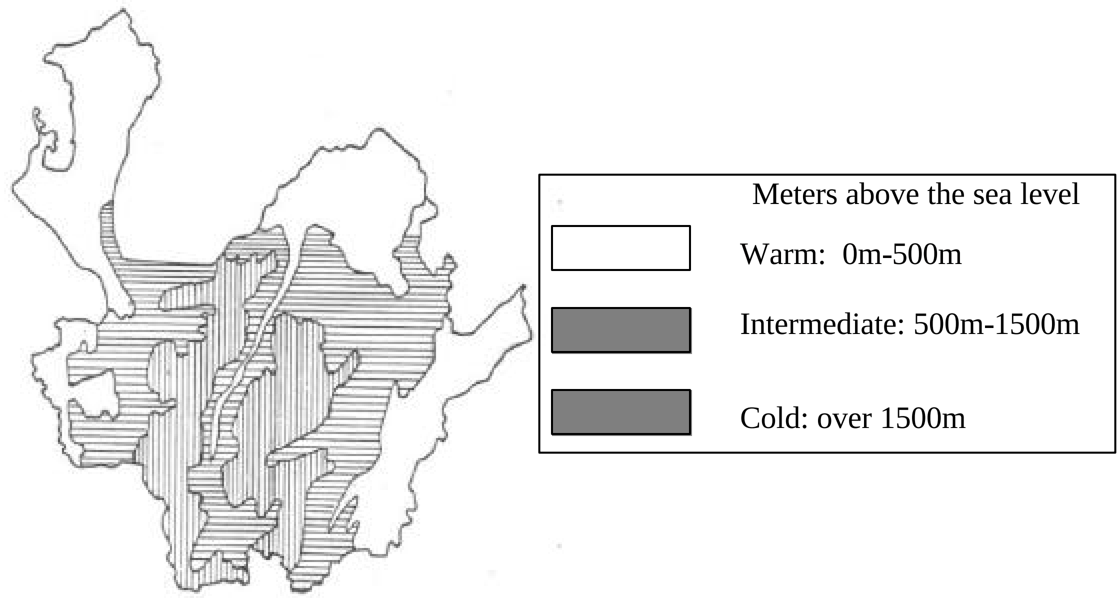
Table I-2. Countries with the highest numbers of species for selected organisms. 1995.

Rank	Country	Mammals	Country	Birds	Country	Amphibians	Country	Reptiles	Country	Angiosperms*
1	Indonesia	515	Colombia	1721	Brazil	516	Mexico	717	Brazil	55000
2	Mexico	449	Peru	1701	Colombia	407	Australia	686	Colombia	50000
3	Brazil	428	Brazil	1622	Ecuador	358	Indonesia	600	China	27000
4	Zaire	409	Indonesia	1519	Mexico	282	Brazil	467	Mexico	25000
5	China	394	Ecuador	1447	Indonesia	270	India	453	Australia	23000
6	Peru	361	Venezuela	1275	China	265	Colombia	383	South Africa	21000
7	Colombia	359	Bolivia	1250	Peru	251	Ecuador	345	Indonesia	20000
8	India	350	India	1200	Zaire	216	Peru	297	Venezuela	20000
9	Uganda	311	Malaysia	1200	USA	205	Malaysia	294	Peru	20000
10	Tanzania	310	China	1195	Venezuela	197	Papua NG	282	Former SU	20000

* Data from N.M Collins and M.G Morris (1985) Threatened Swallowtail Butterflies of the World. The IUCN Red Data Book. IUCN, Gland, Switzerland Adapted from: Linkages OECD and Major Developing Economies. OECD. 1995

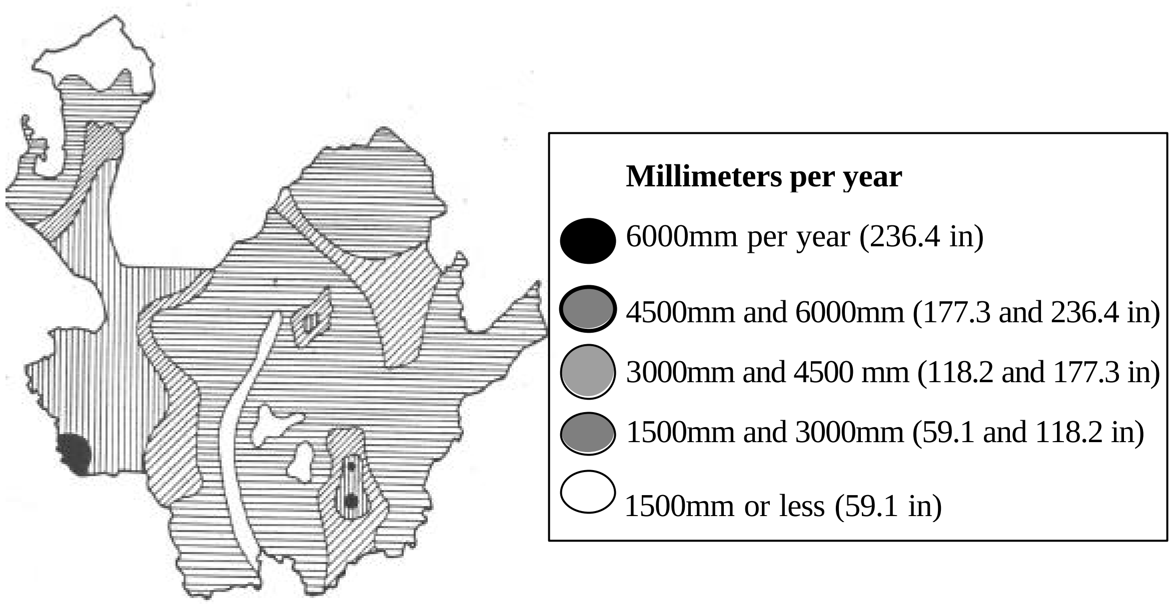
The state of Antioquia receives significant precipitation, which is distributed as shown in Figure 1.3. There are some areas in the state that receive an annual average of 6000mm of precipitation. Some other small areas have recorded an annual average of 1500mm or less of rainfall. The average annual precipitation in the watershed of study is 2100mm. Precisely because of the amount of annual rainfall and the variety of elevations in the region, water flow control and sediment are crucial issues to be studied in relation with land cover and the management practices observed in the region.

Figure I-1. State of Antioquia (Colombia)



Source: Alviar (1983)

Figure I-2 Elevations of Antioquia



Source: Alviar (1983)

Figure I-3 Rainfall distribution in Antioquia

Table I-3. Land use distribution in hectares (1000), 1996

	Current Use			
Land Use	Colombia	%	Antioquia	%
Agriculture	5317	0.05	346	0.05
Livestock (Cattle)	40083	0.35	2345	0.37
Forests	55939	0.49	2135	0.34
Bushes	3998	0.04	1109	0.17
Other Uses	8835	0.08	426	0.07
Total	114172	1.00	6361	1.00

Notes: Other uses means wetlands, lakes, snow mountains.

Source: Ministerio de Medio Ambiente. Política Nacional Forestal. Bogotá,1996

Antioquia is well endowed with natural forests. Table 1.3 compares the distribution of land for Antioquia and the country. Agriculture and livestock in Antioquia follow the same distribution of land as the nation as a whole. Pasture for livestock is the predominant land use in the state followed by forests. Primary natural forests are present in the region but most forest is secondary in the intermediate and late succession stages. Currently, there are 2.13 million hectares occupied by forests; 0.346 million hectares in Agriculture; 2.34 million hectares in pasture and 1.1 million hectares in brushwood and weeds and 0.426 million in other use (Regional Secretary of Agriculture, 1998).

Most studies of the forestry sector in the region agree that there is a potential for forest development and reforestation (Regional Secretary of Planning, 1995). A study done by a reforestation company (El Guasimo, 1998) shows there is a potential to develop a reforestation program on about 1.5 million hectares (24 percent of the total area). However, most of the deforestation process has taken place in the highlands to expand the agricultural frontier and also to expand cattle production. For example, between 1968 and 1975, 525 thousand hectares were cleared in Antioquia at a rate of 75 thousand/Ha/year. Since then, there is no evidence that deforestation has ceased (Regional Secretary of Planning, 1995). Moreover, in 1933 a study showed that in the province of Antioquia alone, there were 140 species of tradable wood (Robledo and Robledo, 1933). Unfortunately, today it is not easy to find even 20 species (Alviar, 1983). This is one of the results of land misallocation between agriculture and forests as a consequence of the indiscriminate and irrational deforestation without any replanting process as well as lack of land management programs. Small farmers generally named *colonos* have basically done the agricultural frontier expansion and cultivation practices. The case of Antioquia reflects what has happened in the rest of Colombia. According to the Ministry of Environment (1996), 68 percent of the Colombian territory, i.e. 78 million hectares, should be kept in forest because of the physical and chemical characteristics of the soils. Currently, however, 20 million hectares have been cleared or are misallocated to wrong land uses. These 20 million hectares constitute a potential for reforestation programs. Out of these 20 million hectares only 165 thousand hectares have been cultivated representing 0.15 percent of the total potential land for reforestation.

Land misallocation, deforestation, and soil erosion are particularly serious in the Andean portion of the country. This phenomena is not uncommon, recent, nor exclusive to Colombia. Ashby (1985) argues that in tropical America (Mexico, Central America and Andean countries) some 40 million people, approximately 30 percent of the agricultural families farm on steep slopes, causing serious erosion problems.

The lack of sound long-run policies to develop the natural resource sector including agriculture has led to land use conflict. In that sense, the Government argues that 45 percent of current land use in Colombia differs from the desired use. For example, the Ministry of Environment has pointed out that current land area occupied by livestock is about 40 million hectares while the desired area is just 15 million hectares. On the other hand, the lands that are considered appropriate for farming, basically in the plains, are now in pasture. In turn, the high lands in the Andes, which are highly productive in forest to protect watersheds, and control runoff, are used in intensive agriculture and pasture. In the long run this results in low agricultural productivity because soil erosion and runoff. Rural poverty and violence are increased with the misuse and deterioration of land quality (Heath and Binswanger, 1998).

The results from efforts to expand the agricultural frontier at high elevations through deforestation have been counterproductive and inefficient in terms of runoff and soil erosion. Alviar (1983) argues that deforestation has caused fluctuations in water flows that compromise the availability of water for different purposes. Even though land use has shifted from forests to agriculture and livestock in the highlands, agricultural production has declined over time. Even the area under cultivation has declined as land is abandoned. At the national level for example, between 1990 and 1997 there was a reduction of the arable land by 900 thousand hectares (Balcazar, et.al, 1998).

The misallocation of land, and its consequence of unsustainable agricultural practices, has been recognized as a problem in Colombia for more than fifty years. In a 1950 World Bank mission to Colombia, Currie pointed out the benefits of doing the appropriate watershed management. He realized that extensive livestock system occupied the bottomlands while farming was developed in the steepest portions of the territory (Currie, 1965). After fifty years, the situation is largely unchanged with vast evidence of deterioration of watersheds from soil erosion and runoff quality in the Andean portion of the country (Heath and Binswanger, 1998).

The exposure of the steepest lands to soil erosion reflects the political and institutional structure of land distribution. Large farms using modern agricultural practices monopolize prime lands for livestock production while small farms are limited and attempt to cultivate the less fertile and most easily eroded uplands (Pichon, et.al, 1999). Of the 2 million farms in Colombia, 67.3 percent have less than 5 hectares, and 87 percent have less than 20 hectares. Eighty seven percent of all farms occupy only 16 percent of the land area. Of some 12 million people in rural areas, 3.5 million are small farmers (Sanint, 1995).

Some economic reasons for land misallocation in Colombia can be given. First, the agricultural policymaking has a bias against small-farmers. The pattern of public investments and trade policies favors production of livestock and grain crops cultivated with modern management practices on large farms. These are generally export-oriented products such as coffee, sugar cane, bananas, and cotton (these products are not produced in the Rionegro watershed). Only coffee is labor intensive. As second reason is that small farmers have been left out of the modern credit market. Third, there has been an indirect taxation on agriculture from policies, which favor industrial activities in the cities. This indirect taxation has converted agriculture into a tax shelter for both income and capital gains taxation providing incentives for holding land as tax shelter instead of developing land as a productive factor (Heath and Binswanger, 1998).

The livestock sector has been more protected than the crop sector through both price and non-price interventions and its expansion has been land extensive favoring the creation of large estates (latifundios) (Heath and Binswanger, 1998). Between 1980 and 1992, beef and milk absorbed 82 percent of the total support from government (price and non-price interventions) conferred to nine farm commodities.

The area under pasture grew from 12.1 million hectares in 1950 to 26.7 million hectares in 1986 and 40 million hectares in 1995. Expansion of livestock has been land extensive: the rate of growth of livestock has only slightly exceeded the rate of growth of the pastureland (Heath and Binswanger, 1998).

Shifting Agriculture

Shifting agriculture has been practiced in tropical grasslands for many years. This practice represents further degradation from the original forest cover (Lawrence and King, 1983). The practice of fallowing the land to recuperate soil fertility is a key feature of farming in the highlands in the Rionegro watershed. Approximately, 42 percent of the farm area is left in secondary brush; scrub pasture or remnants of woodland for the purpose of regaining soil nutrients (Ashby, 1985). The practice of fallow land rotation begins with cutting and burning off trees and brush from the plot. Land is prepared by using rudimentary tools such as ox ploughing, (this is common in the small intermediate valleys) or it is done manually with the pick and spade, and exposed to the rains for two or three months until crop cover is established. Two successive crops, usually corn, are normally planted and the area is left again with the soil exposed until some kind of pasture grows. After leaving the land in pasture for 8 or 10 years, natural vegetation is re-established in a period of 10 years, and the cycle starts over again (Alviar, 1983).

Alternative land use for sustainability

Sustainable management of soil resources in the tropics has been seen as a crucial task in order to promote rural development, alleviate poverty and protect the environment. Soil degradation, a symptom of land misuse, can be reduced if land is used for in its best capacity and by using methods of soil and crop management that are ecologically compatible (Lal, 1995). One of the alternative land uses that has been shown in the literature (Young, 1991) as a mean to achieve sustainable soil resources is called the agroforestry system, which consists of a combination of trees, crops and/or livestock in order to improve soil conditions, diversify agricultural output, and generate revenues for rural populations.

A principal advantage of these systems is the reduction on the fallow period and the potential for continuous and intensive cropping. Agroforestry can facilitate intenive land use for multiple uses, basically in fertile soils. It also has the advantage of intensively using land on steep lands and marginal soils, which cannot be used otherwise. A major benefit of agroforestry system on sloping lands is erosion control. At the same time, two of the limitations of agroforestry practices are the requirement of high labor input, and in some cases, of highly skilled management. Little systematic research has been done in Colombia on these issues neither from the biological point of view nor from an economic perspective.

To conclude this brief background, one can say that the small farms located in steep-sloped portions of the watershed when they are highly susceptible to soil erosion and runoff, adapt to environmental processes of soil erosion and decline in fertility with practices that provide them with income in the short-run but exacerbating the long-run process of soil degradation. This compromises the sustainability of the economic activities associated with the primary agricultural sector.

Objectives

The general objective of this research is to estimate the economic, social, and environmental effects of alternative land uses such as shifting cultivation, agroforestry, and forestry on sediment, runoff, and yields in the Rionegro watershed in order to promote sustainable land use management. The specific objectives are to:

1) Simulate the effects of natural forests, shifting cultivation, and agroforestry on soil erosion, runoff, and organic carbon.
2) Estimate the net private benefits derived from shifting cultivation, agroforestry, and forests, less the environmental costs of soil erosion and runoff, under current versus under sustainable management,
3) Estimate the output of water and sediment under current and sustainable management by each activity in the watershed,
4) Build a linear programming model to maximize the net present value of the revenues associated with current and sustainable agricultural practices subject to erosion, runoff, land, and labor constraints

CHAPTER II

LITERATURE REVIEW

Watershed Definitions

In this study, the definition of a watershed will be taken from Dearden (1996), which states that a watershed is a catchment area or the area contributing to a specific watercourse. This area is subject to different planning activities in order to achieve the goal of sustainability of natural resources such as soil, water, forests and crops. At the same time, the integrated watershed management is a concept that involves all biophysical, socio-economic and political factors needed to achieve that goal of sustainability using the watershed as the primary unit of concern. Integrated watershed management allows the identification of the environmental effects of different land covers on water yield and sediment, which in turn identify the feedback loops between the economic activities and the ecological systems.

Multiple Use Management

The literature about multiple-use management is quite abundant. From the point of view of concepts and theoretical issues two main works have been published. Loomis (1993) published an analysis of the public lands in the U.S., which included prescriptions, and management plans to manage forests lands. Although his study was not concerned with agriculture, the concepts of multiple and integrated land use management are very useful. The author also reviewed the linear programming approach used by the U.S. Forest Service to solve a variety of problems associated with land management.

Bowes and Krutilla (1989) also discuss multiple use land management. They present an extensive number of examples for the U.S. forestland. They discuss the issue of joint production for certain activities such as timber and water augmentation and also timber and recreation for specific areas. In addition, several applications of the principles of multiple use management can be found in the literature. The Forest Service of the U.S. Department of Agriculture is required to conduct a multiple use analysis of all natural forests. One of the studies that illustrates very well all the principles, criteria, methods and procedures of multiple use management is the Land and Resource Management Plan of the Ouachita National Forest (U.S. Forest Service, 1990).

Land Management in the Tropics

Although the literature on tropical lands is quite vast, little work has been done on watershed and multiple land use management. The literature on tropical lands can be divided by topics such as tropical deforestation, soil erosion or conservation, agriculture in steep lands, and agricultural productivity. The literature about tropical rainforests is abundant from the conservation perspective as well as from the deforestation point of view. Southgate (1998) discusses economic alternatives for tropical Latin America. He also discusses the main elements that explain deforestation in many tropical countries. There is a consensus that the most important causes of deforestation in Latin America are associated with poverty in rural areas, the expansion of the agricultural frontier due to the colonization process fueled by population pressures, the lack of policies for reforestation, a lack of knowledge, and a lack of infrastructure.

There are two studies that discuss the relationship between agriculture and forests in terms of optimal control theory. Ehui and Hertel (1989) discuss the effects of deforestation on land productivity via soil erosion in the tropics. The control variable was the rate of deforestation. One conclusion was that the optimal rate of growth of deforestation depends on the preference for current deforestation and on the motivation for conservation. A truncated, quadratic yield function was used to derive an expression for the optimal steady state forest stock. The optimal forest stock was shown to decrease with increases in net agricultural returns (relative to those in forestry) and with increases in the social discount rate. Parks (1995) tried to explain why farmers with marginal agricultural lands resist converting those croplands to more profitable forests. Parks also follows an optimal control approach. He points out that the role of risks associated with forest activities and subsidies are crucial to explain the apparent "irrational" farmers decision-making process. These authors do not extend their models to a watershed management level. They do not consider outputs such as water or sediment and there is no interaction between climatic and topographic factors.

Watershed and soil erosion management

Soil management within a watershed is a concern in the tropics. The literature on soil erosion in the tropics is also abundant and there are several papers and books from the points of view of hydrologists, economists, and agronomists. These include studies by Bornemizsa and Alvarado (1975); Lal and Greenland (1979); Lal and Stewart (1995);

Moldenhauer and Hudson (1988); and Pimentel (1993). Most authors approach soil erosion in the tropics in terms of the Universal Soil Loss Equation (USLE). Because of the lack of accurate soil profiles descriptions in many tropical countries, the results are biased. Most soils in tropical America have originated from volcanic ashes. Those soils have been less studied in the U.S. with the exception of some soils in Hawaii and Oregon.

Cook (1988) shows that most of the world land that is not currently farmed is located in the tropics. This land has abundant rainfall and appropriate temperature for productive agriculture. However, 400 million hectares or 25 percent of this land are located on steep lands in tropical Latin America and the Caribbean. Cultivation of these steep lands is associated with problems such as widespread deforestation, erosion, and silting of reservoirs downstream.

In an article about soil conservation in the humid tropics, El-Swaify (1993) argues that a major consequence of total and seasonal abundant precipitation is the establishment of dense forests. Undisturbed natural forests have the ability to provide protection against soil erosion despite the impact of abundant rainfall. Using the USLE, El-Swaify provides estimates on soil erosion for different continents from available geologic data. Thus, the leading continent is Asia with 166 t/ha followed by South America with 93 t/ha. Australia exhibits the smallest value (32 t/ha). These data are derived directly from sediment loads in major rivers. While specific conclusions may be difficult to draw from these data, there is evidence of the association between overall erosion rates and population densities in these areas. This is corroborated by the fact that most populated areas in Asia discharge the highest global sediment loads in the major rivers (El-Swaify, 1993).

El-Swaify also supports the argument that mitigating the aggressive rainfall of the humid tropics requires good vegetation protection, particularly in those terrains characterized by steep slopes. Leaving soils bare and without vegetal cover even for a short period of time or with some temporary crops is the most significant source of soil erosion. Some of the figures that El-Swaify presents are insightful. For example, corn cultivated in areas with slope greater than 30 percent in Jamaica produce soil loss equivalent to 133 t/ha/year. This figure is consistent with that obtained in this study which is approximately 120 t/ha/yr on average as it will be shown in Chapter 4. Another interesting case presented by El-Swaify and supported by this research is the effect of forest cover on reducing soil erosion. For example, montane forest undisturbed in Java (Indonesia) produces 0.3 t/ha/year. In contrast, forest with no undergrowth or litter generates 43.2 t/ha/year (El Swaify, 1993). Erosion is also affected by the level of inputs (fertility, tillage, supplemental irrigation, etc) applied to these lands. However, in many tropical developing countries, poor small farmers are not able to deal with the costs of those inputs, which reduce erosion (Barbier and Bishop, 1995).

Pimentel, *et al*., (1993) estimated the effects of soil erosion on productivity by relating the removal of topsoil to the impact on crop yields. Based on an average U.S. corn yield of 6500 kg/ha, a 7cm soil loss would reduce yields by 2730 kg. In other words, 7cm of topsoil loss generates a 6 percent corn yield reduction per centimeter. However, it is not easy to estimate the loss of other soil components such as nutrients, and organic matter. The major benefits of erosion control are in conserving water and retaining soil nutrients and organic matter as well as maintaining soil depth. Several experiment studies (Pimentel, et.al, 1993) have found that soil conservation techniques retain about 10cm more water than conventional plow-plant technologies. Five centimeters (50mm) of water applied to corn, spring wheat, and sorghum crops, which normally experience transient droughts periods during the growing season, have been calculated to increase yields by 15, 25 and 23 percent respectively (Pimentel, et.al, 1993). These calculations assume that 50mm of water lost because of conventional tillage system would be fully utilized by crops grown under conservation tillage systems. The USDA calculations, cited by Pimentel, place the cost of pumping 50mm of ground water at $15/ha/yr in the United States (USDA, 1981).

There have been some attempts at watershed management programs in Latin America. Vonk (1988) discusses a watershed management program carried out in the Peruvian Andes. The conclusion was that, by developing sound conservation practices such terracing, infiltration ditches, or contour farming, crop production in steep lands can be sustainable, profitable and can also contribute to reduce soil erosion.

Currie (1965) pointed out: "the country [Colombia] is reaching a point in which almost all natural forests have been destroyed; erosion has been extended; soil fertility has been reduced; wildlife is disappearing, and fish yields are declining." Today, the situation has not changed significantly. Currie, with a very limited information and computer technology, was able to recognize important issues that have not been understood even today, much less incorporated in the policy making process toward sound watershed management. For example, focusing on a specific watershed located between 1,700m and 2,700m above sea level and precipitation between 2,000 and 4,000mm, Currie concluded the following: 1) coffee grown with shade produces little erosion; 2) small coffee areas without shade should be converted to forests; and 3) pasturelands experience overgrazing in steep-slope land. Those areas should also be converted into forests. Currie also wrote that there is a consensus about the risks associated with steep-slope farming. Currie cited an example based on cultivated land in a watershed in Puerto Rico. The area under cultivation represented only 3 percent of the watershed surface but contributed 23 percent of soil loss.

Although the Rionegro watershed, the object of the present research, does not contain coffee plantations in a significant proportions, it is worth while to say that today most of the coffee plantations in Colombia are cultivated without shade in steep-slope lands. This is contrary to the recommendations made by several scientists who have been alerted about the risks of tremendous soil erosion when the vegetative cover has been removed (Lal, 1977).

In order to develop a plan toward a more sustainable livelihood in the future, it is necessary to establish a comprehensive and integrated system of land allocation. Dearden (1996) discusses the information requirements for watershed management programs with a focus on northern Thailand. Dearden points out the threat that water scarcity is imposing in some parts of Thailand. Dearden system explains the watershed management system should be based on sound and complete information regarding the physical, chemical and socio-economic characteristics.

Agroforestry Systems

Literature on soil degradation, and its consequences on soil fertility and rural poverty in developing countries, is abundant (Young, 1991). However, little work has been done on alternative land use to recover soil fertility, particularly in the steep-sloped land in the tropics.

Agroforestry systems represent an alternative land use to recover soil fertility and control erosion[2]. The effectiveness of agroforestry systems has been recognized in the literature (Long, et.al, 1999; Place, et.al, 1999; Evans, 1999, Noordwijk, 1999; Sanchez, 1999; Klass, et.al, 1999; Pichon, et.al, 1999). Agroforestry systems take a variety of management practices in agriculture such as home gardens, alley cropping, improved fallows, intercropped trees for shade and fodder production, and trees planted in hedgerows and along fence lines. Another definition of agroforestry (Young, 1991) states that it "is a collective name for land use systems in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) and/or livestock in a spatial arrangement, a rotation or both, and in which there are both ecological and economic interactions between the tree an non-tree components of the system." All agroforestry practices represent a major form of small-scale tree planting where trees combined with agricultural crops and/or livestock in order to take advantages of tree-crop interactions and thereby to enhance, crop production, diversify farm output, stabilize or improve soils, or mitigate poor environmental conditions (Long, 1999).

Economic Benefits of watershed management

From the economic point of view, the objective of any watershed management plan should be to improve people's welfare. In other words, society should be able to evaluate the changes in welfare due to different human actions exerted on a particular

[2] The literature acknowledges other systems for recovering fertility such as terraces and contours (Lal, 1995).

watershed. These human actions are exerted by economic activities such as agriculture. However, any human intervention affecting the natural environment has consequences that affect the long-run productivity and assimilative capacity of the environment. For example, soil is an essential input to farming. This is particularly true in poor countries where agriculture production is crucial to development and survival. Yet, agricultural land use in poor countries often results in the degradation of soil fertility, and reduced productivity.

Farmers and policy makers, due to market and policy failures that mask the full cost of degradation to society, generally neglect both the on-site and off-site effects of soil degradation. An important challenge for farmers and policy makers in developing countries is to identify the causes of excessive degradation, evaluate the economic significance and implement the incentives toward more sound practices that lead to a sustainable agriculture and development. In that sense, Barbier and Bishop (1995) recognize the difficulties to measure the costs of on-site and off-site impacts of soil degradation in developing countries. They argue that, it is more common to estimate the on-site costs of soil degradation in terms of soil loss on crop production. Off-site costs such as downstream sediment, and runoff are more difficult to measure and value. The available evidence indicates that the cost of soil erosion and thus the benefits of conservation may be substantial in developing countries. Barbier and Bishop (1995) present some figures for the cost of soil erosion for selected developing countries. The values vary from 1 to 17 percent of the GDP. For example, coastal fisheries destruction, deforestation and soil erosion in Costa Rica counts for 7.7 percent of GDP. Soil erosion and deforestation in Indonesia represent 4 percent of GDP. In Nigeria, soil degradation, deforestation, and water pollution count for 17.4 percent of GDP. An additional difficulty is that social and private valuation of soil conservation differs. For society, the valuation includes both on-site and off-site impacts. However, farmers do not normally consider the latter. Understanding the private land use decisions that influence soil erosion is critical.

Vieth, Gunatilake and Cox (2001) estimate the costs and benefits of soil conservation for the Mahaweli watershed in Sri Lanka. The authors use the replacement cost method (RCM). This method assumes that the productivity of soil can be maintained if lost nutrients and organic matters are replaced artificially. Generally, the RCM is assumed to provide a lower limit to the on-site costs of soil erosion, although on-site costs may be overestimated if the soils have deep, fertile layers. The RCM determines monetary values for eroded soil nutrients (Nitrogen, Phosphorous and Potassium). One of the main findings from this study was that off-site costs (costs of lost hydropower production, the loss of irrigable area and cost of purifying water were included) were not greater than on-site costs and the former represented just 3 percent of the total costs. The authors argue that in the absence for water recreational uses, the off-site costs of soil erosion may be less significant in developing country watersheds than they are in developed countries. This conclusion can be questioned since the off-site costs of soil erosion can be high for countries that generate hydropower.

Despite all of the work done on deforestation, agriculture and watershed management in the tropics, there is still need of more systematic research and studies that put all components of hydrology, soils, and management practices together into a watershed management program. Particularly, for the case of the state of Antioquia in Colombia this research constitutes the first attempt to design a long-term land watershed management program. What is new in this research is the use of the EPIC model in a tropical setting including two main elements: abundant rainfall and steep-slope lands. Seasonal water yield and sediment are the most important environmental outcomes from land use, which have been a matter of concern because their association with sustainable development. It is also the first attempt to combine three important economic activities, forests, agriculture and pasture in relation to altitude and rainfall in order to produce a better social valuation of the net benefits obtained from these activities. Given more precise outcomes obtained from EPIC in terms of sediment and streamflows, such outcomes enable environmental economists to come up with better estimations of the social benefits derived from different land use and compare different scenarios of management practices.

CHAPTER III

WATERSHED DESCRIPTION AND MANAGEMENT PRACTICES

Watershed Description

The region of study is located in the southeast part of the state of Antioquia in Colombia (South America). The watershed is called Rionegro (Cuenca del Río Negro). It includes 9 counties (Rionegro, Marinilla, Guarne, El Retiro, La Ceja, El Santuario, El Peñol, and La Unión). The population of the watershed is approximately 130 thousand people. The total area of the watershed is 76,603 hectares (Corporación Autónoma Regional Rionegro-Nare, 1998). Based on the data provided by Cornare (1998), Figure III-1 gives the distribution

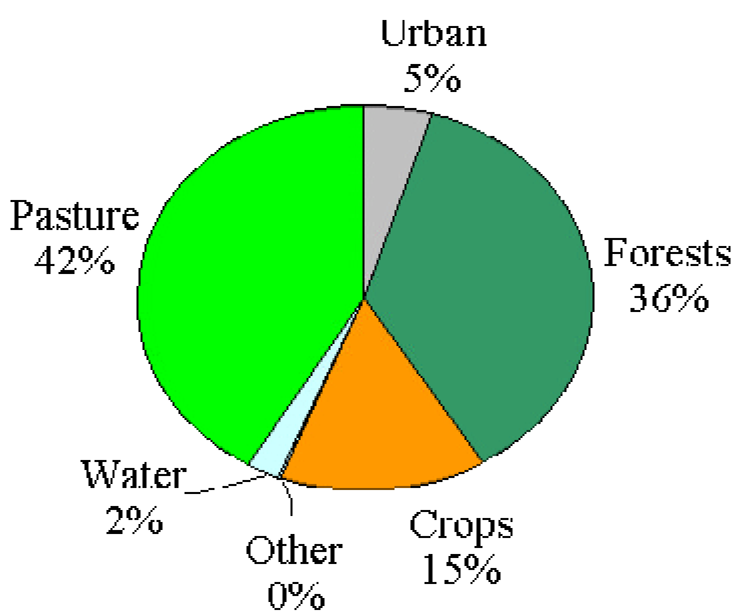


Figure III-1. Land use distribution
Source: Cornare, 1998

of land by cover within the watershed. The dominant land use in terms of area is pasture (42 percent), followed by forests (36 percent) and crops (15 percent). The portion of the watershed occupied by urban areas represents just 5 percent. Water bodies represent 2 percent of the total area (Cornare, 1998). Within each broad category of land use, several subcategories can be distinguished. Pasture is subdivided into improved and non-improved. The most common pasture species used in the watershed is called Kikuyo (*Pennisetum clandestinum*), which is a Bermuda like grass introduced from Kenya. In second place, forests are subdivided into natural and planted. The region also shows a significant number of hectares cultivated with coniferous forest (8 percent), basically cypress (*Cupresus lusitanica*). Agriculture is the third activity in terms of area. Corn is the main crop occupying 9 percent of the total area.

The watershed has a variety of elevations that range from 1000m to 3100m above sea level. Ninety five percent of the territory is between 1950m and 2550m above sea level. At these elevations the climate is considered cold. Figure III-2 shows the distribution of the watershed area among different elevation ranges. Three main physical

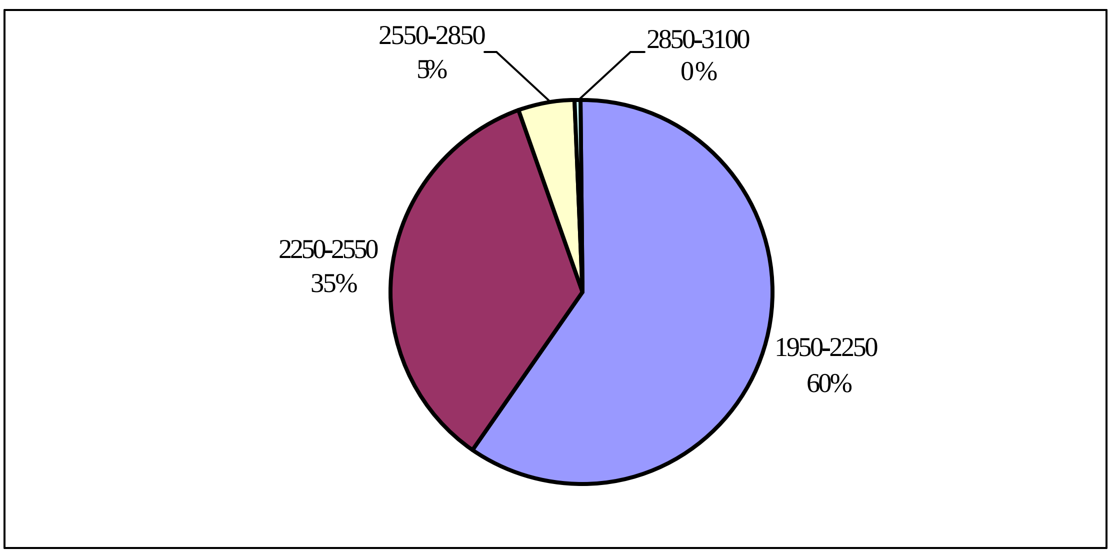


Figure III-2. Percentage of area by elevation ranges (meters)

Source: Cornare, 1998

aspects characterize the watershed: are abundant rainfall, high elevation and very steep lands with some small inter-valleys.

Climate

The average monthly precipitation in this area is shown in Figure III-3. Precipitation in the region is distributed between two main seasons: 1) the rainy season, which occurs between March and May and also between September and November and 2) the dry season with small amounts of rainfall occurs in the remaining months.

Precipitation occurs generally as heavy rain with short duration. Because of the abundant amount of rainfall in the region, artificial irrigation is not necessary. This represents an advantage for agriculture especially, in the intermediate valleys. However, some spots would benefit from irrigation during the driest months of December, January and February. Average temperature is moderately cold (16.2°C). In the high lands of the region however, average temperature can be lower than 14°C.

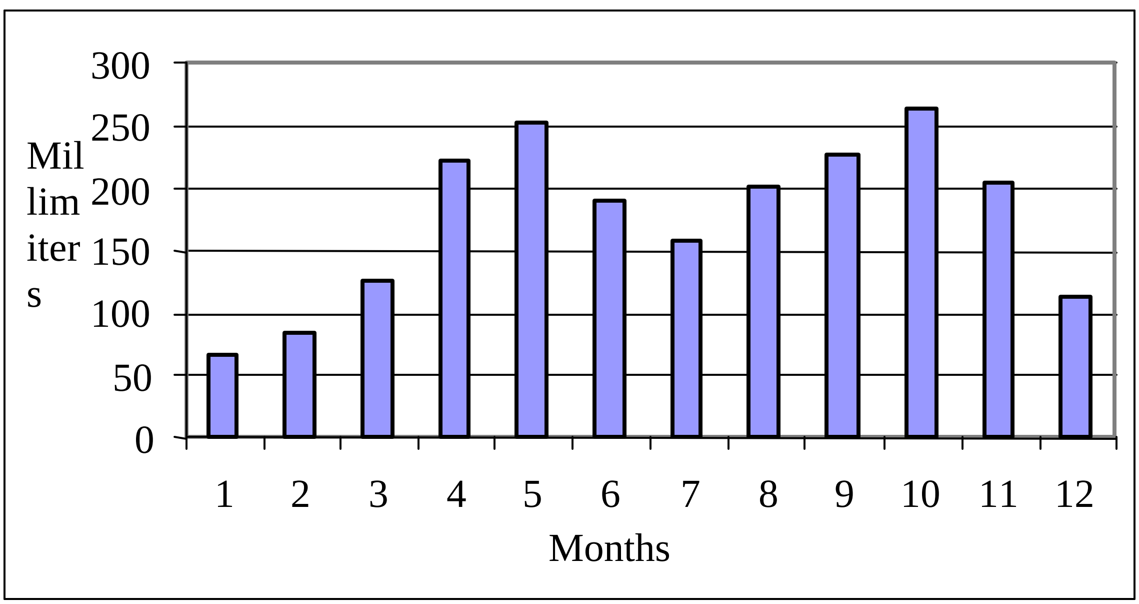


Figure III-3. Average monthly precipitation in mm

Geomorphology

Three main types of landscape can be distinguished in the region: 1) valleys, 2) hillside and 3) high mountains. The most important valley in the region is located southeast of the city of Rionegro. The Valley is called Llano Grande. The predominant relief is made up of terraces of several levels. Two types of terrace levels are distinguished: the inferior one, which exhibits poor drainage sectors and, the superior one, which exhibits good drainage (Cornare, 1998).

The hillside, on the other hand, is the kind of landscape that occupies most of the territory. It is characterized by low and intermediate hills. However, there are some plots where slopes are greater than 25 percent. Some hilltops are also present in this type of landscape. It is also common to find very narrow intermountain valleys. The high mountain type of landscape includes the very steep elevations. Very abrupt changes in shape characterize this portion of the landscape. Hilltops and some narrow intermountain valleys can be seen in the area. Figure III-4 gives the watershed distribution by slope ranges. It is clear from the figure that steep slopes dominate the landscape. In fact, 81 percent of the watershed has slopes greater than 12 percent and 64 percent of the watershed has slopes greater than 25 percent. Slopes coupled with rainfall and land cover are key determinants of sediment and runoff. As it will be shown later, most of the cropland is located in the steepest portions of the watershed and farmed without using sustainable production methods.

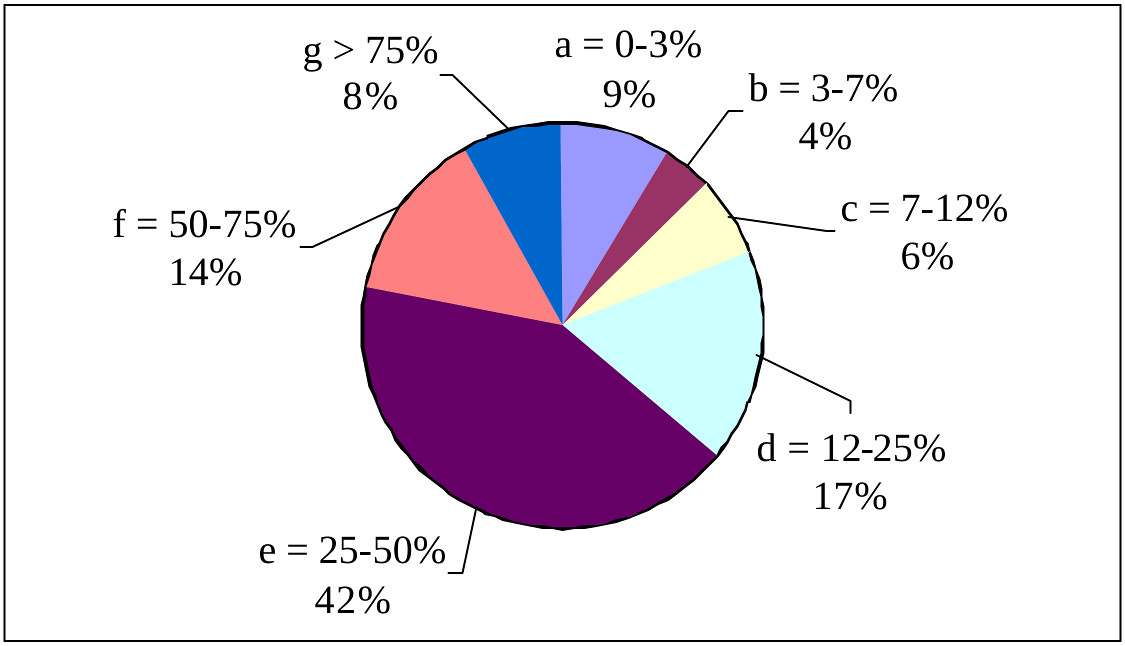


Figure III-4. Percentage area by slope ranges

Source: Cornare, 1998

Soils

The soils in this watershed were developed from volcanic-ash type of parent materials due to the volcanic activity that took place in the Holocene times (Cornare, 1998). The differentiation of the soil profiles has been verified through the action of the basic processes of additions, losses, transformations and translocations in the soil system. Soils derived from volcanic ashes have the property of exhibiting a very uniform morphology in profile even in contrasting physical conditions. Volcanic soils can be distinguished by the following characteristics (Cornare, 1998):

- Deep A, B and C profile. Layer A presents a dark color contrasting with the dark yellowish brown B and C layers.
- The organic matter in layer A is high and relatively stable
- Weakly developed B layer structure

- High water content and low bulk density (less than 0.9 gr/cc)
- High porosity and permeability
- High content of organic carbon
- pH between 5.0 and 6.0

The generalized presence of volcanic ashes causes the soils to be classified as Andisols. Andic properties must exist in at least 35cm of the top 60cm of soil. Many Andisols are considered the most productive soils of the planet but they require appropriate management practices (Miller et al., 1990). This type of soil is able to hold large amounts of water. Erosion is a concern even though the aggregates are often quite resistant to rainfall disintegration. The erosion concern increases with the current management practices and land cover observed in this region. Table III-1 gives the soil taxonomy, bulk density and texture of the main soil types observed in the watershed. As the table shows the bulk density with the exemption of two soil types is less than 0.9 g/cm^3 meaning that the ratio of the mass of solid particles to the total volume of the soil is lower in volcanic soils. Most of the soils in the watershed have a sandy loam texture. Texture is an important soil characteristic because it will, in part, determine water intakes rates (infiltration), water storage in the soil, the ease of tilling the soil, the amount of aeration (vital to root growth) and will influence soil fertility.

Table III-1. Soil taxonomy, bulk density and texture

		Layer 1				Layer 2				Layer 3			
		Bulk Density	Texture			Bulk Density	Texture			Bulk Density	Texture		
Code[a]	Taxonomic Class	g/cm^3	Clay	Silt	Sand	g/cm^3	Clay	Silt	Sand	g/cm^3	Clay	Silt	Sand
SV	Typic Hapludands	0.77	15.00	20.00	65.00	0.80	45.00	5.00	50.00	0.80	30.00	15.00	55.00
TE	Typic Melanudands	0.68	15.00	20.00	65.00	0.80	15.00	20.00	65.00	1.40	15.00	25.00	60.00
ST	Typic Melanudands	0.68	15.00	20.00	65.00	0.80	15.00	65.00	20.00	1.40	30.00	10.00	60.00
LC	Typic Melanudands	0.68	15.00	20.00	65.00	0.80	30.00	15.00	55.00	1.40	15.00	20.00	65.00
AV	Typic Endoaquands	1.17	35.00	35.00	30.00	1.23	35.00	35.00	30.00	1.23	40.00	50.00	10.00
CA	Aquic Dystropepts	0.80	15.00	20.00	65.00	1.00	15.00	20.00	65.00	0.50	15.00	20.00	65.00
EH	Typic Endoquands	0.80	15.00	20.00	65.00	0.82	30.00	15.00	55.00	1.30	30.00	15.00	55.00
LG	Typic Hapludands	0.80	15.00	20.00	65.00	0.82	30.00	15.00	55.00	1.30	30.00	15.00	55.00
MP	Typic Endoquands	0.80	30.00	15.00	55.00	1.00	30.00	15.00	55.00	0.50	15.00	20.00	65.00
RI	Hydric Hapludands	0.77	15.00	20.00	65.00	0.80	35.00	10.00	55.00	0.80	35.00	55.00	10.00
SD	Typic Dystropepts	1.25	20.00	40.00	40.00	1.23	15.00	20.00	65.00	1.23	30.00	15.00	55.00

[a]Code is a special name that Cornare gives to the soils present in the watershed
Source: Cornare, 1998

Current Land Use

Agriculture

Annual or temporary crops are very important in this region. Corn, potatoes, beans and vegetables such as carrots, beets and cabbage are the most important crops. The area under crop cultivation is 9,380 hectares representing 12.9 percent of the total area. Corn occupies 73 percent (6931 ha) of the total area under cultivation. Other crops such as beans and vegetables are also cultivated basically between two corn harvests (Cornare, 1998). Figure III-5 shows the cropland distribution by slope. Thus, 79 percent of the cropland is located in areas with slopes greater than 12 percent, and 57 percent is located in areas with slopes greater than 25 percent. This illustrates the problem already mentioned according to which the Andean slopes have being denuded of

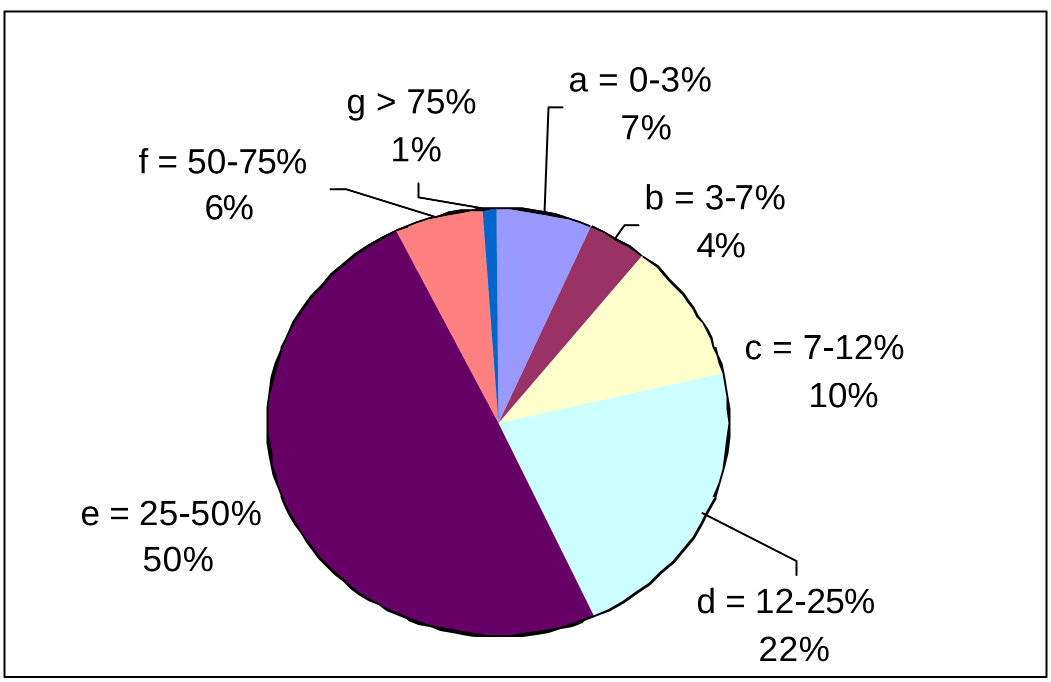


Figure III-5 Cropland Area by Slope

Source: Cornare, 1998

vegetative and soil cover and the resulting soil loss of moisture retention. This also has an adverse effect on the flow of streams and affecting the seasonal availability of water for agriculture and for hydropower generation.

One important feature of the Rionegro watershed is the presence of small farmers (campesinos). The average farm size is approximately between 5 and 10 hectares. In general, tillage and cultural activities are considered traditional because the shape of the landscape does not allow any mechanization with the exemption of some plots in the inter-valleys where potatoes grow with some degree of mechanization. Figure III-6 shows that more than 58 percent of the corn area is located in very steep lands with slopes greater than 25 percent. This can be considered non-sustainable use of land since there are no practices like terracing or contours observed in the watershed. The amount of sediment and runoff generated in the corn areas are high compared to other land uses (see Chapter 4).

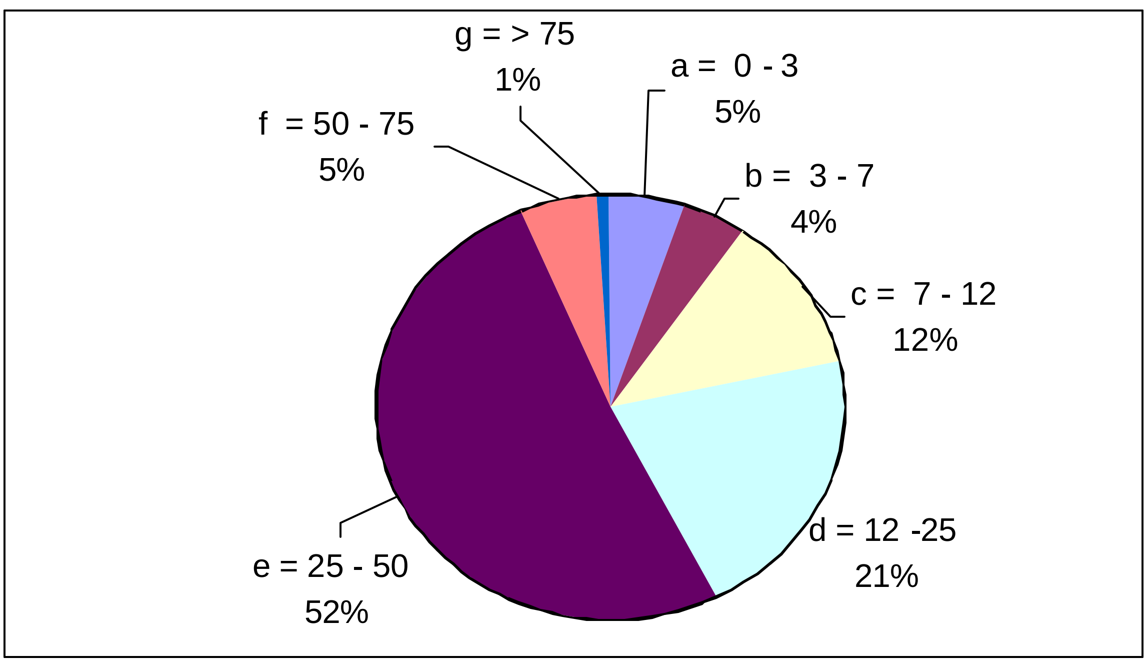


Figure III-6 Area of corn by slope

Source: Cornare, 1998

Perhaps the most significant characteristic of diversity in agriculture in this region, which is not uncommon in Latin American countries is the so-called rural dualism also defined as functional dualism. It refers to the coexistence of a relatively modern type of agriculture and an impoverished, traditional agriculture practiced by indigenous people called "campesinos" (Pichon, et.al, 1999). Traditional farms are not only small and unable to support increasing consumption and production demands of families; they are also, in general, located on lands with inherently low productive capacity, characterized by poor soil conditions, steep terrain, unfavorable climate or a combination of these factors.

Livestock

The production of livestock complements other agricultural activities. Most livestock are used to produce milk. The herds feed on pastures of improved grasses basically in the valleys and also in the moderately hilly and steep terrains. Pasture occupies approximately 40,000 hectares or 52.3 percent of the watershed. There are 34,222 hectares of improved pasture (kikuyo) used to produce high quality milk. The remaining pasture area (5,827 Ha) is basically in native grasses with poor management and growth located in the most abrupt landscape generating erosion (Cornare, 1998). Figure III-7 shows that 52 percent of the improved pasture is located in areas whose slopes are greater than 25 percent. At the same time, there is an important portion of pasture located in flat areas (small valleys). Thus, 42 percent of the area in improved pasture is growing in fields with less than 12 percent of slope; 22 percent is located in the slope range of 0 percent and 3 percent. Livestock production is characterized by extensive production methods.

Forests

Currently, the watershed has 9,818 Ha in planted forests. Out of this, 8,984 hectares are planted with coniferous, basically cypress and pine trees. This planted forest corresponds to mature forest representing 27 percent of the total forestland and 8 percent of the total watershed area. This is the result of a past reforestation programs whose objective was to establish protective and commercial forests. However, the reforestation program is still small compared to the potential. A study done by a group of reforestation companies (El Guasimo, 1998) argues that the potential for reforestation in the whole state of Antioquia is about 1.5 million hectares or 24 percent of the province and 60 percent of the study watershed.

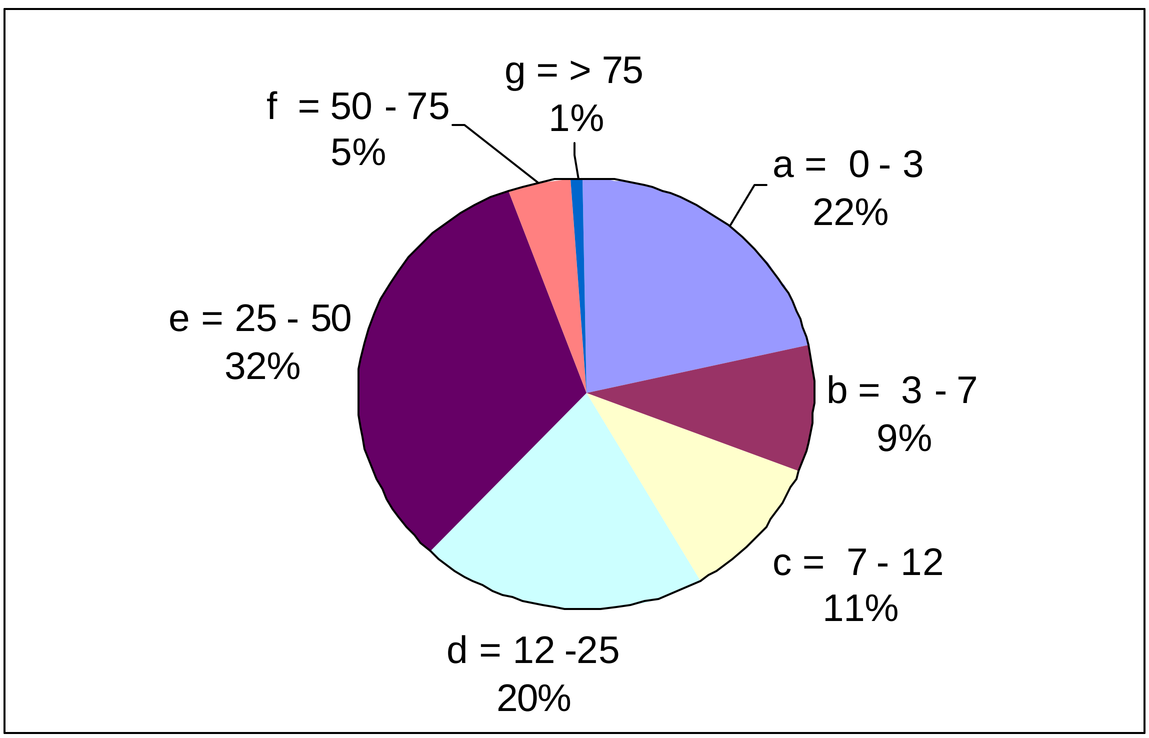


Figure III-7 Area of improved pasture (Kikuyo) by slope

Source: Cornare, 1998

There are also about 22,563 Ha of natural forests. These natural forests are still the shelters for biodiversity despite some degree of human intervention. Most of the natural forest in the region (90 percent) is considered secondary forest. These are forests that have grown after the primary forest has been clear-cut or harvested. Table III-2 shows the distribution of forestland in different categories. For example, secondary natural forest is disaggregated into three categories: early (trees between 7 and 10 years old), intermediate (trees between 11 and 18 years old) and late succession (trees between 19 and 30 years old). In the watershed, intermediate succession is the dominant category in terms of area (25.6 percent). It is important to mention that the age ranges for each category depend not only on the species but also on the climatic conditions.

Table III-2 Forestland by category (Hectares)

Code	Category	Hectares	Percentage
Bn1i	Disturbed Primary Natural Forest	2059.4	6.36
Bn1m	Severely Disturbed Primary Natural Forest	23.92	0.07
Bn2a	Early Succession Secondary Natural Forest	7858.3	24.27
Bn2i	Intermediate Succession Secondary Natural Forest	8300.3	25.63
Bn2t	Late Succession Secondary Natural Forest	4322.9	13.35
Bp1c	Mature Planted Coniferous Forest	8984.2	27.74
Bp1l	Mature Planted Decidious Forest	351.3	1.08
Bp2c	Unmature Planted Conifers Forest	482.9	1.49
	Total	32383.22	100.00

Source: Cornare, 1998

Figure III-8 shows the distribution of forestland by slope. In this case, 84 percent of the land covered by forest is located in areas with slopes greater than 25 percent. Coincidentally, 84 percent of the coniferous-planted forest is also located in areas with slopes higher than 25 percent. Reforestation in the steepest lands is important given the type of soils in the watershed and the amount of precipitation in order to control runoff and soil erosion.

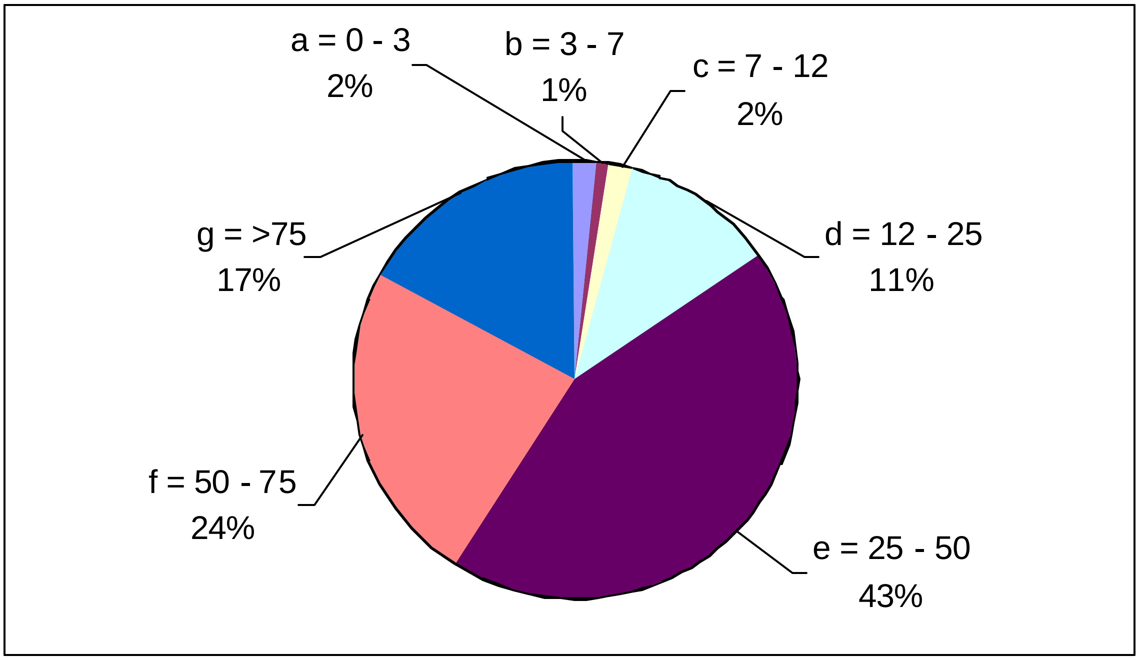


Figure III-8 Forestland by slope

Source: Cornare, 1998

Management Practices

The observed management practices are those often associated with rural poverty, insecure land tenure, lack of access to credit markets, difficult geographical conditions, and a lack of knowledge. In Colombia, unsustainable agriculture in the Andean slopes has long been recognized as a problem and has profound roots in the way land was colonized. A pioneer study by Suarez de Castro (1951) in the coffee region of Colombia reported annual loss from runoff and soil of 216.4 mm and 11.8 t/ha respectively, without contour planting as compared with 87.4mm and 0.65 t/h with contour cultivation. Currie (1965) noted for the first time on a national scale the extent to which flat, apparently rich bottomlands were occupied by low-intensity livestock ranching estates, while slopes steep enough to make cultivation a hazard to life were occupied for crop farming. The situation has not improved since then.

Deforestation has played a crucial role in explaining unsustainable agriculture in the Rionegro watershed, as well as in the whole Andean portion of the country. The current land use and management practices in the Rionegro watershed reflect the way in which Colombia and perhaps most countries in Latin America have dealt with the natural resource sector including agriculture.

The Shifting Agriculture Scheme

The rate of deforestation and soil erosion in tropical countries caused by human activities has been increasing over time. According to FAO (cited by Amelung and Diehl, 1992) deforestation, defined as the total removal of tree cover has increased from 0.6 percent per year in the 1970s to 0.9 percent per year in the 1990s. This means an increase in the rate of deforestation of 30 percent in a decade. Myers (1994) argues that in 1994 this rate was about 1.8 percent.

In many areas of the Andes, the slopes have been denuded of vegetative and soil cover, resulting in the loss of moisture. This has a negative effect on the flow of streams, reducing the availability of water for agriculture both for poor upland farmers and the richer farmers located in the valleys. There are no exact figures for deforestation in the Rionegro watershed but some argue that in the state as a whole, between 1968 and 1975, 525 thousand hectares were cleared at a rate of 75 thousand/ha/year (Regional Secretary of Planning, 1995). Since then, there is no evidence that deforestation has ceased.

Several economic activities have contributed to deforestation in tropical countries: agriculture (shifting agriculture, permanent agriculture, excessive grazing), logging, mining and generation of hydropower. However, shifting agriculture accounts for the greatest portion of deforestation and soil erosion in the tropics. Bulte (1997) points out that shifting agriculture is responsible for about 40 to 60 percent of total deforestation in contrast with the timber industry, which is responsible just for 10 percent. In general, erosion rates on cropland have been increased over those prevailing under the former forest cover. Shallow (1956) cited by Lawrence et al. (1983) studied sediment yields and extrapolated back to give erosion for the Cameron Highlands of Malaysia. He found that cultivating vegetables in steep areas produced $404m^3/km^2/yr$ in contrast with $14m^3/km^2/yr$ produced by forest. Manam (1981) cited by Lawrence et al. (1983), found that in Waspada, Garut, West Java (Indonesia) on a 30 percent slope with a monthly rainfall ranging from 214mm to 2440mm land cover and erosion rates in $m^3/ha/month$ are as follows: plantation forest, 0.00; corn and peanuts 3.18; potato, 13.00. Brunig et al. (1975) reported that in Sabah (Malaysia) on moderate to steep slopes natural forest had annual erosion rates of 10-40t/ha, while annual field crops had over 1000t/ha.

Figure III-9 shows the scheme under which the shifting agriculture has taken place in Colombia. This is the way the agricultural sector has been developed in the country. Since the second half of the XIX century Colombia started a process of colonization, which consisted of domination of the land by rural inhabitants meaning an intense deforestation process. They start by cutting trees, in basically virgin forests, selecting the most valuable and commercial trees. After that the *colonos* burn the remaining biomass and prepare the land for one or two or three harvests of corn. After the second harvest of corn they sell the land to the landlords who have capital to buy cattle.

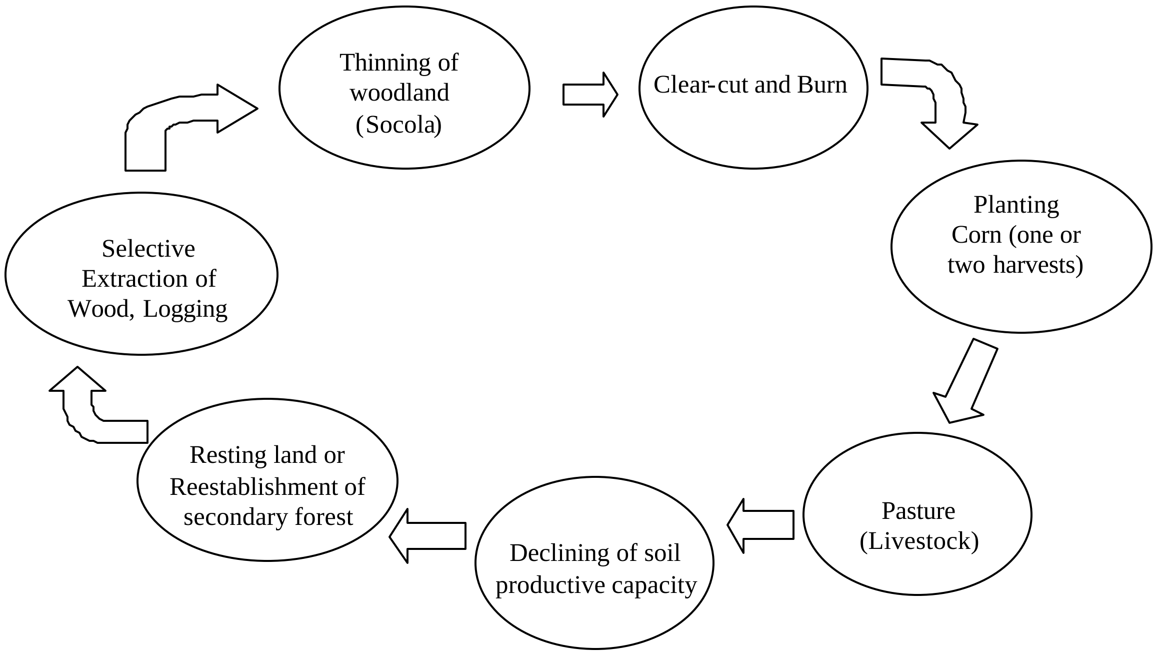


Figure III-9 Shifting Agriculture Scheme

The *colonos* move on in search of new land to deforest and the process starts somewhere else over again. After the two or three harvests of corn a grazing period takes place in the land they already clear-cut. The pastureland occupies the area for about eight or ten years during which the soil continues to lose nutrients and fertility (Alviar, 1983).

In order for the land to regain soil fertility, it is left to fallow land for another period of time generally nine or ten years. In that period, the secondary natural forest starts growing. At that point some woody plants appear and contribute to soil fertility and nutrient recovery. In other words, the practice of fallow land rotation includes the slash and burn of the trees and brush from the plot. Some manual and rustic tools are used to prepare the land for two successive crops and the plot is left again with pastureland and secondary forest in early succession (Ashby, 1985). Figure III-10 illustrates the rotation of a typical hectare in the Rionegro watershed for a period of 24 years. This Figure shows the land use rotation corresponding to the aggregate level of land use, that is, forest, pasture and crops. In the following chapters, the land use rotations would be disaggregated by slope, and soil type. It is important to keep in mind that abundant rainfall, steep-slope lands, and elevations ranging from 1,950m and 2,550m above sea level characterize this watershed.

1 Corn	2 Corn	3 Corn	4 Pasture	5 Pasture
6 Pasture	7 Sec. Forest	8 Sec. Forest	9 Sec. Forest	10 Sec. Forest
11 Sec. Forest	12 Sec. Forest	13 Sec. Forest	14 Sec. Forest	15 Sec. Forest
16 Sec. Forest	17 Sec. Forest	18 Sec. Forest	19 Sec. Forest	20 Sec. Forest

Figure III-10 Rotation of a typical hectare in a 20 year rotation period

Population

Four decades ago, the problem of intense deforestation in steep slopes was seen as a problem of population growth in rural areas. Most of the literature (Pereira, 1989) argues that the rapid population growth in tropical developing countries in the last three decades has pushed very large numbers of subsistence cultivators into the remaining forests. This is still true for most countries in Africa. In Colombia population growth does not seem to be a serious problem today. However, rural poverty continues to exert strong pressure on land (Heath and Binswanger, 1998).

Currie (1965) argued that too many poor inefficient farmers living in rural areas caused deforestation. The solution for both, rural poverty and resource depletion was to promote rural-urban migration for towns and cities to absorb the excess of labor supply in rural areas and leave lands in the hands of fewer and more efficient farmers (Currie, 1965). In fact, in the late 1960's, several national policies were implemented to promote rural migration to the cities basically through massive housing building plans. However, more than forty years later, the population of poor people in rural Colombia has more than doubled, despite massive rural-urban migration (Heath and Binswanger, 1998).

Recently, the rural population growth rate has slowed substantially helping to reduce the pressure on the resource base. Since 1985, Colombia has observed a rural population decline for the first time in absolute terms. Despite that decline, poor farmers have still limited access to good lands and the pressure on steep-slopes is still in place (Heath and Binswanger, 1998). At the same time, access to education and credit markets is limited in rural areas and there are no incentives to pursue sustainable agriculture. Today, extreme poverty in the country is mainly a rural problem. Seventy percent of the people with incomes below subsistence level live in rural areas (World Bank, 1994). According to the Regional Secretary of Planning of Antioquia, the population growth rate for the whole state has been estimated in 1.3%. Table III-3 shows the rural population distribution by county and also the labor force in the agricultural sector for the Rionegro watershed.

Table III-3. Rionegro watershed. Population and labor force, 2001

County	Total Population	Age 15-70	Total Labor Force	Labor in Agriculture	Labor days Planting	Labor days Harvesting
Retiro	10,348	5,746	3,649	2,080	24,961	14,561
Guarne	20,513	11,389	7,234	4,123	49,481	28,864
La Ceja	13,630	7,568	4,807	2,740	32,878	19,179
Marinilla	16,986	9,431	5,990	3,414	40,973	23,901
Peñol	10,252	5,692	3,615	2,061	24,730	14,426
Santuario	13,774	7,648	4,858	2,769	33,225	19,382
La Unión	11,796	6,550	4,160	2,371	28,454	16,598
Rionegro	33,625	18,670	11,858	6,759	81,110	47,314
Total	130,924	72,693	46,171	26,318	315,813	184,224

Source: Regional Secretary of Planning of Antioquia, 2001

Land distribution

Binswnager and Heath (1998) have suggested that the real challenge for the Colombian policy makers is to improve the access for the poor to better and fertile lands at lower elevations. They argue that it is necessary to change the agricultural policy framework that influences the operation of land markets. While this is true, they also recognize the costs associated with policies to improve land market access. In he past, there have been poor results of agrarian reform programs oriented to democratize the land tenure structure.

Colombia has made some attempts to reform land tenure with little success. In fact, the agrarian structure is still quite concentrated. Between 1960 and 1988 the area occupied by holdings under 5 hectares declined from 6 to 5 percent, the area of medium-size farms (5-50 hectares) increased from 24 to 26 percent though the area in larger farms (more than 50 hectares) decreased from 70 to 69 percent (Heath and Binswnager, 1998).

The Colombian land market is very narrow because the price of land is not just determined by capitalized agricultural profits. The price also includes the land attribute of serving as a hedge against inflation. Its immobility makes it a preferred form of collateral in credit markets, giving it an additional utility. One aspect that has to be mentioned is the role of drug trafficking in pushing up the price of land. It is estimated that at the end of the 1980s, traffickers invested (laundering of money) between 8 and 23 percent of the cocaine revenues in the purchase of land. Some estimate that the drug business has accumulated approximately 1 million hectares, which is equivalent to 3 percent of the total farmland area (Heath and Binswnager, 1998).

Although the literature on the relationship between farm size and productivity has shown that small farms exhibit higher factor productivity than large farms (Berry and Cline, 1979), the landowners in large farms do not parcel out or sell land to small farmers. For example, between 1976 and 1988 the yields of small farmers increased on average by 82 percent in contrast with only 2 percent for medium and larger farms.

The shifting agriculture pattern observed in the country and particularly in the Rionegro watershed characterized by the intense deforestation has resulted, among other things, in the loss of many valuable wood species as well as soil erosion and runoff. A 1933 study presented an inventory of 140 commercial tree species in the state of Antioquia alone (Robledo and Robledo, 1933). Today, it is not possible to find more than 20 species (Alviar, 1983). This means that the colonization process and its subsequent shifting agriculture scheme did not envision the future and therefore no one was able to anticipate the consequences of indiscriminate deforestation. Certainly, sustainability was not an issue of concern and even today it can be considered marginal in decision-making, particularly among small farmers.

Soil Resource Depletion

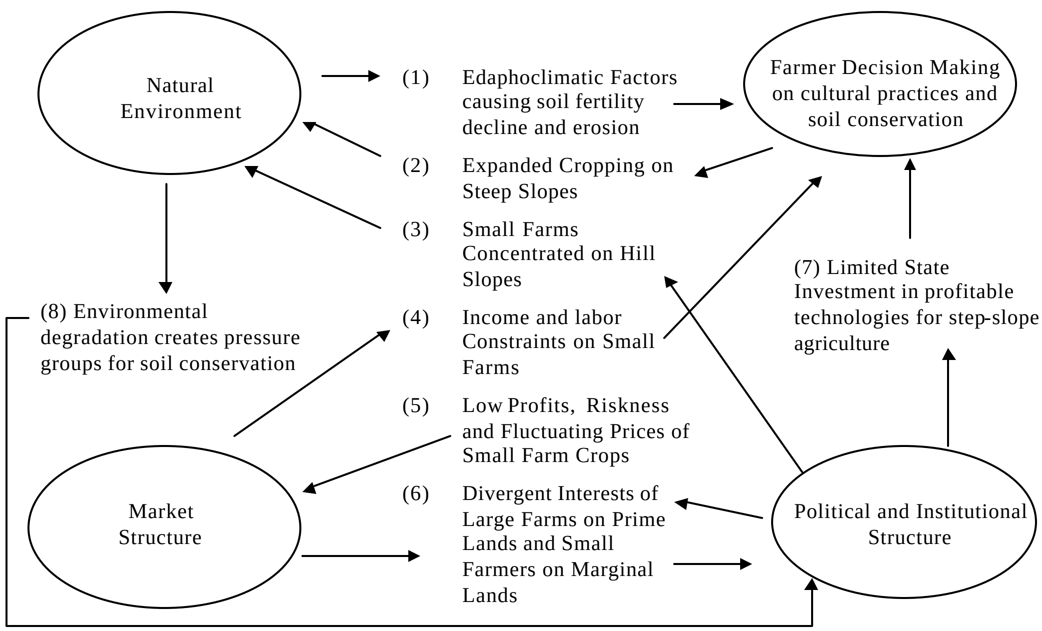
The Political Economy of Soil Erosion

A central hypothesis to explain why the small landholders keep overexploiting the soil resources in the third world is the fact that small farmers place a higher value on the short-term benefits they may obtain from agriculture than on the benefits they could obtain in the long run from soil conservation practices. Of course this behavior has deeper explanations, as it will be discussed later. The value placed on short-term benefits is commonly seen as responsible for the failure of small farmers to adopt sustainable practices within the watershed. However, the "predator" behavior of small landholders could be an adaptive response to particular technological, ecological, and social constraints faced by the rural people in low-income countries (Ashby, 1985).

The short-term for the poor small farmer often means that he can only plan from one harvest to the next. In extreme cases of poverty, this may be from one operation such as crop establishment to the next operation such as weeding. Ashby (1985) illustrates the difference between the short-term horizon and that required to implement soil conservation practices. Thus, strip contour or terracing has been highly recommended for steep-slopes lands in Colombia. It requires the farmer to plough only parallel strips on the contour of a hillside plot, leaving the uncultivated strips as barriers to runoff and soil erosion. Any soil conservation practice requires the farmer to make an investment of additional capital or labor time in establishment and in maintenance. The compensation for implementing soil conservation practices may take some cropping seasons (Ashby, 1985).

In Figure, III-11 Ashby (1985) presents the factor interactions that explain the vicious cycle of unsustainable agriculture of steep-slope lands and soil erosion for small farmers. There are four key elements that interact to produce several relationships leading to the exposure of ecologically fragile lands. Those elements are: *Natural Environment, Market Structure, Farmer Decision-Making and Political Institutions*.

The Natural environment determines the physical and climatic characteristics of the



Source: Ashby, 1985

Figure III-5. System Relationship in the Social Ecology of Soil Erosion

steep-sloping lands, which in turn make soils vulnerable to erosion. Volcanic ashes and the abundant rainfall in tropical environments determine the degree of soil vulnerability once the vegetation is cleared for agricultural purposes. In turn, soil vulnerability depends on physical and chemical properties of soil, such as texture, structure, and nutrients. The impact of unsustainable agriculture is that small farmers continuously move to areas where the soil has not been overexploited. They expand cropping on steep-sloping lands because they lack access to the less intensively used prime lands. This is due, in part, to the *decision making process,* which favors short-term benefits, and, in part, due to the *political and institutional structure* of land distribution. Large-scale capitalist and modern plantations such as sugar cane, cotton, sorghum, bananas, and oil palm monopolize prime lands, while small farms are limited to the least fertile and most vulnerable lands (Ashby, 1985).

Barbier and Bishop (1995) suggest the following economic factors influencing a farmer's decision to implement soil and water conservation measures:

- The value that farmers place to future which may reflect the attitude to risk and uncertainty, as well as the level of household poverty and access to credit and off-farm income
- The costs that farmers may incur in order to make efforts for conservation such as labor, purchased inputs and credit
- Relative input and output prices, which determine the current profitability of eroded versus less eroded cropping lands. It includes price fluctuations overtime
- The future returns of the cropping system, as affected by technological improvements and also affected by the current cultivation techniques.

Limited empirical evidence suggests that the impact of these factors on farm-level erosion can be complex and in some cases counterintuitive. Barbier and Bishop (1995) argue that the effects of agricultural input and output producer prices seem to be straightforward in theory but are difficult to substantiate. For example, they argue that the relationship between erodibility and profitability of different cropping systems must be carefully analyzed, particularly in relation to the changing relative prices and income over time. Moreover, these effects are not easy to separate from other interactions, such as the relationship between erosion and the availability of labor, off-farm employment, population pressure, tenure security, the development of post harvesting capacity, infrastructure, and access to credit among others (Barbier and Bishop, 1995).

One could say that farmers will not modify their land management practices and farming systems unless they perceive any gain from introducing any change in those cropping systems. In other words, unless soil erosion is perceived as a threat to farm profitability, or unless changes in land management lead to an economic gain, farmers may be unwilling to bear the costs that soil and water conservation would imply (Barbier and Bishop, 1995). The role of research and knowledge is crucial in letting the farmers know the implications of soil erosion costs on future profitability.

Agricultural Policies and Misallocation of Land

The economic development path followed by Colombia for more than fifty years, between 1940 and 1990, emphasized import substitution to protect the national industry. Parallel with the protectionist policies, agricultural prices were artificially lowered by ceiling and floor price mechanisms in order to keep urban wages low and favor urban labor markets and industrial production. Barbier and Bishop (1995), argue that agricultural output and input policies such as taxes, subsidies, price controls, marketing, infrastructure policies, credit and interest rate policies can stimulate or retard land degradation through impacts on the choice of agricultural inputs, outputs, income, rates of time preference, and other economic factors.

Garcia (1993) points out that policies that artificially depress agricultural prices tend to reduce real agricultural income and increase rural poverty. This is true for policies that reduce the price of food or subsidize imports of food products to increase the real income of the urban population. In view of the fact that agricultural producers respond to prices, when prices are artificially lowered they discourage capital accumulation. The impoverishment of the rural population pushes the small farmers to the marginal lands mostly located in the slopes of the mountainous system as well as preventing them to follow sustainable agricultural practices.

In the depletion of soil resources not only the small farmers on the steep-sloping lands are to be blamed. The whole country shows a land use picture that reflects the pattern of misallocation of land even in the flatter portions of the nation. Heath and Binswanger (1998) state this situation clearly. The agricultural land in Colombia has been estimated to be 16 percent of the territory. However, just 4 percent is cultivated. In terms of livestock, 13 percent of the territory is appropriate for pasture, but now approximately 35 percent has been devoted to this use. Most of the extensive livestock (beef) are located in the plains, which are considered the best land for cropping and mechanized agriculture. There is also extensive livestock production in the steep-sloping lands, mostly for milk production. Two-thirds of the country's territory is suitable for forestry and should be left under tree cover. However, only half of the territory is still forested. This means that about 20 million hectares have been deforested.

Agricultural policy-making in Colombia shows significant elements of large-scale farm bias. Public investments in infrastructure and technologies have traditionally favored extensive livestock and grain crops for exports, neither of which uses labor intensively in contrast with small farms. Policies on output prices, agricultural input prices, farm wages, import tariffs have benefited the modern agricultural sector while small farms have to face low profit margins, and high risks associated with the uncertainty from the world market system (Ashby, 1985). Such uncertain economic conditions make the small farmers reluctant to adopt conservation practices and also make them to prefer short-term benefits. Other factors that influence the short-term benefit preferences among small farmers are the lack of knowledge and education, which prevent farmers to value future income from conservation practices.

Parks (1995) argues that the persistent movement of marginal land to agriculture when land users make dynamic land conversion decisions can be explained by risk aversion and expected capital gains. Parks finds that land users respond positively to cost sharing, rental payments, and technical assistance since those practices reduce uncertainty. When returns to agricultural and forests are uncertain and the correlation between benefits is not positive, increased risk-aversion will lead the land user to diversify the land allocation among uses. Risk and uncertainty are key components of the discount rate in the sense that the future is unknown an farmers put higher value to the present. In a situation characterized by uncertainty and lack of knowledge on the environmental effects of land management, it is not surprising that small farmers show high preferences for short-term benefits. High discount rates discourage sustainable forests and agriculture practices and typically accelerate harvesting, depress investment in sustainable management, and reduce the weight attached to the needs and desires of distant future generations (Parks, 1995).

CHAPTER IV

EPIC SIMULATIONS AND THE ENVIRONMENTAL EFFECTS OF LAND USE

Findings in Tropical Humid Countries

The main concern of this research is how agricultural practices affect soil productivity, soil physical conditions and the ability to achieve sustainable land management. Predominant farming systems of the humid tropics include shifting cultivation alternated with bush and fallow systems (Lal, 1995). A farming system implies a resource management strategy involving integrated management crops, trees and animals, along with labor and capital to utilize land resources. Primary resources involved in the farming system are land, climate, vegetation, soil and water (Young, 1991; Lal, 1995; Pichon, 1999). The shifting cultivation systems observed in most tropical countries including Colombia are based on little or no inputs and are practiced mainly on steep lands.

Traditional systems like shifting cultivation are ecologically viable and can be socially acceptable as long as there is enough land for lengthy restorative fallow, and the population pressure, and the expectations for yields and life conditions are not very high (Lal, 1995). However, in most developing humid tropical countries increasing population pressure contributes to shortened fallow periods and its consequently reduced soil quality

(Pichon et.al, 1999). In the case of the Rionegro watershed, the abundance of rainfall and steep slopes reduce the chances that shifting cultivation systems can be sustained. Other land management practices such as agroforestry and permanent forests are more sustainable, particularly for steep lands (Sanchez, 1995). Erosion, runoff, and organic carbon are the most relevant variables to evaluate sustainability for different agricultural practices (Young, 1991).

Erosion

The effects of shifting cultivation systems on erosion have been acknowledged in the literature. Vieth, et.al (2001) estimate erosion rates of 70 tons/ha/yr of erosion for shifting cultivation in Sri Lanka. Sfeir-Younis and Dragun (1993) estimate that rates of soil erosion range from 37 ton/ha/year up to 114 tons/ha/year occur on 76 million hectares in developing countries. Juo and Franzluebbers (2003) compare soil loss from one cropping season (4 months) between two contour barriers in the Philippines and Peru. The regions of study in both countries have similar rainfall regime (1300-1500mm). In the case of the Philippines with a slope of 19% and using *Desmanthus* as a vegetative barrier the soil loss was estimated in 3 tons/ha/year while using tilled control produced 127 tons/ha/year. In Peru, comparing the same systems but using *Inga* instead of *Desmanthus*, and for a slope equal to 16% the estimated figures were 1 and 54 tons/ha/year respectively.

Forest cover plays an important role in controlling erosion, providing habitat for biodiversity, maintaining the water cycle, recycling of nutrients, sequestering carbon, among other environmental services (Lal, 1995). Following the model of C.W. Rose, Young (1991) discusses the relationship between vegetation cover and sediment concentration. The model uses a cover factor that varies from 0 (bare soil) to 1.0 (100% cover). When the cover factor is zero, the sediment entrainment factor is equal to 0.7. When the cover factor goes to 0.9 the sediment factor drops to 0.25 meaning that a cover of just 10% reduces soil loss by two thirds.

Vieth et.al (2001) have found a soil loss of 1 ton/ha/yr in the dense forest of the Upper Mahaweli Watershed in Sri Lanka which exhibits a flat landscape. In Indonesia soil erosion on teak as taungya system was 5.2 tons/ha when the trees were 1 year old and it decreased to 1 tons/ha when the trees were 3-4 years old (Evans, 1992).

Organic Carbon and Organic Matter

One of the most important effects of land use (given soil characteristics, temperature, and precipitation, among others) on soil quality is the effect on soil organic carbon and soil organic matter accumulation. Trees differ from crops in providing litter and roots as well as herbaceous residues that helps the process of soil organic matter (Young, 1991).

Brown and Lugo (1982) carried out a study to measure the storage and production of organic matter in tropical forests and their role in global carbon cycle. Analyzing tropical moist forest, premontane, and montane forests in Africa, Central and South America, and Asia they found an average annual accumulation of soil organic carbon for a period of 40 years equal to 230 tons/ha in a site characterized by an average temperature of 18°C and rainfall equal to 2000mm. Delany et.al (1997) found soil organic carbon average accumulation ranging from 302 tons/ha to 468 tons/ha in a study of five life zones in Venezuela. These zones ranged from the driest to the wettest forests, exhibited temperatures from 10.5°C to 27°C, elevations from 130m to 3000m, and rainfall from 800mm to 3200mm. Although the authors do not specify the species analyzed, they studied 60 permanent plots established in late 1950's and 1960's and covered by rainforest. Hughes et.al (1999), on the other hand, show that in the state of Veracruz (Mexico) with volcanic ash type of soil, temperature ranging from 16° C to 32°C, elevations from 100m to 300m, and average annual rainfall of 4000mm the aboveground biomass accumulation of 50 year tall evergreen trees was estimated to be 287 tons/ha.

Soil organic matter (SOM), on the other hand, is a complex process that takes decomposition, oxidation and nutrient cycles into account to maintain and improve soil fertility (Young, 1991). Some of the key functions of SOM in maintaining soil fertility are: 1) under all land use systems: maintains soil physical features which, includes water-retention capacity; 2) under low input systems: provides a balanced of nutrients, protected against leaching until released by mineralization; 3) under medium and high input systems leads to more efficient use of fertilizers due to improved ion exchange capacity and better supply of micro nutrients (Young, 1991).

The physical state of the organic material present in a soil consists of two parts: litter (including root residues) and humus (fully decomposed organic matter). This is relevant for forest and agroforestry systems unlike crop system since they have both woody and herbaceous residues that fall into the soils. The decomposition of litter, and root and herbaceous residues by oxidation is a process called *litter-to humus-conversion loss* since there is loss of carbon through microbial oxidation. Young, (1991) estimates this conversion loss is 80-90% for above ground plant residues and 50-80% for roots. After the litter has converted into humus soil carbon loss continues due to oxidation. The proportion of humus carbon lost by oxidation during one year is called *humus decomposition constant* (Young, 1991). Nye and Greenland (1960) estimated such a constant for forest fallow (K_f) to be 0.03 and for shifting cultivation (K_c), 0.04 (3% and 4% respectively). These two concepts can be expresses by equation (1) (Young, 1991):

$$C_1 = C_0 - KC_0 \quad (1)$$

Where C_0 is the initial soil humus carbon; C_1 is the carbon after one year, and K is the decomposition constant (fraction). Gonzalez and Sauerbeck (1982) estimated a litter-to-humus conversion loss of 65 percent and the humus decomposition constant of 13 percent for Costa Rican forests, which are similar to the humid forests in Colombia. Nye and Greenland (1960) estimated the same parameters for tropical India to be equal to 75 percent and 3.3 percent respectively. This approach is still valid in most applied research for carbon balance.

When carbon-14-enriched plant residues are added to soils there is a downsloping curve of the same form as for both temperate and tropical soils. This shows a rapid loss over the first 3 to 6 months and after that a slower and exponential rate of loss. A comparative study was performed to show the carbon loss in England, South Australia and Nigeria. Figure IV-1 shows that the three curves can be superimposed.

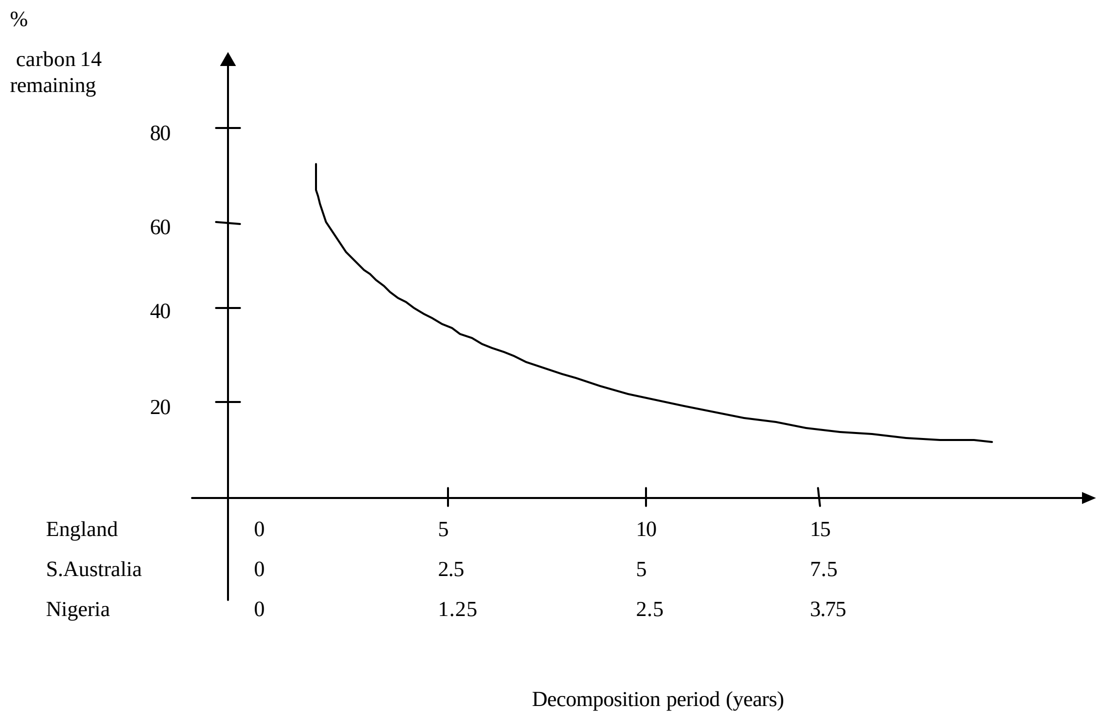


Figure IV-1. Decay curves for loss of carbon-14 labeled plant residues added to soil Source: (Young, 1991)

Apparently, when mature natural forests reach their steady state the total organic carbon balance reaches equilibrium. However, a combination of factors such as high elevations in steep lands coupled with abundant rainfall and some degree of erosion can alter such balance generating some carbon loss through leaching and also through soil depth loss. The type of species can also alter the organic carbon balance Hartemink (2003). *Pinus* tree plantations show a decreased accumulation of soil organic carbon. Hartemink (2003) argues that on *Pinus* plantations it took at least 20 years before the declining trend in soil organic carbon was stopped whereas other studies show that there was no increase in soil organic carbon after 22 years. Yeates et.al (2000) show a case in New Zealand where soils previously under pasture were planted with *Pinus radiata* in

1975. Measures were taken at the time of plantation and also in 1998. Soils were volcanic and classified as Typic Udivitrands. The annual rainfall at site was 1490mm. Between 1975 and 1998, soil organic carbon and nitrogen under *Pinus* declined up to 0.60m depth. For example, at the soil depth 0-18cm, soil carbon was reduced from 47g/kg to 44.5 g/kg. Similarly, at soil depth 30-40cm, soil carbon declined from 43g/kg to 24.6 g/kg.

Hartemink, (2003) shows that on abandoned pastureland in the Atlantic lowlands of Costa Rica, soils were planted with *Pinus, Gmelina*, and *Acacia*. There were measurements of nutrients at the time of plantations and 4 years later. The soils were classified as Typic Tropohumultsand. Soil organic carbon increased significantly in the plots with *Acacia*, but no changes in the carbon levels were found in the soils under *Pinus* or *Gmelina*. Total nitrogen increased under *Acacia* but decreased under *Pinus* (Fischer, 1995). On Sabah, Malaysia, a decrease in soil fertility in a 4-year old *Acacia mangium* plantation on Ultisols was reported (Hatermink, 2003). Soil organic carbon and levels of major nutrients decreased and amounts were much lower in the plantation than before planting probably due to plant uptake and leaching (Hatermink, 2003).

Altitude influences temperature and moisture in the tropics, which can, in turn, influence the rate of decomposition of organic matter (Coutêaux, et.al 2002). A study performed in the tropical Andes of Venezuela, shows six sites along an altitudinal climatic transect from 65m to 3968m where an experiment took place to measure decomposition of standard plant material. The sites were selected either in natural herbaceous formations or managed grasslands to minimize the variability because of the introduction of different kinds of vegetation (Coutêaux, et.al, 2002). The soil types were Inceptisol, Alfisol, Mollisol and Entisol. The parental material of these soils came from volcanic ashes as that observed in the Rionegro watershed. The experiment was conducted for three years. The main results were: the decomposition rates decreased with increasing altitude. Two groups appeared: 1) Altitudes between 65m and 165m where 50% of the straw was decomposed within 1-2 months and after the first year 75% of ^{14}C was lost. 2) Altitudes between 780m and 1800m where 50% decomposition was reached within 3-4 months and after the first year about 65% of ^{14}C was lost. This altitude is similar to that in the Rionegro watershed. The warmer conditions in the tropics produce more rapid decomposition of unprotected organic material, whereas the interaction between cationic nutrients or changes in mineralogy may have a specific influence in tropical soils. For example, the pH of the soils is neutral at low altitudes and become acid as the altitude increases. The differences in soil organic matter between sites are mainly due to temperature (Coutêaux, et.al. 2002).

Tropical forests contain as much as 40% of the C stored as terrestrial biomass and account for 30 to 50% of terrestrial productivity (Phillips, et.al., 1998). Therefore a small perturbation in this biome could result in a significant change in the global C cycle. Phillips, et.al (1998) conducted a study using what they have called permanent sample plots (PSP) to monitor tree growth and mortality. These PSP have the potential to produce C accumulations estimates both geographically extensive and of high spatial and temporal resolution. They tested changes in mature tropical forest biomass in each of the four types of regions: the humid tropics (153 plots); the humid neotropics (120 plots); the humid lowland neotropics (108 plots) and Amazonia (97 plots). These plots represented more than 600,000 individual tree measurements tropics-wide. The mean value of biomass change has been positive for most years since widespread PSP monitoring began. Biomass has increased in mature forest sites of the humid neotropics (1.11 tons/ha); the humid lowland neotropics (1.08 tons/ha), and in Amazonia (0.97 tons/ha) There are a number of mechanisms that can explain this change: i) a response to continental scale cyclical climate change: ii) recovery from widespread disturbance, either natural or anthropogenic: iii) enhanced forest productivity due to secular change in climate or increased nutrient availability. To estimate regional C sequestration rates they converted the aboveground biomass into C stock.

At the same time, Phillips, et.al (1998) argue that because Earth's climate fluctuates, forest stocks of C might be responding to past climate events. The El Niño southern oscillation may be one long-term driver of cyclical changes in forest dynamics. The results suggest that mature Neotropical forest biomass may account for 40% of the so-called "missing" terrestrial C sink (Phillips, et.al., 1998). Hence, intact forests may be helping to buffer the rate of increase in atmospheric CO_2, thereby reducing the impacts of global climate change. However, the C sink in mature forests appears vulnerable to several factors. Deforestation, logging, increased fragmentation, and edge-effect mortality regional drying and warming and possible intensification may limit and even reverse the sink provided by mature forest (Phillips, et.al., 1998).

Gunadi, et.al. (1998), shed light on soil organic carbon under forest cover and on why soil carbon could decrease over time in the tropical mature forest. Decomposition of coniferous litter was studied from March 1990 until March 1991 in a pine forest plantation in two 0.2 ha plots. The variables used to monitor decomposition were weight loss, C content and N content. Carbon content of litter in both plots decreased from 49 to

35-37% in the L layer[3] and from 38 to 28-31% on the F layer[4]. The objective was to discriminate between the relative importance of the different driving forces behind litter decomposition. Temperature and water content of the litter in relation to the dry and wet seasons were measured as seasonal factors, which are supposed to influence the decomposition processes. Mean temperature in L and F layers, inside and outside the litterbags were similar, about 22°C in the two plots. Decomposition fluctuated during the study year. Water content was positively correlated with weight loss and negatively correlated with C content (Gunadi, et.al., 1998).

The reduction in soil organic carbon accumulation in the humid tropics can be observed between wet and dry season due to decomposition and mineralization (Juo, et.al., 2003). Tropical soils from volcanic ashes tend to show low bulk density, which means a high proportion of pore space which may accelerate decomposition.

Total Organic Carbon: Biomass, Soils, and Roots

Carbon cycle interactions can be extremely complex. For example, agricultural practices increase erosion, which tends to decrease the fertility and carbon content of soil, the largest carbon reservoir on the land surface (Young, 1991). Some of the carbon depleted by erosion from upland soils is transported downslope and buried at the base of hillslopes, on floodplains and in reservoirs. Once buried, most of this carbon is no longer available for exchange with the atmosphere. Fertilizer application, however, enhances soil productivity, and freshly eroded substrates enhance the rate of organic matter

[3] L layer is the upper layer of the organic horizon at the surface of mineral soil constituted by the annual litter (Lozet, at.al, 1991)

[4] F layer: in the organic horizon at the surface of mineral soils, layer of fermentation situated just below the annual litter, in which the plant remains are in the process of being transformed (Lozet, et.al, 1991)

formation. Thus, while land-surface disturbance increases erosion, which degrades the soil, the combined effects of agriculture and the redistribution of carbon across the landscape may promote carbon accumulation on land (Greenland, 1994).

Carbon dioxide forms when the carbon in biomass oxidizes as it burns or decomposes. Many biological processes produced by human activities release carbon dioxide (Malhi et.al, 1999). These include slash-and-burn agriculture; clearing land for permanent pasture, cropland, or human settlements; the development of infrastructure, such as roads and dams; accidental and intentional forest burning; and unsustainable logging and fuelwood collection. Clearing vegetation cover from a forested hectare releases much of the carbon in the vegetation to the atmosphere, as well as some of the carbon lodged in the soil. Logging or sustainable fuelwood collection can also degrade vegetation cover and result in a net release of carbon (Juo and Franzluebbers, 2003).

The release of CO_2 from deforestation is the forest's single most important contribution to climate change, but human activities in tropical forest zones produce several other greenhouse gases, too (Malhi et.al, 1999). When pastures or grasslands are regularly burned to maintain fertility and keep out woody plants, methane, carbon monoxide, nitrous oxide, and ozone are emitted. When fertilizers are applied to cleared lands to increase agricultural production, nitrous oxide can be released (Rhoades and Coleman, 1999).

About half of the weight of a mature tree is in carbon. As long as that tree is alive and productive, more carbon is removed than returned to the atmosphere. Forests are therefore considered carbon sinks (Gifford, 2000). Older forest soils contain deep layers of slowly decaying carbon compounds, layers that gradually build up over time. Living trees add to the soil carbon pool when they lose their leaves, and old trees contribute dead wood when they are damaged or die. The lesson here is simple: Planting trees can help to sequester atmospheric carbon, but long term carbon storage requires a system where old plant material can build up over time (Gifford, 2000).

Nevertheless, the practice of shifting cultivation has been very common precisely in those areas where the potential for carbon sequestration is significant. Clearing tropical forests to intensify agriculture, particularly in upper and steep lands, has been a process that has contributed to land degradation and organic carbon content reduction through time (Lal, 1995).

McDonald et.al (2002) show that as pressure on land and forest resources increases, there is growing need to assess the sustainability of the agricultural practices in the tropics. A study was carried out on steep-hillslopes (24-32°) in the forest buffer zone of the Blue Mountains of Jamaica, following clearance of secondary forest. The purpose was to determine the relative impact of three land-use treatments on soil properties: maintained weed-free without cultivation (bare); cultivated with herbaceous crops (agriculture); and cultivated with herbaceous crops with intercropped with *Calliandra cakithyrsus* contour hedges (agroforestry). The clearance of the secondary forest led to large change in most measured soil properties. Over 5 years, concentrations of organic matter declined by 31%, total N by 38%, exchangeable K by 47%; over the same period bulk density increased by 48%. Agriculture caused a seven-fold increase in surface runoff and 21-fold increase in erosion (McDonald, et.al, 2002). The study was conducted in an area with 1300m of elevation and 2180mm of rainfall and soil texture characterized by sandy loam formation.

Fallows have been practiced in many areas of the world for hundreds of years. There are different kinds of fallows each having different impacts on land fertility (Nye and Greenland, 1960). For example, Sanchez (1999) distinguishes between natural fallows, enriched fallows, improved fallows, and managed fallows. The term "managed fallow" is used in the literature to mean both enriched and improved fallow. In general, natural secondary forest fallows have been used extensively as a component of traditional shifting cultivation systems in humid tropics (Sanchez, 1999). However, improved or managed fallows have been given less attention perhaps because of rural population and poverty pressures (Lal, 1995). The observed trend in many tropical countries is that fallow periods are becoming shorter and consequently the accumulation of organic carbon becomes insufficient for cropping (Klass and Somarriba, 1999).

Accelerated erosion adversely affects the quality of top soil and its capability of producing crops (Kimble, et.al, 1999). The soil organic matter (SOM) is generally located at the soil surface horizon and having a low bulk density the SOM can be easily removed by flowing runoff water and blowing wind. Kimble, et.al (1999) found a negative relationship between erosion and soil carbon in different types of soils in Iowa in a study performed between 1984 and 1986. Thus, soil organic carbon content ranged from 1.8 to 2.5% for the slightly eroded phase, 1.2 to 1.6% for the moderately eroded phase, and 0.9 to 1.3% for severely eroded phase. A total of 250 soil profiles were selected randomly from the sites representing 206 Mollisols, 27 Alfisols, and 15 Entisols. Yoo et.al (2000) measured total soil organic carbon (SOC) storage (kg/m^2) as a function of erosion rate along two Australian toposequences[5] with different precipitation rates, 600mm/year and 900mm/year. The long-term erosion rates were calculated based on cosmogenic isotope measurements and geomorphic soil transport model (Yoo, et.al, 2000). The results suggest that soil erosion removed 60-90% of annual plant inputs at the dry site and up to 50% for the wetter. At the dry site the percent carbon in the top 10cm increased significantly from 0.9 to 4.2% on the downslope.

Liu and Bliss (2003) conducted a study to model carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. The study site was at the Nelson Farm located in Tate County, Missisippi. It is a small watershed with an area of 2.09 ha. Annual precipitation is about 1340mm and annual average daily maximum and minimum temperature are 23.9° C and 10.6° C respectively. The Nelson farm was converted from forest to agriculture around 1870 and used for cotton production until 1950. The SOC contents were measured in different slope positions (upper, middle, and lower) in 1996. The results indicated that soils were consistent sources of carbon to the atmosphere at all landscape positions from 1870 to 1950. The lowest was on the eroding sites (13 to 24 $gC/m^2/year$), intermediate levels at the ridge top (34 gC $m^2/year$) and highest at the depositional sites (42 to 49 gC $m^2/year$). During this period erosion reduced carbon emissions by replacing surface soil with subsurface soil that had lower SOC contents. Failing to account for the impact of erosion in soil organic carbon content may potentially contribute to overestimate both the total historical carbon released from soils due to land use change and also the current carbon sequestration rates at the eroding sites (Liu and Bliss, 2003).

[5] Toposequence means a complex unit of soils the succession of which is constantly found in a defined order without any apparent genetic link between them and the predominant pedogenetic factor provoking the differentiation is relief or topography (Lozet, et.al 1991).

Runoff

Surface runoff, sometimes called overland flow is the part of the streamflow coming from net precipitation that fails to infiltrate the ground and runs over the surface of the soil to the nearest stream channel without infiltrating at any point (Hewlett, 1982). Runoff is influenced by different factors such as evapotranspiration, land cover, precipitation and temperature. Evapotranspiration refers to any process by which liquid water in plant; soil or pond becomes a vapor. In the tropics, evapotranspiration accounts for one third of precipitation (Alviar, 1983). Transpiration is the vaporization of water from the living cells of plant tissues (excludes interception loss) (Hewlett, 1982). The term interception loss is the vaporization of water intercepted during rainfall from living or dead plant surfaces including leaves and stems, down trees forest litter and humus layer. Interception loss in forest can be divided in two categories: 1) Crown interception loss and 2) forest floor interception loss. In the humid tropics the interception loss is high because of the abundant rainfall (Hewlett, 1982).

The removal of vegetation is a critical issue in the steep lands of the tropics, particularly in those areas with high rainfall since the runoff can alter soil properties and produce sediment downstream (Alviar, 1983). Soil degradation is one of the greatest challenges for tropical countries today, where soils are vulnerable due to intense rainfall, higher temperatures, and deforestation (Lal, 1995).

Chandler and Walter (1998) conducted a study in the hills above Matalom in Leyte Philippines in order to estimate runoff responses among common land uses practiced on that region. The soils of the area are Lithic Troporthents and Rendolls derived from limestone and calcareous shale. Analyzing five types of land use (Pasture-fallow; Pasture-fallow with contour-hedgerows; Plowed; Slash-mulch; and Forest), they found that forests exhibit the smallest percentage of annual rainfall as total runoff (3%). The other four uses of land showed 76%, 31%, 17%, and 13% respectively (Chandler and Walter, 1998).

El-Hassanin, et.al (1993) show for a 17 runoff-erosion plots which represent different conditions of vegetation cover, slope gradient and slope length in Burundi, that soil loss from bare fallow soil per unit of rainfall and also per unit of runoff increased as the slope gradient increased. The associated runoff-rainfall ratios were always high under the steep slopes. The highest values for soil erosion and runoff were obtained under cultivated soils and the lowest values under forest and grass soils.

Shorter Fallow Lengths

Shifting cultivation has been the most widespread means of restoring soil fertility. However, in the last decades because of shortening of fallow lengths it has become soil degrading (Young, 1991; Lal, 1995; Pichon, 1999). Population pressure, land tenure shortcomings, concentration of the best lands in just few hands, and increasing rural poverty have influenced the practice of shorter fallow periods with negative consequences on soil fertility (El Swaify, 1993). Some authors (Lal, 1995) consider at least twenty-year rotation for a fallow to regenerate soil fertility. The observed trend in many developing tropical countries is to have shorter fallows between 12 and 15 years (Lal, 1995). Although there is abundant literature on the importance of fallow lengths regarding soil productivity (Sanchez, 1995), there has been no attempt to measure or estimate the effects of shortening fallows on erosion and runoff.

The EPIC Model

The EPIC (Erosion Productivity Impact Calculator) model (Williams, 1984) is a widely used and tested model to simulate soil erosion, runoff and soil productivity. It has since evolved into a comprehensive agro-ecosystem model capable of describing the behavior of many types of crops grown in a complex sequences and tillage operations. EPIC takes into account not only crops and plant characteristics but also the different weather patterns, soil structures, elevations and slopes. The model contains parameters to simulate about 100 crops and up to 12 plant species in field. EPIC has several routines to deal with the effects of CO_2 fertilization on plant growth and water use, hydrological balance, N, P, C cycles, soil density changes, tillage, erosion, and leaching (Izaurralde, et.al, 2001).

EPIC is driven by precipitation, air temperature, solar radiation, wind speed, wind direction and relative humidity. Field data on daily observations can be input directly to the model. If data on climate conditions are not available, EPIC is able of simulating daily estimates for missing variables. As in the case of the Rionegro watershed, it is possible for EPIC to simulate some missing variables when, for example, there is no or missing data available for precipitation. Table IV-1 shows precipitation and temperature in the Rionegro watershed from which other climatic variables were estimated by EPIC.

Table IV-1. Rionegro watershed. Average monthly precipitation and temperature

Month	Precipitation mm	Temperature Max. ° C	Temperature Min. ° C
January	67.4	22.1	7.6
February	86.2	22.7	7.4
March	126.4	22.6	7.1
April	224.7	22.5	8.0
May	256.2	23.0	8.3
June	189.5	22.2	7.3
July	159.9	22.0	6.3
August	202.4	22.2	6.0
September	225.8	22.7	7.1
October	264.4	22.0	7.3
November	204.4	21.8	7.2
December	110.2	21.8	7.3

Source: Regional Secretary of Agriculture

Simulation of Agricultural Practices

Three types of simulations were performed in EPIC in order to show the environmental effects of three different land covers: mature forest, shifting cultivation, and agroforestry systems. The variables considered were erosion, runoff, organic carbon and soil depth. Two types of soils were taken into account: TE and SV (see Table III-1). These types of soils together represent the greatest area of the watershed being soil type TE the more representative. Three slopes were simulated, 20%, 30% and 40% with a slope length of 10m, 20m and 30m for each slope. The results show no substantial differences between soil types and slope lengths. The substantial differences occur among slopes. Hence the discussion of the results will focus on soil type TE and slopes 20%, 30% and 40%. Figures for soil type SV are shown in the Appendix.

The typical shifting cultivation scheme was assumed to consist of two years of corn, 3 years of pasture and 15 years of secondary forest for a total of twenty-year rotation. Using a pine plantation over a period of 100 years simulated mature forest. The agroforestry system simulation consisted of two years of corn, two years of plantation of *Sesbania sesban*, which is a woody plant capable of providing nitrogen to the soil without applying any chemical fertilizer and mixed with pasture. Sanchez (1995) showed that in Malawi, sesbania trees accumulated about 1.7 tons/ha of leaves, with very high nutrient concentrations (3.6% N and 0.37P). Farmers were able to harvest 1.7 tons/ha of sesbania for fuelwood (in Colombia there is a woody plant popularly called Guandul that works similarly to *Sesbania sesban*). After two years of growing *Sesbania*, land is planted with corn for two more years. After that, land is planted with *Pinus radiata* trees. All simulations were performed for a 100-year horizon divided into five periods of twenty-year rotation. It is important to acknowledge that there are some other forest species that could perform much better in terms of nitrogen fixation (Alviar, 1983). However, the lack of data made *Pinus radiata* the only species capable to simulate natural forest and forest plantations in the case of agroforestry.

EPIC Simulation Results

<u>Erosion</u>

The main results obtained from the simulations are shown in Table IV-2 considering 20%, 30% and 40% slopes and a slope length of 10m. As it is shown, when land is covered by forest the average impact on erosion is the lowest. The steeper the slope the greater the erosion measured in tons per hectare per year. In this case for a slope of 40% and soil type TE, the annual average amount of erosion in 100 years is 8.72 tons/ha/yr. Slopes of 20%, on the other hand, are associated with a much lower amount of erosion (1.64 tons/ha/yr). These results are consistent with those presented above for some other tropical regions.

Table IV-2. Rionegro watershed. Erosion, runoff, organic carbon, yield, and biomass. Soil type TE, different land use. Annual average over 100 years.

		A. Slope length 10m	
Land Use	**40% Slope**	**30% Slope**	**20% Slope**
Natural Forest			
Soil Erosion (tons/ha)	8.72	4.27	1.64
Runoff (mm)	286.85	258.96	219.26
Soil Organic Carbon (kg/ha)	263.34	270.25	275.64
Biomass (tons/ha)	212.21	236.18	237.28
Shifting Cultivation			
Corn			
Soil Erosion (tons/ha)	196.56	155.87	101.33
Runoff (mm)	540.00	510.09	471.51
Soil Organic Carbon (kg/ha)	135.92	151.29	170.08
Yield (tons/ha)	0.77	1.00	1.15
Pasture and Secondary Forest			
Soil Erosion (tons/ha)	24.28	13.55	6.23
Runoff (mm)	571.73	542.38	503.35
Soil Organic Carbon (kg/ha)	128.58	146.01	166.52
Pasture Yield (tons/ha)	1.63	1.72	1.82
Sec.Forest Biomass (tons/ha)	28.15	28.18	28.07
Agroforestry			
Soil Erosion (tons/ha)	31.29	20.35	9.14
Runoff (mm)	410.83	373.37	324.29
Soil Organic Carbon (kg/ha)	90.56	110.73	136.14
Corn Yield (tons/ha)	0.80	1.12	1.35
Biomass (tons/ha)	261.36	270.78	276.19

On the other hand the shifting cultivation scheme and particularly, the cultivation of corn, has a perverse effect on soil erosion. Table IV-2 shows, for a slope of 40%, and a slope length of 10m, an average rate of soil erosion of 196.56 tons/ha/yr. This figure is significantly higher than that exhibited by the agroforestry system, 31.29 tons/ha/year, which also includes corn cropping. Soil degradation by erosion can be explained by indiscriminate and intensive land use for seasonal crop production or for pastures at high stocking rates, resource-based production systems with low purchased inputs to replenish nutrients harvested, and poor and steep soils (Pichon, et,al, 1999). Figure IV-2 shows the soil erosion trend for mature forest, shifting cultivation, and agroforestry systems through time.

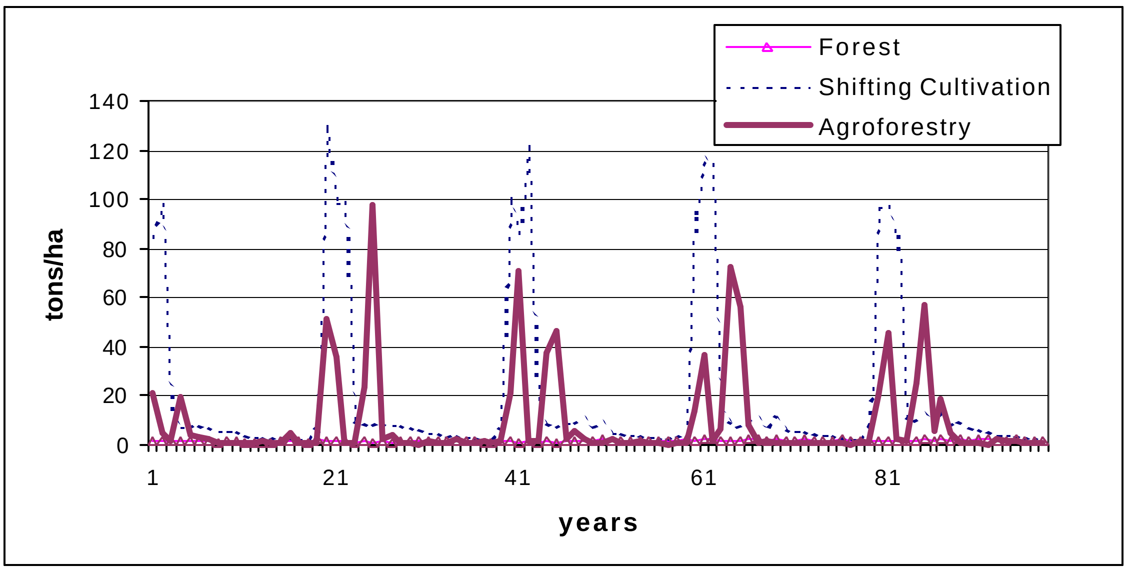


Figure IV-2. Rionegro watershed. Erosion. mature forest, shifting cultivation, and agroforestry system. Slope 20%. Soil type TE

It is observed that when crops (corn) are cultivated every twenty years, erosion goes up significantly. After cropping, the simulation shows significant decreases in erosion when the soil is covered by pasture and secondary forest, and also when the soil is cultivated with a woody plant (*Sesbania*) in the case of the agroforestry system. The amount of erosion produced by mature forest is considerably smaller and constant through time. However, given the steepness of the Rionegro watershed, and the intense rainfall regime (see Chapter 3) it is possible, even for a mature forest, to exhibit some amount of erosion which is concentrated in the first years of the EPIC simulation. It is noticeable from Table IV-2 that the agroforestry system gives the best results in terms of its contribution to sustainability compared to shifting cultivation. The amount of erosion generated by the agroforestry system is considerably lower for all slopes; runoff is also lower and corn yields are higher. In addition, in the agroforestry system, the accumulation of organic carbon takes place at a higher level than shifting cultivation.

Organic Carbon and Organic Matter

Table IV-2 shows that, on average, natural forest cover is capable of retaining more soil organic carbon than crops and pasture in all slopes, slope lengths and soil types according to the EPIC simulation. The estimated value of soil organic carbon obtained from the EPIC simulation for the Rionegro watershed (275.64 tons/ha) is close to that observed in the literature for tropical regions with similar characteristics (230 tons/ha, Brown and Lugo, 1982).

Figure IV-3 shows the soil organic carbon trend for forests, shifting cultivation and agroforestry systems in the Rionegro watershed resulted from EPIC simulations. This trend is consistent to that observed in the literature and shown above. However, the rate of the decay seems to be slower. Three key factors may influence the results in the Rionegro watershed: rainfall (2000mm), elevation (2400m a.s.l), and slopes greater than 20 percent, as it will be discussed below. However, it is worthy to notice the difference between forests, shifting cultivation, and agroforestry in terms of organic carbon. Shifting cultivation scheme and agroforestry have a similar path explained basically as a result of cropping. Both of these types of land use are contributing more to the deterioration of the nutrient recycling process than forests and also to the soil carbon reduction. When land is converted from its natural cover to agriculture or pasture soil organic carbon is predicted to fall from 43 to 25 tons/ha/year (Greenland, et.al, 1992).

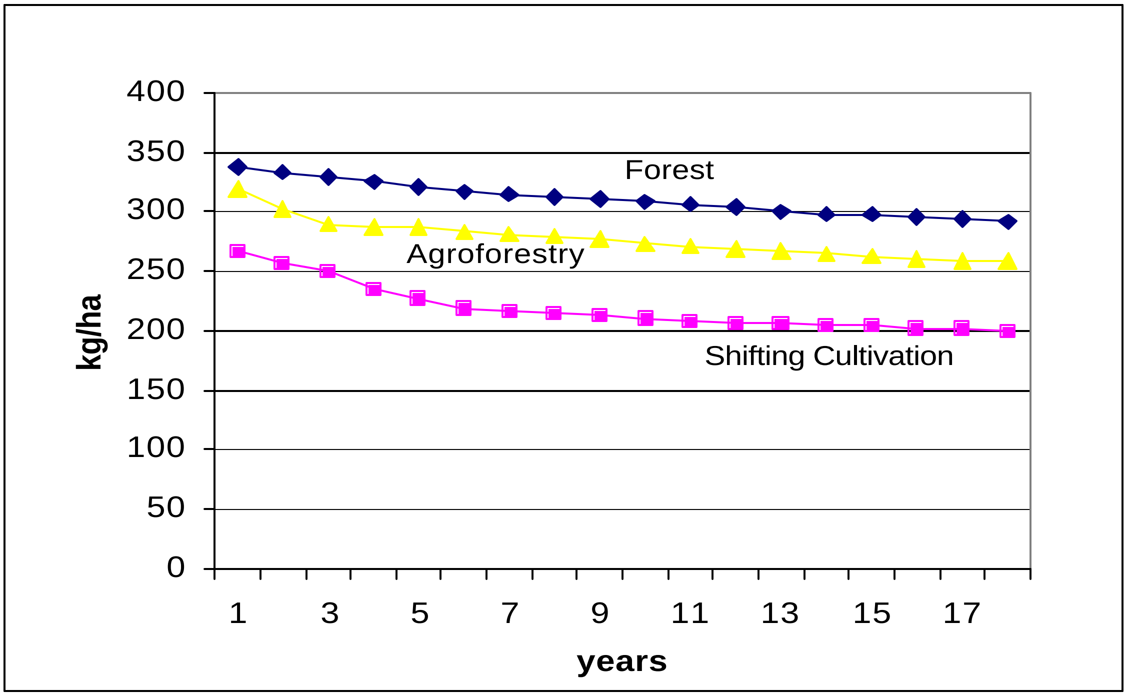


Figure IV-3.. Rionegro watershed. Soil organic carbon. Slope 20% soil type TE

However, a combination of factors such as high elevations in steep lands coupled with abundant rainfall and some degree of erosion can alter such balance generating some carbon loss through leaching and also through soil depth loss. The type of species can also alter the organic carbon balance as it is shown later (Hatermink, 2003).

<u>Total Organic Carbon: biomass, soils, and roots</u>

Figure IV-4 shows a comparison of total organic carbon dynamics when land is covered by natural forest, and two agricultural practices: shifting cultivation and agroforestry within a period of 100 years from the EPIC simulations.

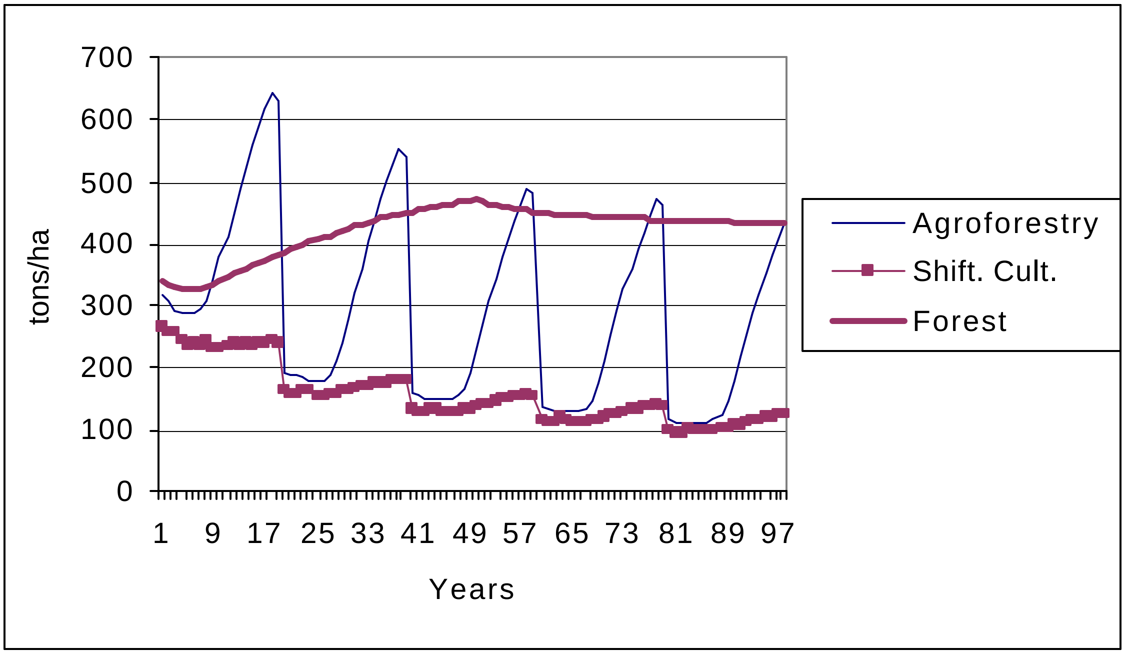


Figure IV-4. Rionegro watershed. Total organic carbon. Soil TE. Slope 20% by land use

From Figure IV-4, natural forest accumulates organic carbon until the forest is mature. According to the EPIC simulation forests were programmed to be mature after 50 years. Worthy of mention is that because lack of data at the site of the simulation, mature forest was simulated using *Pinus radiata* trees for which growth parameter data were available and which are comparable to species in the study area. The EPIC simulation generates values for biomass and roots for natural forest, shifting cultivation and agroforestry. Following Gifford (2000) two factors (0.5 and 0.46) were used to multiply the amounts of biomass and roots respectively in order to convert them into organic carbon in tons per hectare for each land use type. Table IV-3 shows the total carbon accumulation for 50 years in tons per hectare for each land use from the EPIC simulations.

For the agroforestry system, after two years of cultivating corn, *sesbania* trees are planted to the soil. *Sesbania* is a woody plant or “green manure” that adds organic carbon to the soil because of rapid decomposition (Sánchez, 1995). Figure IV-5 shows an increasing accumulation of organic carbon in each rotation. However, in the long run the system seems to be unsustainable because of carbon losses at harvest each rotation starts with a lower level of organic carbon. The shifting cultivation scheme appears to be less sustainable than agroforestry. Shifting cultivation has implied, in many areas of the world, the conversion of lands from a native state to agriculture.

Table IV-3. Rionegro watershed. Organic Carbon in soil, biomass and roots. Soil type TE. Slope 20% by land use (EPIC simulations).

	Carbon in Roots (tons/ha)			Carbon in biomass (tons/ha)			Carbon in soil (tons/ha)		
Year	Agroforestry	Shifting Cult.	Forest	Agroforestry	Shifting Cult.	Forest	Agroforestry	Shifting Cult.	Forest
1	0.0	0.0	0.1	0.3	0.5	0.3	319.4	267.6	337.3
2	1.3	0.0	0.2	4.1	0.3	0.6	302.2	255.4	333.9
3	0.6	1.5	0.4	3.1	4.3	1.1	289.9	250.9	329.2
4	0.1	2.5	0.7	0.8	7.9	2.0	287.8	235.1	324.8
5	0.0	2.4	1.3	0.4	7.0	3.8	286.9	226.1	320.8
6	1.0	5.1	2.2	2.7	15.2	6.6	282.6	218.4	317.3
7	3.5	5.1	3.3	9.8	15.0	10.3	281.1	217.3	314.6
8	8.4	7.6	4.9	23.9	22.9	15.0	278.7	215.4	312.2
9	16.1	5.0	6.6	46.9	15.1	20.1	276.3	212.8	309.9
10	25.8	5.7	8.3	76.9	17.4	25.5	273.2	210.8	307.5
11	35.4	6.8	10.0	107.7	21.2	30.8	270.4	208.8	305.3
12	44.8	7.5	11.6	139.6	24.1	36.1	268.0	206.8	303.2
13	53.5	7.4	13.3	170.4	24.3	41.4	265.8	205.4	301.0
14	61.3	8.0	14.8	200.0	26.5	46.4	263.8	204.2	298.9
15	68.4	7.8	16.2	228.6	26.7	51.3	262.0	203.2	297.0
16	74.5	8.3	17.6	255.2	28.9	56.2	260.4	202.1	295.2
17	79.4	8.8	18.8	279.6	31.2	60.9	258.8	201.2	293.7
18	83.9	9.4	20.1	303.0	34.1	65.4	257.5	200.4	292.4
19	80.1	8.5	21.3	296.7	31.8	69.8	256.1	199.8	291.2
20	0.0	0.0	22.2	0.4	0.5	73.9	194.9	164.1	290.1
21	0.0	0.0	23.1	0.4	0.3	78.0	187.9	159.4	289.2
22	1.2	0.0	23.9	3.7	0.4	82.0	182.6	157.0	288.5
23	0.5	1.5	24.7	2.3	4.4	85.9	180.2	158.0	287.8
24	0.1	2.3	25.5	0.8	7.1	89.8	180.4	154.2	287.3
25	0.0	2.0	26.2	0.3	6.0	93.6	180.2	146.9	286.9
26	0.8	2.4	26.9	2.3	7.2	97.2	179.3	144.9	286.5
27	3.1	3.1	27.3	8.7	9.2	100.6	178.9	144.9	286.3
28	8.3	3.9	27.9	23.6	11.7	104.2	178.1	144.7	286.1
29	16.4	4.3	28.4	47.8	12.6	107.4	177.4	144.2	285.9
30	26.2	4.7	28.8	78.1	14.3	110.4	176.7	143.8	285.7
31	36.2	5.9	29.1	110.1	18.4	113.5	175.9	143.4	285.6
32	45.5	6.6	29.5	141.5	21.0	116.3	175.3	142.9	285.6
33	54.2	7.0	29.7	172.7	22.9	119.1	174.7	142.6	285.6
34	62.3	7.4	30.0	203.1	24.5	121.8	174.2	142.1	285.6
35	68.8	7.9	30.2	229.9	27.0	124.4	173.7	141.8	285.7
36	74.3	7.9	30.4	254.5	27.8	127.0	173.3	141.5	285.7
37	79.2	8.6	30.5	278.0	30.9	129.5	172.9	141.2	285.7
38	83.1	8.7	30.5	299.2	31.7	131.7	172.5	141.0	285.9
39	78.9	8.1	30.5	291.6	30.3	134.0	172.1	140.8	286.1
40	0.0	0.0	30.5	0.4	0.5	136.1	157.0	131.9	286.2
41	0.0	0.0	30.5	0.4	0.5	138.1	153.1	127.6	286.5
42	0.7	0.0	30.4	2.2	0.3	140.2	149.3	126.4	286.7
43	0.4	1.4	30.4	2.1	4.2	142.1	148.3	128.1	286.8
44	0.0	1.5	30.2	0.7	4.6	144.0	148.6	125.3	287.1
45	0.0	1.6	29.9	0.3	4.9	145.9	148.5	121.3	287.3
46	0.5	2.0	29.7	1.3	5.9	147.6	148.1	120.8	287.5
47	1.4	2.4	29.6	4.0	7.1	149.4	147.9	120.8	287.8
48	5.0	2.9	29.3	14.4	8.6	150.8	147.4	120.6	288.0
49	12.1	3.7	29.0	35.3	11.1	152.4	146.9	120.4	288.0
50	21.0	4.4	28.7	62.6	13.5	153.7	146.5	120.1	288.2

Figures IV-5, IV-6, and IV-7 show the dynamics of organic carbon for the three management practices in question: forest, shifting cultivation and agroforestry system by three slope types.

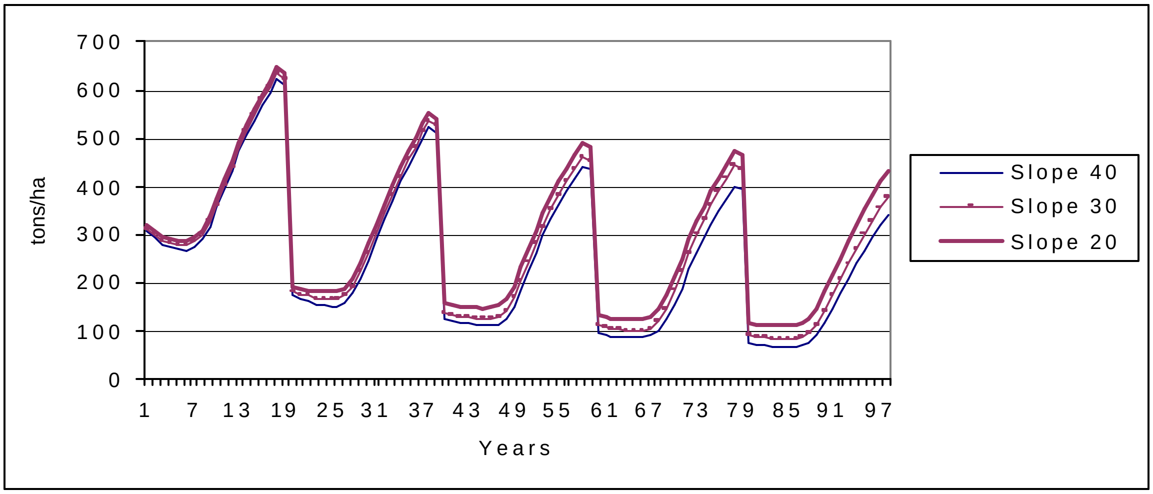


Figure IV-5. Rionegro watershed. Total organic carbon under agroforestry. Soil TE by slope

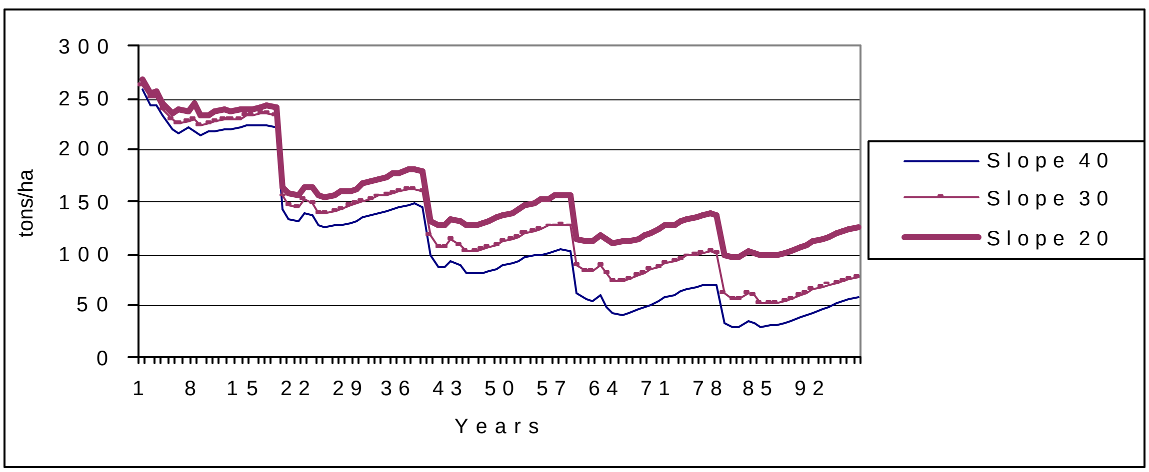


Figure IV-6. Rionegro watershed. Total organic carbon under shifting cultivation. Soil TE by slope

Slopes play a crucial role, particularly for shifting cultivation and agroforestry. The greatest organic carbon loss takes place in the steepest slope (40%).

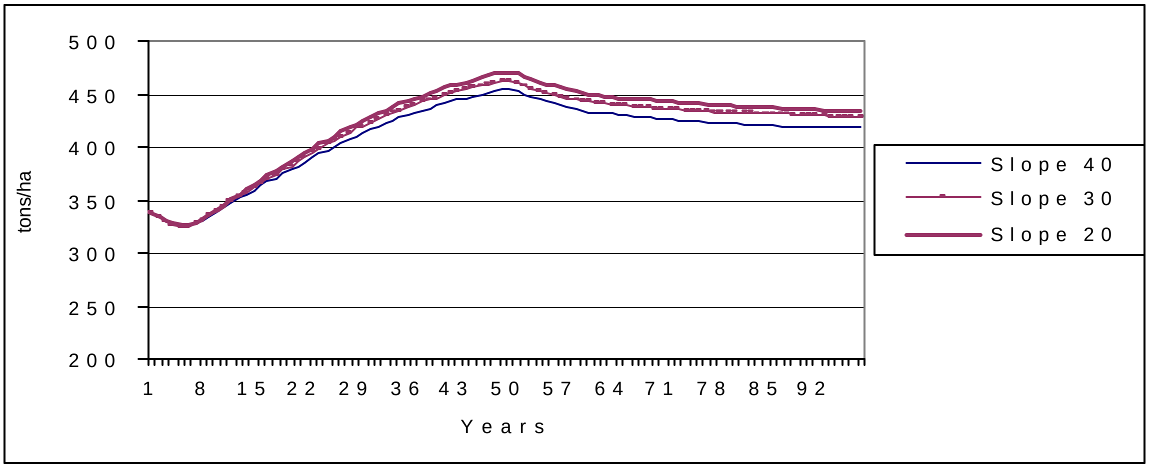


Figure IV-7. Rionegro watershed. Total organic carbon under mature forest. Soil TE by slope

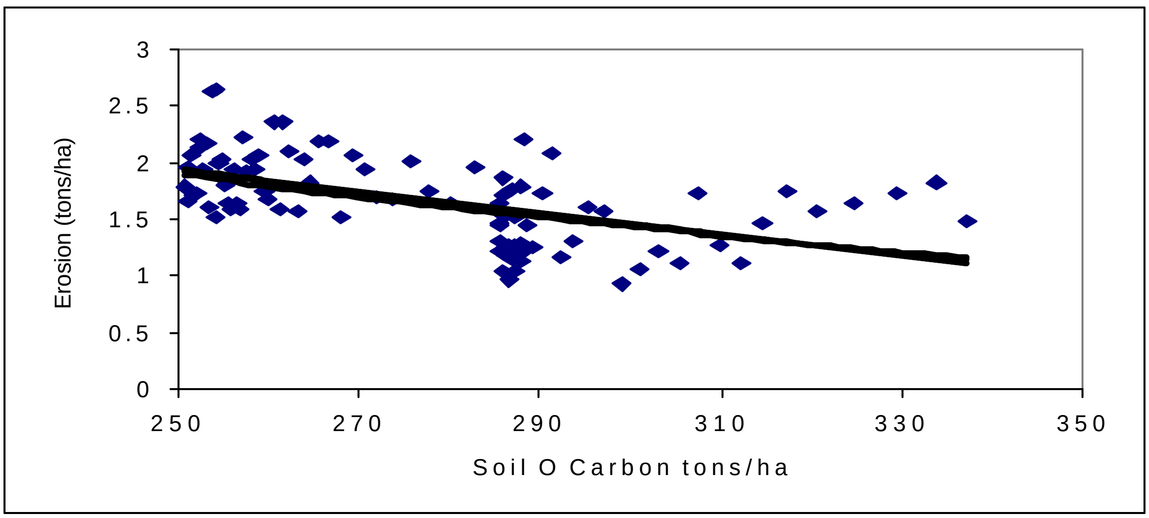


Figure IV-8. Rionegro watershed. Erosion and soil organic carbon. Soil type TE by slope 20%.

<u>Erosion effects on organic carbon</u>

Figure IV-8 shows the relationship between erosion and soil organic carbon in the Rionegro watershed for mature forest soil type TE and slope of 20% from the EPIC simulations.The negative relationship between erosion and organic carbon can be explained by the loss of soil top due to runoff, abundant rainfall, and steepness (El-

Hassanin, et.al, 1993). The combination of slopes and rainfall without vegetation cover is a critical issue in the Rionegro watershed. (Alviar, 1983).

Runoff

Figure IV-9 shows runoff for forest, shifting cultivation, and agroforestry for a 20% slope in the Rionegro watershed. An annual average the estimated figures by EPIC are 498mm for shifting cultivation, 327mm for agroforestry, and 219mm for forest.

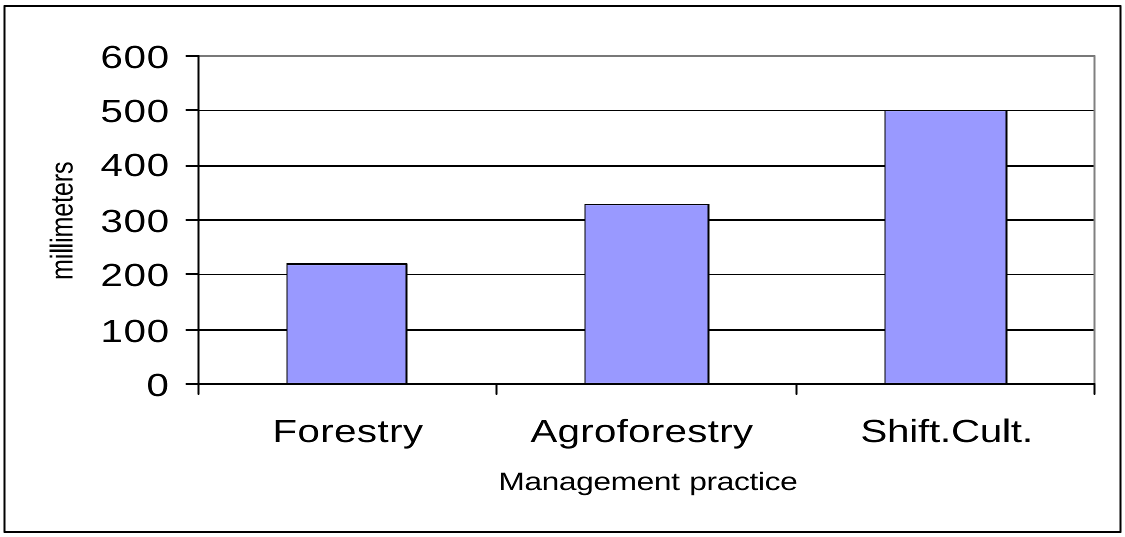


Figure IV-9. Rionegro watershed. Runoff under forest, agroforestry and shifting cultivation. Soil type TE, slope 20%

Shifting cultivation produces more runoff than forest because of the deterioration in soil quality due to the removal of vegetation cover which reduces transpiration. Cultivated lands and pasturelands have less vegetation cover for evapotranspiration and as a consequence runoff is higher than from forested lands. In addition, if cultivated lands and pasturelands are very steep and degraded, runoff will be increased producing downstream floods. Figure IV-9 and Table IV-2 show that runoff is the lowest in natural forest due to higher evapotranspiration and also infiltration and root consumption.

Shortening fallow lengths

As it was mentioned above, shortening fallow periods has been a common practice in the tropics basically because of population pressure and increasing rural poverty. The consequences of shorter fallows in terms of yields and organic carbon are shown in Figures IV-10 and IV-11 for 12, 15, 17 and 20 year-rotations from the EPIC simulations. It can be seen that the shorter the fallow the lower the corn yields because soils cannot fully recover its fertility. At the same time, the slopes play an important role in reducing yields. Thus, shortening fallows in steeper lands reduces yields significantly.

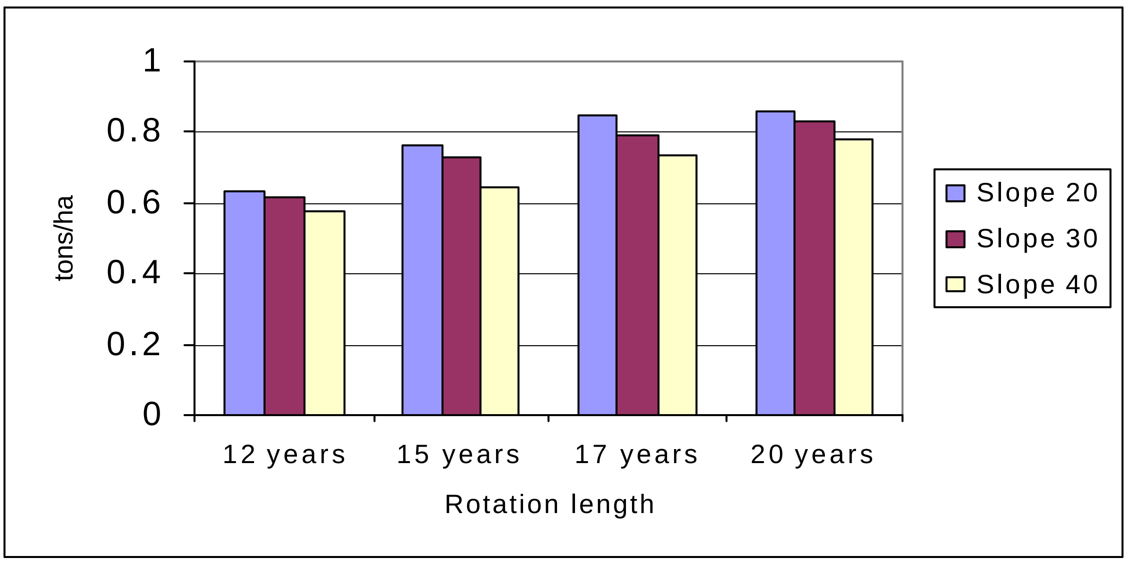


Figure IV-10. Rionegro watershed. Average annual corn yield by rotation length and slope. Soil type TE.

These results are correlated with the carbon accumulation since less organic carbon means low fertility and consequently lower yields. Figure IV-13 shows carbon accumulation by rotation length and slope.

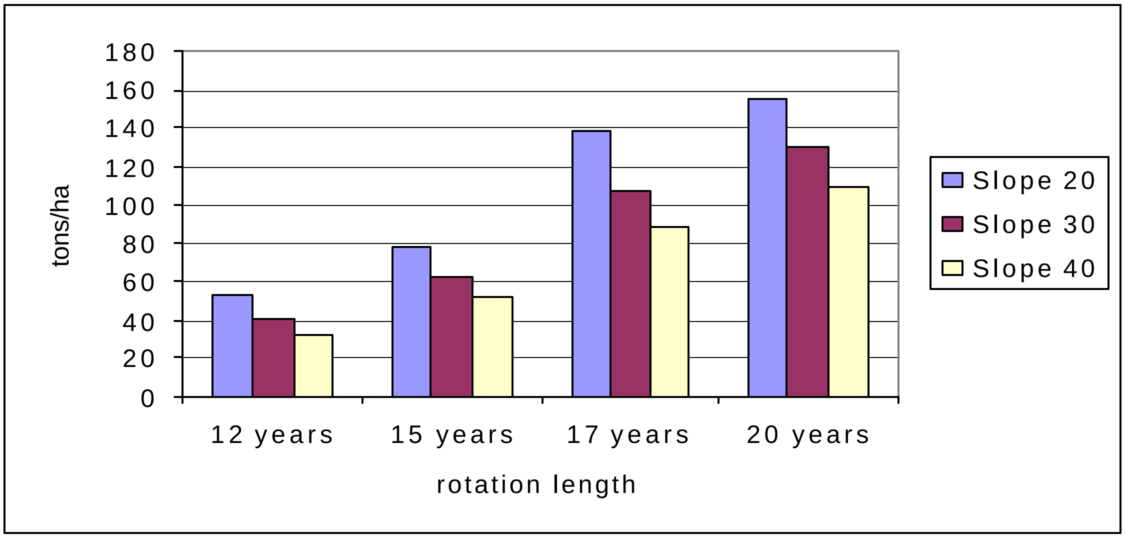


Figure IV-11. Rionegro watershed. Average annual accumulation of total organic carbon by rotation length and slope. Soil type TE.

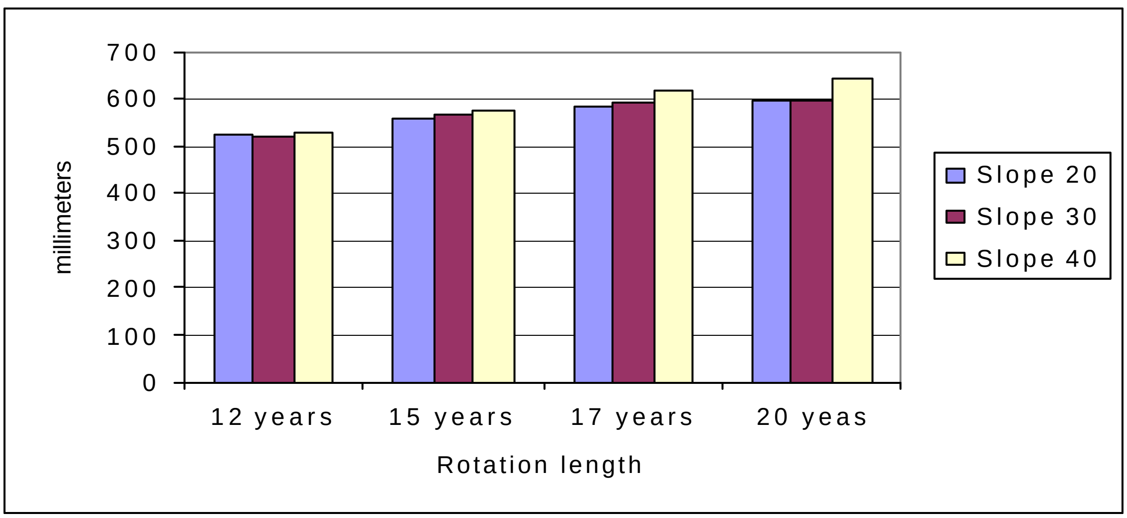


Figure IV-12. Rionegro watershed. Average erosion by rotation length and slope, soil type TE

After growing corn for two or three years in the steep lands of the Rionegro watershed without any sustainable practice and considering the amount of rainfall in the region (2200mm/year), erosion can be severe and hence the top soil depth is reduced taking nutrients and then yields decline.

Figure IV-12 shows the average amount of erosion by rotation length and slope. Erosion is by itself a means of soil degradation and organic carbon loss. When the rotation length is shortened the crops in the rotation are grown more frequently and the annual erosion is increased. As a consequence of the reduced land cover associated with shifting cultivation, runoff is increased. This situation can be seen in Figure IV-13 by rotation length and slope.

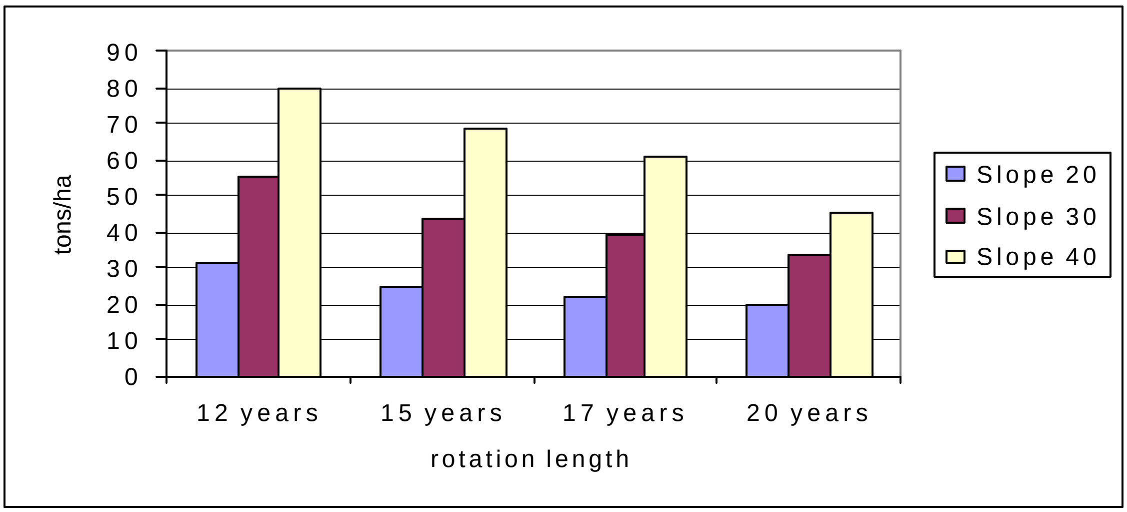


Figure IV-13. Rionegro watershed. Runoff by rotation length and slope. Soil type TE

The EPIC simulations were designed to study the impacts of current land use in the Rionegro watershed. Shifting cultivation generates the greatest soil erosion and runoff from the two soil types (TE and SV) and also from all slopes considered (20%, 30% and 40%), followed by agroforestry and forest. Since the observed trend in the region of study is a decreasing rotation length of the fallow period, the environmental effects of this management option seem to worsen the soil conditions of the watershed with the economic consequences that will be discussed next chapter.

Summarizing, this chapter has shown the main results from the EPIC simulations for the Rionegro watershed considering soil type TE, slopes of 20%, 30%, and 40%, and slope length of 10m. Three management practices were simulated, shifting cultivation, agroforestry and forests, in order to compare erosion, runoff and total organic carbon accumulation to see how sustainable these practices are. The differences between soil types were not significant but the differences among slopes were quite significant. Results for soil type SV are very close to soil type TE and can be seen in Appendix.

Two main conclusions can be derived from this chapter. 1) The EPIC simulations results are consistent with the main findings in the related literature in the humid tropics. Converting natural forest into cultivation, particularly, in the high and steep lands in the tropics has accelerated soil and runoff losses. 2) The most effective management practice against soil loss, runoff, and organic carbon loss is forest followed by agroforestry and shifting cultivation.

CHAPTER V

ECONOMIC ANALYSIS OF ENVIRONMENTAL EFFECTS OF LAND USE

Economics of land use management practices

Practices that minimize the rate of soil degradation, improve soil fertility, increase crop yields and raise farm income are key to sustaining agricultural productivity in the tropics (Neupane and Thapa, 2001). Agroforestry and vegetation cover have been recommended in the tropics, particularly on steep lands, in order to control erosion and runoff when precipitation is intense (Sanchez, 1995). Agroforestry is the traditional practice of growing trees on farms for the benefit of the farm family. Agroforestry was brought from the realm of indigenous knowledge into the forefront of agricultural research less than two decades ago and has been promoted as sustainability-enhancing practice that combines the best attributes of forestry and agriculture, and also increases farm income (Sanchez, 1995).

The improved yield response of crops following improved fallow normally depends on biomass and N accumulation during the fallow period (Barbier, 1990). Literature exists that show how agroforestry practices contribute to increased yields, income, and soil fertility as well as controlling erosion. Ramirez, et.al, (1992) presents the results of a study conducted in the Ecuadorian Amazon region. Improved agroforestry practice in this region was found not only to be technically viable but also economically feasible. Thirteen smallholdings were assessed during a 15-month period from 1988 to 1989. The set of agroforestry practices involved: 1) managing natural regeneration of shade trees and marketable timber trees intercropped with *Coffea canephora var robusta* (agrisilvicultural system) and grass legume associations (silvopastoral systems). 2) using more appropriate techniques of coffee pruning and 3) planting *Desmodium ovaliforlium* as ground cover crop in coffee plantations and as a forage legume. In addition, 190 farms out of 1626 farms within the area of study were included in a one-time random stratified sample in order to assess the rate of farmer adoption of new practices. Average annual coffee yields in the improved treatment were 63.2% higher than in the traditional system. All least 2-3 manual weedings of coffee per year were eliminated (saving 10-15 man-days/ha per year) and herbicide use was lowered by 91.8%. The later could have resulted from introducing *Desmodium ovalifolium* as ground cover. Pasture production also increased by 11.2%. It was found that timber output could be increased by 233.3% just by managing natural regeneration of on-farm woody trees intercropped with pasture swards and coffee plantations. Calculated internal rates of return for investment in improved agroforestry practices within the agrisilvopastoral system were significantly higher than those for traditional ones (13.93% vs –6.27% respectively). The rates of return for agroforestry were higher than the opportunity cost of capital (8%) (Ramírez, 1992).

Vieth et.al, (2001) estimated the benefits and costs of soil conservation in the Upper Mahawelli Watershed in Sri Lanka by comparing shifting cultivation, poorly managed seedling Tea, seedling tea with some conservation, market gardens and degraded grasslands. The conservation measures analyzed were stoned terraces; lock and spill drains; bench terraces; and an agroforestry system called the sloping agricultural land technique. According to the Land and Water Resource Center of the Department of Agriculture of Sri Lanka, these conservation measures reduce soil erosion by 90%, 80%, 85%, and 85% respectively. The shifting cultivation and all conservation measures, except for "the sloping agriculture land technique", had positive net present values. If the NPV were higher than shifting cultivation at a 10% discount rate, they could be profitably adopted. It is important to mention however, that the negative present value for the agroforestry system measure was lower than for shifting cultivation and both types of tea cultivation. The result of the benefit cost analysis indicates that welfare generally will be increased if soil conservation measures are implemented on all lands within the upper Mahaweli watershed (Vieth, et.al, 2001).

Barbier (2000) discusses some case studies in Africa showing the net economic benefits of undertaking soil conservation practices ranging from cropping technology to agroforestry systems. In most cases the net benefits are positive. In Sudan, farmers are encouraged to cultivate gum arabic trees (*Acacia Senegal*) because they represent valuable economic and ecological functions. This species is used in pharmaceutical, and other manufacturing industries. In addition, its extensive lateral roots contribute to reduce erosion and runoff, and as a leguminous tree it fixes nitrogen, which encourages grass growth for livestock grazing. Barbier (2000) argues that the choice by farmers in Sudan to incorporate gum arabic trees in their farms will depend on whether the benefits exceed those of alternative systems. The potentially high financial rate of return to a gum arabic-based farming system coupled with its ecological benefits, would suggest that this would be the ideal system to recover soil fertility and also improve farmers income. However, Barbier argues that because of government intervention through exchange rate, export, and pricing policies the real producer price of gum arabic in Sudan has varied considerably. These fluctuations explain why the relative profitability of gum compared to other crops in each system is generally lower and farmers are reluctant to intensively grow gum Arabic (Barbier, 2000).

Barbier (2000) presents another case study were soil conservation practices resulted in increasing productivity and income for farmers. This is the case in the Machakos District in Kenya. The source of the success in this case appears to be innovation, particularly, in terms of farming systems, choice of crops and the adoption of land management techniques. This is relevant for the case of the Rionegro watershed because innovation is a key component of the extension service in Colombia that has been strongly criticized in recent years for being poor and inefficient. This issue will be discussed later.

The most striking land improvement investment in the case of Machakos District in Kenya has been terracing. More than 200,000 hectares of land have been terraced, which is estimated to have cost of over $50 million in 1990 prices. In addition, the improved land management practices not only have to be compatible with the existing farming systems but also they must be affordable. The investments made in the Machakos region to improve soil fertility and income, have the attribute that they were made without any subsidy or credits targeted specifically for conservation investments. Instead, cash earned from off-farm work and from sale of commercial crops was used to fund those investments in addition to some family work. Another relevant finding from this case study is that on steeper slopes, the conservation investment appears more worthwhile, since on a 20% slope the payback period of the investment is reduced to 13 years comparing to 48 years needed to recover the investment for slopes of 15%. However, Barbier argues that in order for farmers to be able to invest in soil conservation practices they must have their land tenure guaranteed to cover those long repayment periods. At the same time improvements in cropping systems must contribute to yield long-term gains (Barbier, 2000).

Barbier (1990) in a study of the uplands of Java suggests that adopting agroforestry system may be extremely difficult for poorer farmers who are depending on very small landholdings for food production and who have no alternative cropland or employment opportunities. Here, there is room for policy intervention through direct subsidies or subsidized credit to encourage poor farmers to undertake soil conservation practices such agroforestry.

Most upland soils in humid and sub-humid tropical countries are characterized by high vulnerability in terms of erosion and runoff. Ehui, et.al (1990) based on a simulation study uses a capital budgeting approach to determine the profitability of alternative land use systems, taking into account the short and long run impact of soil erosion on agricultural productivity in southwestern Nigeria. The fallow systems include: 1) two continuous cultivation alley cropping systems with leucaena hedgerows planted at 2m and 4m interhedgerow spacings; 2) no-till farming system; and 3) two traditional bush fallow systems with a 3-year cropping period and in 6 and 12 year cycles. Under a 10 percent discount rate the 12-year cycle shifting cultivation system was most profitable followed by the 4m alley cropping. Ehui, argues that this is the case when there is low population density and abundance of forestland . When land is taken out of production because of fallow vegetation the 4m alley cropping is most profitable, followed by no-till, the 2m alley cropping, the 12 and 6-year cycle. This seems to be the case in many tropical countries where shifting cultivation has taking place as the typical cultivation management. Farmers fell and burn the fallow vegetation, cultivate the cleared land (typically 1 to 3 years) and then abandon the site to forest or bush cover. Until recently enough arable land was available to maintain this management practice. However, today because population pressure and increasing rural poverty (Alviar, 1983), fallow periods have decreased leading to more intensive cultivation of marginal lands as well as the clearing of new forest lands for agriculture. A major consequence has been increased soil erosion from cropland, resulting in declining soil fertility (Ehui, et.al, 1990).

Pattanayak and Mercer (1998) present a three-stage model to estimate the economic benefits from adoption soil conservation practices, particularly agroforestry in the Eastern Visayas in the Philippines. The first stage relates soil quality as a function of management practices and a vector of environmental variables such as geologic material, topography, climate, time and biota. Then they define soil conservation as a flow variable represented by the difference between two levels of soil quality associated with and without agroforestry. The second stage relates soil conservation to the agricultural profile including yields and allocation of inputs. The final stage establishes a link between a measure of economic welfare (profits) and agricultural productivity as induced by soil conservation. To implement this framework, the authors develop and estimate a set of econometric equations that describe the agroforestry adoption decision, the resulting soil quality changes, and their impacts on farm profits. Investments in agroforestry in this region to improve or maintain soil capital can increase annual agricultural profits by US$53 for the typical household, which is 6% of total income. However, the authors find significant costs. Given that small farmers in tropical uplands play an important role in the management of deteriorating soil and forest resources, policy makers may want to consider supporting farmers in the early years of agroforestry adoption.

In the same line of research, Ngambeki (1985) shows that alley cropping is an aspect of agroforestry being developed for small farmers in the tropics in order to recover soil fertility and increase farm income. It consists of establishing fast-growing leguminous shrubs or tree species in rows, then controlling the shading from the trees during cropping by pruning the branches, which can be used as mulch or green manure to benefit crops. The results of this study show that despite an increase in labor requirements by 50%, agroforestry can sustain and increase maize production by 60%, reduce the use of nitrogenous fertilizers, and increase income and the rate of return per unit cost (Ngambeki, 1985).

Subsistence agriculture in the tropics has contributed to soil degradation because of a lack of sustainable practices (Neupane and Thapa, 2001). However, the complementary relationship among trees, crops, and livestock seems to shed light on how to recover soil fertility and improve life conditions for rural populations (Lal, 1995). Neupane and Thapa (2001) conducted a study to examine the impact of an agroforestry intervention project on soil fertility and farm income based on a sample of subsistence farm household in Dhading district in Nepal. The area under study has similar characteristics to those observed in the Rionegro watershed. Dhading is one of the least developed areas in central Nepal with mean annual rainfall of 1819mm. The altitude varies from 488 to 7500 m, with most of the area lying within the range of 700-2000m. More than 90% of the farmers practice susbsistance agriculture. A total of 223 household (82 project and 141 non-project) were interviewed to collect information. The project consisted of promoting the introduction of some fodder and grass species such as *Flemingia congesta, Morus alba* and *Gauzuma ulmiformis,* among others. The benefit-cost analysis showed that the agricultural system with agroforestry was more profitable than the conventional system. The results also showed that the introduction of multipurpose trees such as *Morus alba* could enhance the profitability of agroforestry based systems. The benefit-cost ratio comparing traditional systems and agoforestry systems was 1.8 and 2.9 respectively. The mean annual net return of farming with agroforestry was estimated to be US$ 1582 per hectare compared to US$804 per hectare without agroforestry (Neupane and Thapa, 2001).

Private Net Returns in the Rionegro Watershed

The literature presented above supports the findings in the Rionegro watershed in terms of the net present value of private returns comparing shifting cultivation and agroforestry. A first approximation to the net present value of income from a 20-years rotation shows that Agroforestry generates the highest present value of net returns estimated in $3.5 million of Colombian pesos (US$1,398) per hectare, and shifting cultivation $1.6 million of Colombian pesos (US$643) per hectare. It means that the traditional agricultural management practice of slash and burn practiced in the Rionegro watershed is the less profitable practice from the private point of view. Table V-1 shows the present value of private returns for the two practices using a discount rate of 6%, which comes from 12 % interest rate of the banking system minus 6% rate of inflation. The rotation period is twenty years.

Table V-1. Rionegro watershed. Net present value of returns by land use ($ Colombian peso)

Year	Agroforestry					Shifting Cultivation				
	Activity	Yield (t/ha)	Cost/ha	Revenues/ha	Benefits/ha	Activity	Yield (t/ha)	Cost/ha	Revenues/ha	Benefits/ha
1	Corn	1.35	-870000	1080000	210000	Corn	1.15	-870000	920000	50000
2	Corn	1.35	-870000	1080000	210000	Corn	1.15	-870000	920000	50000
3	Sesbania	0.152	-413000	876000	463000	Bermuda	0.152	-413500	1051200	637700
4	Sesbania	0.152	-413500	876000	462500	Bermuda	0.152	-413500	1051200	637700
5	Sesbania	0.152	-413500	876000	462500	Bermuda	0.152	-413500	1051200	637700
6	Corn	1.35	-870000	1080000	210000	Sec. Forest			0	0
7	Corn	1.35	-870000	1080000	210000	Sec. Forest			0	0
8	Pine		-1666000	0	-1666000	Sec. Forest			0	0
9	Pine		-724.1	0	-724.1	Sec. Forest			0	0
10	Pine		-402500	0	-402500	Sec. Forest			0	0
11	Pine		-276100	0	-276100	Sec. Forest			0	0
12	Pine		-452000	0	-452000	Sec. Forest			0	0
13	Pine		-78900	0	-78900	Sec. Forest			0	0
14	Pine		-23300	0	-23300	Sec. Forest			0	0
15	Pine		-23300	0	-23300	Sec. Forest			0	0
16	Pine		-23300	0	-23300	Sec. Forest			0	0
17	Pine	85	-2452600	2975000	522400	Sec. Forest			0	0
18	Pine		-23300	0	-23300	Sec. Forest			0	0
19	Pine		-23300	0	-23300	Sec. Forest			0	0
20	Pine	281	-2223100	12645000	10421900	Sec. Forest			0	0
				NPV, r=6%	$3,494,425.68				NPV, r=6%	$1,608,739.52
				$US	1,398				$US	643

The data used to estimate the net present value come from the EPIC simulations regarding corn yields, timber, and also from the Regional Secretary of Agriculture in terms of the production costs and producer prices as well as livestock, and forest production. Corn yields were estimated from EPIC as an annual average from the three slopes of 20%, 30%, and 40%. This was the case because there were no disaggregate data available of prices and costs by slope. Tables V-2, V-3, and V-4 present labor and input costs for different land management practices and economic activities in the Rionegro watershed.

Table V-2. Rionegro watershed. Production costs of a hectare of corn ($1000 of Colombian pesos)

Description				
Labor	**Unit**	**Quantity**	**Unit Value**	**Total**
Site Preparation	days	15	15	225
Planting	days	9	15	135
Soil mixing	days	10	15	150
Corn weeded manually	days	14	15	210
Harvest	days	8	15	120
Cleaning and packing	days	2	15	30
Total Costs				**870**
Total days/ha/year		**58**		

Source: Regional Secretary of Agriculture, 2002

On average, labor represents 73% of total costs of producing one hectare of corn or $870 thousand of Colombian pesos (US$348). Labor requirements are equal to 58 days/ha/year. Other inputs and materials are equal to $0.41 million (US$166). The average corn yield per hectare reported by the Regional Secretary of Agriculture in the region of study is equal to 1.4 tons/ha, which is consistent with the values estimated by the EPIC simulations (Regional Secretary of Agriculture, 2003). The average price per kilogram of corn is equal to $800 Colombian pesos (US$ 0.32).

Table V-3. Rionegro watershed. Production costs of a hectare of pasture and livestock($ 1000 of Colombian pesos)

1. Establishment Costs				
Labor	**Unit**	**Quantity**	**Unit value**	**Total**
Site Preparation (Manual)	days	12	15	180
Application of correctors	days	2	15	30
Planting	days	4	15	60
Replanting	days	1	15	15
Fences	days	8	15	120
Total Establishment Costs		27		**405**
2. Maintenance Costs				
Pest Conotrol	days	1	15	15
Fence	days	2	15	30
Total Maintenance Costs		3		**45**
3. Cost of livestock				
Days/cow/calf/year	days	10	15	150
Value/cow/year				74.3
Fodder cost				189.2
Total Cost per animal/ha/year				**413.5**
Total days per hectare/year		**40**		

Source: Regional Secretary of Agriculture, 2002

The average production costs of pasture and livestock are presented in Table V-3. On average, a hectare of pasture can to sustain 2 adult animals for meat and milk. The cost of production is $413.5 thousand Colombian pesos (US$165.4). Milk production has been estimated to be equal to 1752 liters per cow/year. Meat has been estimated to be equal to 152 kg/year. The average price a liter of milk is equal to $500 Colombian pesos (US$0.2). The price of meat is reported to be $6000 of Colombian pesos (US$2.4) per kilogram. Labor requirements for pasture and livestock are 40 days/ha/year.

Table V-4. Rionegro watershed. Production costs of a hectare of pine trees ($1000 of Colombian pesos)

1. Establishment Costs				
Labor	**Unit**	**Quantity**	**Unit value**	**Total**
Site Preparation (Manual)	days	6	20.85	125
Prescribed burning	days	1	20.85	21
Fire break	days	2	20.85	42
Spacing	days	2	20.85	42
Drilling holes	days	5	20.85	104
Cleaning	days	6	20.85	125
Transport of small trees	days	2	20.85	42
Planting	days	7	20.85	146
Refilling	days	1	20.85	21
Subtotal		**32**		**667.2**
Total Establishment Costs				
2. Maintenance Costs				
Pest Control	days	1	20.85	20.85
Total Maintenance Costs		**1**		20.85
. Compartment boundary Costs				
Drilling holes for fences	days	0.5	20.85	10.425
Hincado Postes	days	0.5	20.85	10.425
Wiring	days	0.5	20.85	10.425
Wire and pole transportation	days	0.5	20.85	10.425
Supervisor	days	3.5	20.85	72.975
Total Compartment Costs		**5.5**		**114.675**
Total Cost				**802.725**
Total days per hectare/year		**38.5**		

Source: Reforestadora El Guasimo, 2002

Table V-4 presents the labor costs of establishment and maintenance of a hectare of pine trees. To establish a hectare of pine trees in the Rionegro watershed costs, on average, $802.7 thousands of Colombian pesos (US$321). The average price of timber from Pine trees is equal to $68,000 Colombian pesos per ton (US$27.2/ton). On average, a hectare of Pine trees can produce 281 tons of timber at the end of 20-year rotation. Data on costs, harvest, and prices for Pine plantations were obtained from a reforesting company in the region (Reforestadora El Guasimo,2002).

The net present value of income for shifting cultivation in the study area has been reduced because of shortening fallow periods. Ehui, et.al (1990) have pointed out that today, due to population pressure, fallow periods have decreased in tropical countries as there has been more intensive cultivation of marginal lands. As a consequence, not only has soil erosion from cropland increased as was shown in Chapter IV, but also farm income has declined reduced because of decreasing crop yields from decreased soil depth and fertility. Figure V-1 shows a comparison of net present values of returns for the shifting cultivation scheme in the Rionegro watershed under 12, 15, 17, and 20-year fallow periods.

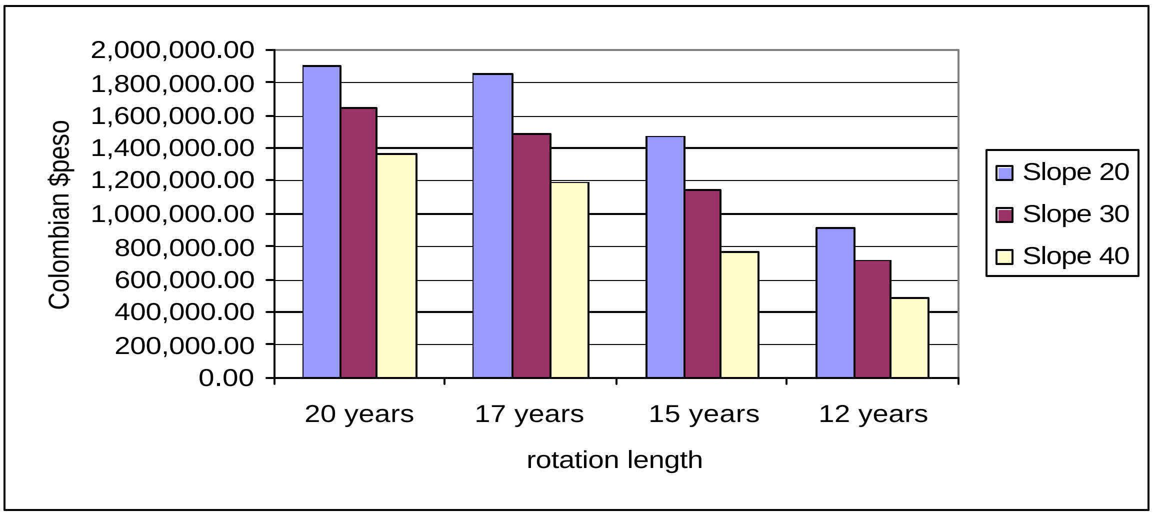


Figure V-1. Rionegro watershed. Net present value of returns from shorter rotations of shifting cultivation.

Two facts are worthy to mention from Figure V-5. First, the results are consistent with findings in the relevant literature that shortening the fallow period reduce yields due to a decline in soil fertility (Ehui, et.al, 1990). This situation translates into lower income for farmers. Second, the situation gets worse when comparing corn yields by slopes. The steeper the slope the lower the net present value of returns in the case of shifting cultivation. It is important to mention that because of data limitations, prices and production costs for shifting cultivation could not be disaggregated by slope. Prices and costs were considered the same for the three slope classes.

The Model

From the perspective of the social planner, it is relevant to optimally allocate land among the uses so as to obtain the highest net present value of income for the watershed area. In order to provide the social planner with a tool to design of soil conservation policies, a linear programming model was developed. Farmers are assumed to maximize net income derived from different land management activities and society is assumed to maximize net social benefits. The model captures both objectives though not necessarily at the same time by including two constraints that are associated with on-site and off-site environmental effects of erosion and runoff, in addition to land and labor constraints. The form of the model used to estimate agricultural income with constraints on erosion and runoff uses the constraints on the left. The form of the model used to estimate the value of electricity, carbon sequestration and agricultural income uses the erosion and runoff constraints on the right.

(2) $$\text{Max} \quad z = \sum_{i=1}^{3} \sum_{j=1}^{6} \sum_{t=1}^{100} \frac{C_{ijt} x_{ijt}}{(1+r)^t} + \sum_{t=1}^{100} \frac{E_t}{(1+r)^t}$$

Subject to:

(3) Land Use $$\sum_{j=1}^{6} x_{ij} = H_i \quad \text{i} = 1,2,3$$

(4) Erosion $$\sum_{i=1}^{3} \sum_{j=1}^{6} s_{ijt} x_{ijt} \le S_t \quad \text{t} = 1,\ldots 100 \ \text{ or } \ \sum_{i=1}^{3} \sum_{j=1}^{6} sv_t + E_t \le 180 Mm^3 \quad \text{t} = 1,\ldots 100$$

(5) Runoff $\sum_{i=1}^{3}\sum_{j=1}^{6} q_{ijt}x_{ijt} \geq Q_t$ t = 1,…100 or $\sum_{i=1}^{3}\sum_{j=1}^{6} -q_{ijt}x_{ijt} + E_t \leq 0$ t = 1,…100

(6) Total labor $\sum_{i=1}^{3}\sum_{j}^{6} l_{ijt}x_{ijt} \leq L_t$ t = 1,…100

(7) Planting labor $\sum_{i=1}^{3}\sum_{j}^{6} pl_{ijt}x_{ijt} \leq PL_t$ t = 1,…100

(8)Harvesting labor $\sum_{i=1}^{3}\sum_{j}^{6} hl_{ijt}x_{ijt} \leq HL_t$ t = 1,…100

(9) $x_{ij} \geq 0$ i=1,2,3; j=1,…,6 t=1,…100

where c_{ijt} is the average gross margin obtained from the activities; z is the net discounted revenue; E is the value of electricity generate from 1 cubic meter of water; sv_t represent the amount of sediment delivered to the reservoir. *180* Mm^3 is the useful volume of the reservoir. H represent the number of hectares in each soil type; x_{ijt} are the decision variables representing the number of hectares of soil type i under land use management j (i = 1,2,3; j=1,…,6).

Soil type 1 = Slope 20%

Soil type 2 = Slope 30%

Soil type 3 = Slope 40%

Land use 1 = Natural Forest

Land use 2 = Agroforestry

Land use 3 = Shifting cultivation

Land use 4 = Conversion from shifting cultivation to agroforestry beginning after year 20

Land use 5 = Conversion from shifting cultivation to agroforestry beginning after year 40

Land use 6 = Conversion from shifting cultivation to agroforestry beginning after year 60

Electricity = Generation of hydropower from runoff. It depends on the reservoir capacity and sediment.

Table V-5 shows a list of the eighteen activities considered as decision variables with the corresponding codes that were used to run the model.

Table V-5. Rionegro watershed. Activities in the LP model

Code	Activities	Slope
Sc2	Shifting Cultivation	20%
Af2	Agroforestry	20%
Fn2	Natural Forest	20%
Sc3	Shifting Cultivation	30%
Af3	Agroforestry	30%
Fn3	Natural Forest	30%
Sc4	Shifting Cultivation	40%
Af4	Agroforestry	40%
Fn4	Natural Forest	40%
sa220	Conversion after 20 years	20%
sa320	Conversion after 20 years	30%
sa420	Conversion after 20 years	40%
sa240	Conversion after 40 years	20%
sa340	Conversion after 40 years	30%
sa440	Conversion after 40 years	40%
sa260	Conversion after 60 years	20%
sa360	Conversion after 60 years	30%
sa460	Conversion after 60 years	40%
Elec	Generation of electricity every year	

Objective Function

Crops, pasture, and timber are activities that generate income as well as erosion and runoff. The social planner in this case may not be interested in choosing an objective such as minimization of soil loss. The more usual situation is to maximize agricultural income, subject to constraints on erosion and runoff can enter as constraints to the solution. The objective function then is expressed as follows:

(10) $$\text{Max} \quad z = \sum_{i=1}^{3} \sum_{j=1}^{6} \sum_{t=1}^{100} \frac{C_{ijt} x_{ijt}}{(1+r)^t}$$

where C_{ijt} is the average income accruing to management option *j* applied to soil type *i* in year *t*, in Colombian pesos per hectare. Z can be interpreted as net discounted revenue from income and costs derived from the agricultural activities and electricity over a 100-year period. Table V-6 shows the main sources of income for a typical farm family in the Rionegro watershed.

Area Constraints

The number of hectares *H* of soil type *i* assigned to all management practices must equal H_i. The total area in soil type *i* in the Rionegro watershed is given by:

(11) $$\sum_{j=1}^{6} x_{ij} = H_i$$

where H_1= 9,506 ha; H_2= 16,776 ha; and H_3=14,539 ha

Table V-6. Rionegro. watershed. Sources of income of a typical family ($Colombian pesos)

Description	Units	Unit value $Col pesos	Subtotal $Col pesos	Total $Col pesos	Total $US*
Average Number of Hectares per farm	3 hectares				
Average family size	5 people				
Farm income sources					
Corn (2 hectares)	1.3 tons/ha	950,000	1,235,000	2,470,000	988
Beans (Cropped between corn harvest)	1.2 tons/ha	2,000,000	2,400,000	4,800,000	1,920
Eggs/chicken	600/year	300	180,000	180,000	72
Milk	876 liters/year	550	481,800	481,800	193
Total Income			4,296,800	7,931,800	3,173
Montly income per family				660,983	264
Monthly value of the basic basket per family				500,000	200
Production for Domestic Consumption					
Vegetables, milk, eggs, chicken					

*: Exchange rate: US$1 = $2500 Colombian pesos

Average annual soil loss constraint

To relate soil losses to management options a constraint is defined as follows:

(12) $$\sum_{i=1}^{3}\sum_{j=1}^{6} s_{ijt} x_{ijt} \leq S_t$$

where s_{ijt} is the estimated annual soil loss, in metric tons per hectare from 1 hectare of soil type *i* managed under option *j* in year *t*, and S_t is the maximum acceptable soil loss from the watershed in tons per hectare in year *t*. The coefficients of soil erosion were obtained from the EPIC simulations.

In the social model for the watershed, the erosion constraints are revised to represent the volume of space required by each ton of eroded soil delivered to the reservoir. The sediment volume required by a ton soil eroded is sv=dr*s/bd where *dr* is the delivery ratio, *s* is erosion in tons, and *bd* is the bulk density of the cubic meter. However, a ton of sediment entering the lake in year 1 is assumed to remain in the lake for the planning period of 100 years. Thus, the above erosion constraints are modified to be

(13) $$\sum_{i=1}^{3}\sum_{j=1}^{6}\sum_{t=1}^{100} sv_{ijt} x_{ijt} + E_t \leq 180Mm^3 \quad \mathrm{t} = 1,\ldots 100$$

Runoff constraints

To relate runoff to land use management, the following constraint was defined:

(14) $$\sum_{i=1}^{3}\sum_{j=1}^{6} q_{ijt} x_{ijt} \geq Q_t$$

where q_{ijt} is the estimated runoff for 1 hectare of land use j applied to soil type i in cubic meters per hectare in year t. Q_t is the minimum acceptable runoff in cubic meters per hectare in year t. The runoff coefficients were obtained from the EPIC simulations. In the social model the runoff constraints are modified so that the amount of electricity generated is determined by the minimum of the runoff in a given year of the remaining capacity of the reservoir shown above. The runoff constraints for the social model are

(14) $$\sum_{i=1}^{3}\sum_{j=1}^{6} -q_{ijt}x_{ijt} - E_t \leq 0 \qquad \mathrm{t} = 1, \ldots 100$$

<u>Labor constraints</u>

Labor constraints are divided into three categories. Labor coefficients pl_{ijt} are measured in days per hectare per year and represent the labor required for the planting season. Coefficients hl_{ijt} represent the labor requirements per hectare for the harvesting season to be used by each activity in year t, and l_{ijt} represent the summation of planting and harvesting labor. PL_t, HL_t and L_t represent total supply of labor. The values were obtained from the Regional Secretary of Agriculture of Antioquia. The labor constraints are represented as follows:

(15) $$\sum_{i=1}^{3}\sum_{j}^{6} l_{ijt}x_{ijt} \leq L_t \qquad \mathrm{t} = 1,2,3, \ldots 100$$

(16) $$\sum_{i=1}^{3}\sum_{j}^{6} pl_{ijt}x_{ijt} \leq PL_t$$

(17) $$\sum_{i=1}^{3}\sum_{j}^{6} hl_{ijt}x_{ijt} \leq HL_t$$

Assumptions

- Different land uses will produce different levels of soil disturbances (erosion and runoff).
- Soil loss and runoff estimates from the EPIC simulations are acceptable (see Chapter IV)
- Soil loss depends on soil type, land use, and slope.
- Runoff depends on precipitation, temperature, soil type and vegetation cover which is derived by coefficients from EPIC
- Time horizon is 100 years
- No capital or inputs, other than labor, are considered as constraints
- Output prices and wages are kept constant through time
- Government intervention is marginal
- Labor is unskilled

The model was run using the C-Whiz program. C-Whiz (Ketron Management Science, 2000) is a linear programming routine for solving mathematical programming models. It is a high performance optimizer, which gives superior speed (increased iterations per minute) and effectiveness (fewer iterations to achieve optimality). C-Whiz accepts input in a standard MPS format matrix file or in matrix format from a Dataform database. C-Whiz makes the transformation of the matrix file into a value table and an index array, performs the necessary iterations to optimality, and produces the results of the optimization. Several runs of the model were performed in order to produce the required output to make a sensitivity analysis. Table V-7 presents the main parameters used in the linear programming analysis.

Table V-7. Parameters used for the LP model

Discount Rates	Erosion	Runoff
6%	12 tons/ha	1,000 m^3/ha
15%	48 tons/ha	5,200 m^3/ha
25%		

The discount rate represents the value that farmers put to the present and the future. The lower the discount rates the higher the value of future and vice versa. The 6% real discount rate was obtained by adjusting an average nominal interest rate of 12% for an inflation rate of 6% percent. Other discount rates such as 8% and 10% were used but the output did not change significantly. Since subsistence level farmers put a much higher value to the present (Barbier, et.al, 1995), much higher values (15% and 25%) were used to obtain significant changes for the optimal distribution of land among the eighteen activities defined above. Erosion limits were applied according to the average observed from the EPIC simulations. No feasible solutions were obtained with parameters lower than 12 tons/ha/year and greater than 48 tons/ha/year. Optimal solutions were found within this range. The feasible average values of runoff per hectare, varied from 3,000 m^3/ha to 5,200 m^3/ha.

Results and sensitivity analysis

Table V-8 summarizes the main results of the LP model. It shows the optimal distribution of land among the eighteen activities under different scenarios of discount rates and soil erosion tolerance levels, keeping the runoff constant at a level of 3000 m^3/ha. A first observation from Table V-8, and consistent with the EPIC simulations presented in Chapter IV, is that natural forests and agroforestry, occupy the greatest portions of all land classes, that is, all three of slopes studied. There were also lands allocated into the conversion from shifting cultivation to agroforestry, particularly after twenty years, for all slopes.

For the lowest level of erosion tolerance equal to 12 tons/ha/year all land was allocated into natural forest and agroforestry under 40% and 20% slopes respectively. For the case of 6% discount rate, there was no shifting cultivation in any of the land classes. For slopes equal to 20% all land was allocated into agroforestry. Lands under 40% slopes were allocated into natural forests. Under 30% slope, land was distributed among agroforestry (33%), natural forest (39%), and conversion from shifting cultivation to agroforestry after 20 years (28%). There was no shifting cultivation under this scenario due to the fact that agroforestry and natural forest presented lower levels of erosion.

Increasing the discount rate up to 25% but keeping the level of erosion equal to 12 tons/ha/year, changed the distribution of land under 30% slopes. Both, agroforestry and natural forests increased the number of hectares by 40% and 37% respectively. Areas under 20% and 40% slopes continued to be allocated into agroforestry and natural forestry respectively. From the conservation point of view it is desirable that natural forests cover the steepest lands in order to control erosion and runoff.

When the level of erosion was increased to 24 tons/ha/year the land under 40% slopes that was allocated into natural forest before, is now allocated into agroforestry. However, 15% of the land remained in natural forest. For the 30% slopes agroforestry allocated accounted for 57% of the land. It is important to mention that the conversion of land from shifting cultivation to agroforestry after twenty years increased substantially as the erosion was decreased. At the same time, increasing the discount rate from 6% to 15% produced a substantial increase in the number of hectares allocated into agroforestry from 4,972 ha to 9,611 ha under 30% slopes.

For erosion levels equal to 36 tons/ha/year and 48 tons/ha/year, the main observation is that no land was allocated into natural forests. As expected, the increased level of erosion brought more land into activities that generate higher erosion levels than natural forests. However, no shifting cultivation was allocated in any of the slope types. Summarizing, the lower the level of erosion the more natural forest was allocated. The higher the level of erosion more activities other than natural forests were allocated.

Table V-8. Rionegro watershed. Optimal distribution of land in hectares by level of erosion and discount rates

Code	Activities	E<=12			E<=24			E<=36			E<=48		
		6%	15%	25%	6%	15%	25%	6%	15%	25%	6%	15%	25%
Slope 20%													
Sc2	Shifting Cultivation												
Af2	Agroforestry	9,506	9,506	9,506									
Fn2	Natural Forest												
sa220	Conversion after 20 years				9,506	9,506	9,506	9,506	9,506	9,506	9,506	9,506	9,506
sa240	Conversion after 40 years												
sa260	Conversion after 60 years												
Slope 30%													
Sc3	Shifting Cultivation												
Af3	Agroforestry	5,648	5,648	7,116	4,972	9,611	9,611	2,083	16,622	16,622	2,083	16,622	16,622
Fn3	Natural Forest	6,466	6,466	8,018									
sa320	Conversion after 20 years	4,662	4,662	1,643	11,804	7,165	7,165	14,693	154	154	14,693	154	154
sa340	Conversion after 40 years												
sa360	Conversion after 60 years												
Slope 40%													
Sc4	Shifting Cultivation												
Af4	Agroforestry				11,650	7,010	7,010	14,539			14,539		
Fn4	Natural Forest	14,539	14,539	14,539	2,889	2,267	2,267						
sa420	Conversion after 20 years					1,934	1,934		14,539	14,539		14,539	14,539
sa440	Conversion after 40 years												
sa460	Conversion after 60 years					3,328	3,328						
Objective Function $US (1000)		**581,577**	**226,573**	**135,054**	**959,154**	**350,604**	**204,704**	**1,015,385**	**365,788**	**212,708**	**1,015,385**	**365,788**	**212,708**

E: erosion tolerance level; * Exchange rate: US$1 = $2500 Colombian pesos

Higher discount rates[6] of 15% and 25% produce more intense use of land as expected. It can be seen that these particular levels of discount rates coupled with the highest tolerance level of erosion (48 tons/ha/year) caused more land to be used in agroforestry and conversion from shifting cultivation to agroforestry.

Labor is a key factor of production. Labor is also the means for people to get income and satisfy their needs. Supply of labor depends, among other things, on population growth. The output from the LP model in terms of labor is showing a result that, despite of data limitations, deserves some comments. Agroforestry is the land use, which requires more labor compared to shifting cultivation and natural forests. Figure V-2 shows the trend for total labor and harvesting labor over a period of 100 years.

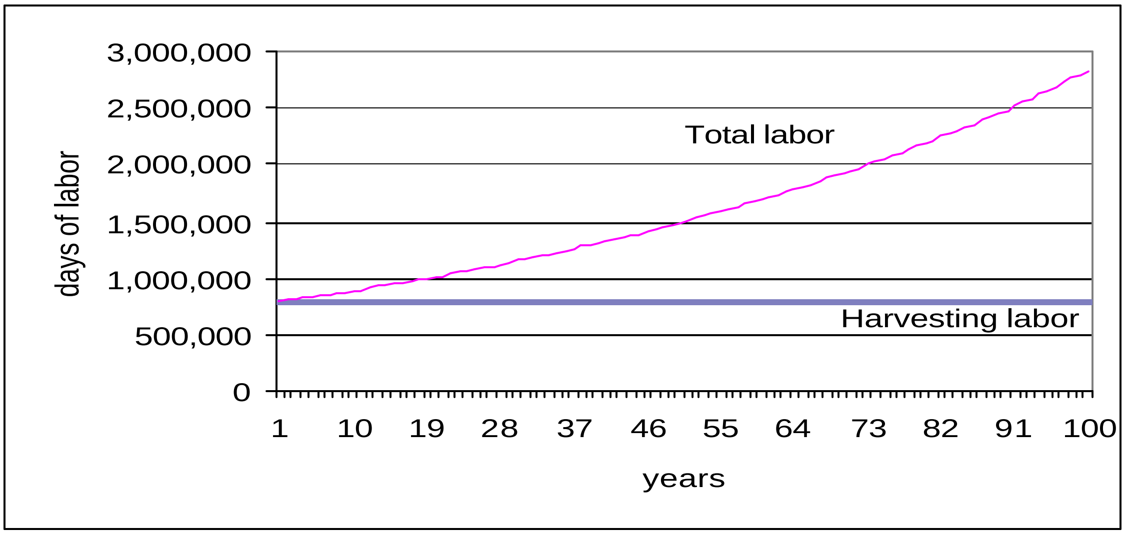


Figure V-2. Total labor and harvesting labor over 100 year period

Total labor was assumed to increased by 1.3% per year. However, the labor used in agroforestry limits the labor constraint in year one. After that, the supply of labor measured in days of labor is increasing over time while the harvesting labor keeps constant. This scenario, despite of data limitations, should make policymakers aware off

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[6] The discount rate depends on time preference and also on the level of aversion to uncertainty

the social problem represented by an excess of supply of labor for two reasons. First, if there is an excess of supply of labor, there could be the case that in the long run, all land would be converted into activities that could result in high amounts of erosion such as shifting cultivation or agroforestry compared to natural forest particularly in areas under 40% slopes which are the areas where one could argue most of the poor are located. Second, it should be the case that the excess of supply could be absorbed by urban activities or more labor intense activities such as agroindustries for example. It would not be wrong to assume that in the long run, the Rionegro watershed may achieve a certain level of development capable to absorb the labor force in a wider range of activities other than shifting cultivation and agroforestry. On the other hand, activities such as terracing which would utilize more labor to maintain soil productivity and reduce erosion could be phased in over time.

A sensitivity analysis from selling carbon sequestration services and energy was performed. In fact, one of the main issues concerning natural forests and forest plantations in tropical countries today is the fact that forests may be a source of income since they represent carbon sinks that contribute to reducing the effects of CO_2 emissions in the industrialized countries. The idea of selling carbon sequestration services has been acknowledged in the recent literature on tropical forests economics (Lopera and Gutierrez, 1998). For this research an approximate price of $10 per ton of sequestered carbon has been used following the study made by Lopera and Gutierrez (1998). On the other hand, hydroelectricity is a main concern in the Rionegro watershed since it feeds one of the most important reservoir and hydropower companies in the country. By converting runoff into energy measured in kilowatts per hectare and assigning an average price of $100 Colombian pesos per kilowatt ($US 0.04), a new source of income was included in the objective function. Following Alviar (1983), one cubic meter of water is equal to 7 kw of energy. This factor was applied to the runoff produced for each activity in the area of study.

Water erosion and runoff tend to move together especially in steep terrains. For hydropower generation, runoff is an input to fill reservoirs. However, erosion and sediment accumulation can compromise the generation of hydropower because they may reduce the useful volume and the lifetime of reservoirs. The sediment delivery ratio is defined as the fraction of the material eroded from a watershed, which reaches a downstream point where sediment yield is measured (Morris and Fan, 1997). Sediment yield depends on several factors such as slope, land used, vegetation, soil, particles, and bulk density, among others. Table V-9 shows the parameters used for the sensitivity analysis of selling carbon sequestration and energy.

Table V-9. Parameters for Sediment Delivery Ratio and carbon sequestration

	Sediment Delivery Ratio		
Carbon values	**Slope 20%**	**Slope 30%**	**Slope 40%**
$25,000 (US$ 10)	0.48	0.57	0.64
$12,500 (US$ 5)	0.25	0.30	0.33

Exchange rate: US$1=2,500 Colombian pesos

Table V-10 shows how land is optimally allocated between activities after including carbon sequestration and energy as sources of income. All simulations produced the same allocation of land. The results presented in Table V-10 correspond to

Table V-10. Rionegro watershed. Optimal distribution of land in hectares with carbon sequestration and energy

Code	Activities	Discount Rates		
		6%	15%	25%
Slope 20%				
Sc2	Shifting Cultivation			
Af2	Agroforestry			
Fn2	Natural Forest	9506	9506	9506
sa220	Conversion after 20 years			
sa240	Conversion after 40 years			
sa260	Conversion after 60 years			
Slope 30%				
Sc3	Shifting Cultivation			
Af3	Agroforestry			
Fn3	Natural Forest	16776	16776	16776
sa320	Conversion after 20 years			
sa340	Conversion after 40 years			
sa360	Conversion after 60 years			
Slope 40%				
Sc4	Shifting Cultivation			
Af4	Agroforestry			
Fn4	Natural Forest	14539	14539	14539
sa420	Conversion after 20 years			
sa440	Conversion after 40 years			
sa460	Conversion after 60 years			
Average electrical generation (1000 kw)		173,686	173,686	173,686
Objective Function $US (1000)		**796,269**	**321,615**	**193,323**

E: erosion tolerance level

the parameters in the first row of Table V-10. According to these results all land was optimally allocated into natural forests. It seems that the value of energy and carbon sequestration make the net present value of income from natural forest to be the highest. The intuitive explanation is that natural forest contributes very little to the sediment accumulation in reservoirs and contributes the most to carbon sequestration.

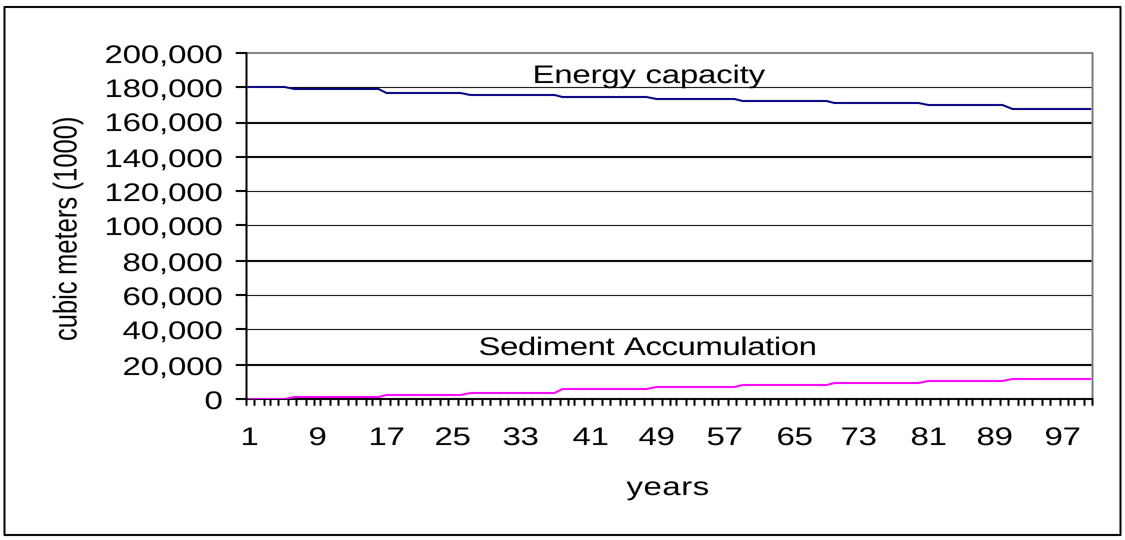

Figure V-3 Comparison between erosion and hydropower generation

Figure V-3 shows the relationship between the accumulation of sediment in cubic meters, considering a level of erosion of 36 tons/ha/year as the tolerance level, and the annual hydropower generation in cubic meters. As the sediment accumulates over time the hydropower generation declines. In order to sustain the hydropower generation actions must be taken in order to control erosion upstream.

However, from natural forest more water would be available for energy generation. Despite data limitations for this research that could have lead to an overestimation of the value of energy and carbon sequestration, the results shed some light for the social planner. There is a trade off or a dilemma that policy makers face regarding soil conservation measures. Thus, if the social goal is to control erosion and runoff, the right policy should be converting land from the most erosive practice, namely shifting cultivation, to the less erosive practice which is forestry and, somewhere in the middle, agroforestry. There is an opportunity cost of erosion that could be determined by the value of water used to produce hydropower and the value of carbon sequestration. More research needs to be done in order to produce accurate estimates of the capability of natural forest and forests plantations to store carbon to impute monetary values and compare the real income generated by both activities.

On the other hand, having more agricultural jobs in cropping practices, which is good for the rural population, can be translated into more erosion and runoff since agroforestry and shifting cultivation are the activities requiring the greater amount of labor. If a policy decision is to be made in terms of controlling erosion and runoff by having the land in forests and agroforestry practices or in terms of increasing employment the policy maker must be aware of this trade off.

Policy implications

Public policies in soil conservation activities and sustainable land allocation have often been justified on two grounds. One is that market's signals do not reflect the gap between social and private values. This means that the external effects, where actions by one economic agent affect the level of economic activity or welfare of other agents in the economy are ignored. The other argument for policy intervention is that soil conservation programs toward sustainability are generally long term in nature (Sfeir-Younis and Dragun, 1993).

Farmer's decision-making tends to privilege short-term decisions. The value the farmer puts to future income is lower than the value of present income, which may reflect the farmer's attitude to risk and uncertainty as well as the level of household poverty and access to credit (Barbier, et.al, 1995). Farmers will not modify their land management practices unless it is in their direct economic interest. This is an appreciation from the conventional economic theory. Some could argue however, that there could be other motivations for farmers to take actions, such as the sense of community and culture, for example. In general, farmers, particularly the poorest farmers, do not take into account the on-site effects of erosion from their practices much less take care of off-site effects (Barbier, et.al, 1995).

Conceptual framework

Soil erosion produces both on-site and off-site effects or damages. On-site damages reduce crop yields and eventually reduce farm income and increase poverty in rural areas. In addition, soil erosion diminishes social welfare since it contributes to downstream siltation, flooding, shortening the useful life of dams, among other environmental effects (Lal, 1995). Soil conservation, on the other hand, is generally undertaken by the landuser. Since there are external effects as a result of doing erosive agricultural practices, and the landuser does not take those into his or her internal costs, there is room for government intervention through incentives (Huszar, 1999).

One key issue in considering soil conservation measures is that the rational landuser undertakes such measures as long as the marginal benefits in doing so are greater than the marginal costs. Unless the landuser is a strong altruist, the benefits and costs weighted in the decision process are limited to those internal to the landuser. Benefits in the form of reduced damages to other members of society are not part of the decision. In tropical developing countries with poor and low skilled rural population, small farmers hardly undertake conservation measures for their own welfare, much less for the society's well being (Alviar, 1983). Figure V-4 illustrates how the landuser faces the benefits and costs of soil conservation.

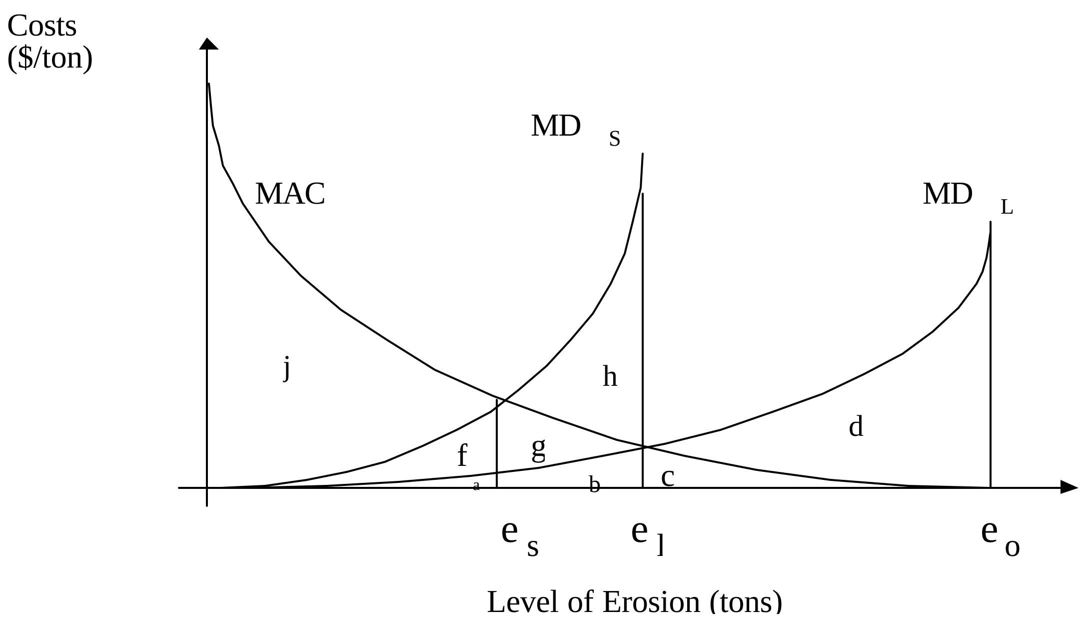

Figure V-4. Marginal damages (MD) and marginal abatement costs (MAC) of soil erosion

As the level of erosion increases, the private marginal damages to the landuser (MD_L) increase. That is, an additional unit of erosion, measured in terms of tons of soil loss for example, results in greater additional damages to the landuser. If there is no erosion control and its level reaches the point e_o, then total damage to the landuser is the area (a+b+c+d). Total damages from erosion can be reduced if the farmer undertakes soil conservation practices. The cost of implementing soil conservation measures is represented in Figure V-4 by the curve labeled MAC (marginal abatement cost), which indicates increasing additional costs of each unit of erosion reduced. Similar to the marginal damage curve, the area under the curve MAC represents the total cost of reducing erosion from e_o to a lower level. Thus, reducing erosion to zero would cost the area represented by (a+b+c+f+g+j). As it can be seen from the figure, the costs of reducing erosion to zero are greater than the benefits to the landuser if the area (f+g+j) is greater than area *d*, which would not be an appropriate decision for a profit maximizing landuser.

In this case the optimal level of erosion for the landuser would be the point where net benefit, represented by the area (d), of reducing erosion from e_o is maximized. This happens in e_l in the Figure. In addition to the damages to the landuser, off-site effects of erosion can be represented by the marginal damages to society (MD_S). When both, on-site and off-site effects are added up, the optimal level of erosion would be e_s, rather than only the optimal level for the landuser (e_l). Thus, reducing the level of erosion from e_l to e_s increases the benefits to society represented by area (h).

The policy question is how to move from e_l to e_s since the rational landuser would reduce erosion to the level indicated by point e_l? Perhaps, better information or education could only be expected to get producers to move from e_0 to e_l (Huszar, 1999). However, Figure V-4 shows that additional benefits for landusers derived from reducing erosion from e_l to e_s and represented by the area (b) are lower than the additional costs represented by the area (b+g). This means that the profit maximizing behavior of the landuser is an incentive for him or her to reduce erosion just to e_l. Additional incentives must be provided to further reduce erosion up to the point e_s.

In order to induce landusers to undertake sustainable land management practices that lead to a social optimum, society must provide an incentive or subsidy (Huszar, 1999). According to Figure V-4, the incentive must be equal to the area (g), which equals the amount by which the additional costs exceed the additional benefits to the landuser of reducing erosion from e_l to e_s. On the other hand, society should be willing to provide an incentive at least equal to the area (g+h), which represents the additional benefits to other members of society. In fact providing an incentive greater than the area (g+h) would make both the landuser and society better off. If this is the case, such an incentive is economically justified (Huszar, 1999).

Soil conservation incentives

The literature on economic incentives for soil conservation is quite vast. Most authors agree that incentives vary from region to region and even from country to country. What seems to be an effective incentive in one place could be counterproductive somewhere else (Barbier, et.al, 1999; Sanders, et.al, (eds) 1999; Sanders and Cahill, 1999). Incentives have been defined in various ways. Some distinguish between incentives and subsidies. Sanders and Cahill (1999) argue that an incentive is something that induces a person to act towards some specific direction, while a subsidy is a payment or service provided to reduce the cost or raise the return on an activity. However, in practice it is difficult to differentiate between them. Incentives can be divided in two broad categories: direct and indirect. *Direct incentives* are those that can be provided in cash in the form of wages, grants, subsidies and loans, in kind to the provision of food aid, agricultural implements, trees, livestock, seeds, etc, or as a combination of the two. *Indirect incentives* include fiscal and legislative measures such as tax incentives; artificially reduced or increased input prices as well guaranteed land tenure arrangements (Sanders and Cahill, 1999).

When should incentives for soil conservation be used? Sanders and Cahill (1999) argue that incentives can be broken down into four categories as Table V-11 shows and should be implemented accordingly.

Table V-11. The effects of soil degradation

	On-site	**Off-site**
Economic	1	2
A. Uneconomic	3	4

On-site economic (1) means that the farmer perceives the preventive measures of conservation to be cost-effective. This means that the landuser is willing to pay the costs to undertake conservation practices by him. In that case the incentive can be reduced to one of extension and provision of information to the landuser and no other incentive should be needed. For example, it can be suggested to grow more perennials rather than annual crops (Sanders and Cahill, 1999).

Off-site economic (2) means that the task is again one of extension advice. If the landuser perceives that the action to undertake is cost-effective then no other incentive than extension should be offered. For example, if the off-site problem is on another farmer's land, it may be possible to safely divert unwanted flows of runoff by advising the on-site landuser to change from clean cultivation to minimum cultivation.

On-site uneconomic (3) is defined when the landuser perceives that the treatment is not worthwile, for example, an expensive terracing system. In this situation, Sanders and Cahill (1999) consider three possibilities: 1) the landuser treats the problem for the public good but contrary to his own economic advantage. 2) the landuser is forced to undertake the required measures (regulation), and 3) the landuser is subsidized to do what he is required to do through one or more incentives.

Finally, off-site uneconomic (4) occurs when the land degradation has an off-site effect and the on-site measure is uneconomic for the landuser to implement. Here the owner of the field is not responsible for the problem (for example a road construction generating runoff and producing and extensive gully system in a farmer's field) and would gain little or nothing by undertaken any action. Under these conditions, it would seem only fair to subsidize the action to be taken with public money (Sanders and Cahill, 1999).

Nevertheless, this distinction among incentives for soil conservation should also consider the poverty level of landusers. This is the case in most developing countries where soil degradation takes place in poor rural areas and the small farmers not only have poor information and education but also lack of financial resources and access to credit to undertake any conservation practices even if they perceive the action as "on-site economic". It is important to differentiate between rich and well-educated and poor and low-skilled farmers. The latter probably need more than just extension and information incentives. They probably need financial support through a subsidized fund to be able to undertake any soil conservation measure. This seems to be the case in the Rionegro watershed, as it will be discussed later in this chapter.

In terms of implementation of incentives for soil conservation the literature recognizes two issues to be addressed. One is the time length for the incentive and the second one is the availability of public funds to support farmers for undertaking conservation measures, particularly in developing countries. Huszar (1999) points out the case of Indonesia in which the government embarked on a national program of land rehabilitation and soil conservation in the mid 1970s. Starting in the 1980s, there have been a number of projects in Java whose costs vary from US$20 million to US$50 million. The basic approach of those projects has been to establish model farms units and to introduce a package of upland agricultural inputs and conservation practices emphasizing the construction of bench terraces and the use of new cropping patterns, seed varieties and inputs of chemical fertilizers and pesticides. Subsidies, either in cash or in kind, have been provided for the construction of bench terraces and inputs. The goals of the program have been to increase farm production, and therefore incomes, while reducing soil erosion (Huszar, 1999). In fact, income increased and soil erosion was reduced, however, four years after the subsidy program ended, farmers were worse off than the farmers out of the project. Huszar (1999) explains that one reason could be that terracing reduces plantable land area and as project farms return to conventional cropping they are at a temporary disadvantage. In many cases terraces were not maintained and even intentionally destroyed. This experience is calling the attention for the sustainability of incentive programs and policy implementation.

A second case presented by Huszar (1999) takes place in the Chaco province in Argentina. This case reflects the budgetary constraint, which is a common bottleneck for soil conservation and sustainability programs in developing countries. The Gran Chaco is a natural region of about one million sq km extending over parts of Argentinca, Bolivia and Paraguay. It is considered the second largest natural biome in South America after the Amazon. The original landscape was mostly grasslands intercropped with hardwood forests. However, today, the Chaco is being rapidly altered and degraded basically because overgrazing and deforestation carried out by "campesino" settlements. An important portion of the region has been converted into unproductive shrub land with significant soil erosion (Bucher and Huszar, 1997). It has been demonstrated that some alternative management techniques are capable of reversing the degradation process. The approach is to integrate the production of timber, charcoal and beef. A key issue to this management system is the use of fencing to regulate the grazing of cattle and goats and allow for the natural regeneration and maintenance of grasses and trees. Restoration of natural cover has significantly reduced erosion and improved the water regime.

Studies at one of the experimental stations in the Chaco region (Los Colorados) show that progressive deterioration of the resource base results in a reduction of annual net income for the present land management exercised by *campesinos* from high of approximately US$15 per ha to as little as US$5 per ha. With the alternative management practice the annual net returns were increased up to a sustainable level of US$30 per ha. However, the initial investment, particularly for fencing, resulted in a negative net return of nearly 10 years. Operating with negative returns is not a viable option for subsistence landusers. One obvious measure to reduce negative returns to the *campesinos* is the use of subsidies. These subsidies can be justified in terms of the external benefits produced for society in general by maintaining the ecological system of the Chaco (Huszar, 1999).

However, as in most of the world, there is a growing tendency to abandon subsidies and other government incentives to favor the role of the free markets. As a consequence of the so-called structural adjustment policies in developing countries, achieving sustainable management practices through subsidies is getting more difficult.

Policy implications for the Rionegro watershed

As it has been shown in Chapter IV and from the LP model, small farmers in the Rionegro watershed and society would be better off, in terms of increasing income and reducing erosion and runoff, if they shift from the traditional agriculture system based on shifting cultivation (slash and burn) to an alternative management practice based on agroforestry systems. Table V-12 shows the net present value of revenues under different

Table V-12. Rionegro watershed. Net present value of income

Activity	Discount Rate		
Slope 20%	**6%**	**15%**	**25%**
Shifting Cultivation	54,110	23,241	14,350
Agroforestry	73,306	29,399	17,548
Conversion 20 years	53,674	20,865	13,313
Conversion 40 years	54,972	23,176	14,344
Conversion 60 years	54,464	23,238	14,350
Slope 30%			
Shifting Cultivation	52,359	22,660	14,040
Agroforestry	72,600	29,385	17,597
Conversion 20 years	52,570	20,307	12,918
Conversion 40 years	53,252	22,594	14,034
Conversion 60 years	52,840	22,658	14,040
Slope 40%			
Shifting Cultivation	49,608	21,648	13,498
Agroforestry	69,623	28,129	16,836
Conversion 20 years	50,776	19,628	12,538
Conversion 40 years	50,628	21,602	13,494
Conversion 60 years	50,061	21,646	13,498

slopes and discount rates. It can be seen that agroforestry represents the highest net present value of revenues. If this is the case, one could expect that the rational farmer would shift from the less to the highest profitable practice. However, farmers in the region continue practicing shifting cultivation (Alviar, 1983). The question is how to make small farmers willing to convert land from shifting cultivation to agroforestry systems.

Given that rural population in Colombia, and in particular in this region, is characterized by low income farmers, and subsistence economic activities, an incentive program must be implemented to improve soil conditions, reduce erosion and increase income and life conditions. Barbier et.al, (1999) argues that in many developing countries, farmers lack access to information, extension services, credit, and in many cases property rights are ill-defined. Even if the small farmers perceived the conservation measures as cost-effective, according to Table V-11 above, and given their precarious income, an incentive program that goes further than just extension is needed.

Taxes and subsidies are mechanisms to achieve desired policy objectives or induce a particular behavior to economic agents, households or firms. However, taxes and subsidies are very sensitive matters, particularly in developing countries where budgetary constraints are in the first place. Something must be done in order to induce farmers in the Rionegro watershed, and also in other eroded regions within the country, to gradually move from the most erosive agricultural practices to the less erosive ones.

Agricultural policies in Colombia to help small farmers to improve their economic and social conditions have been concentrated on extension services (Garfield, et.al, 1995). Small farmers are defined as those with less than two family agricultural units. The definition of this unit is based on the requirement of extra family labor and the share of family income. However, Colombia has radically modified the way extension is delivered to small farmers. The most important transformation of extension has been the decentralization of the services from the national level to the municipal level. Several decrees, laws and regulations were issued during 1989-1993 in order to make each municipality capable to create its own extension office, which has been named UMATA (Unidad Municipal de Asistencia Técnica Agropecuaria). The main purpose of the UMATA is to provide technical assistance to small farmers on agricultural, livestock, fishery, environmental, social, and gender issues. Financially, the UMATAs are funded by the municipal government, which receives budgetary transfers from the central government, and also has access to grants from the national cofinancing system (Garfield, et.al, 1995). Comparing the results from the previous centralized extension service to the UMATA, one can see an impressive progress. However, the criticism arises when some argue that agricultural extension services in Colombia have been mainly focused on promoting the use of fertilizers and pesticides not always generating the best results in terms of environmental quality (Alviar, 1983; Garfield, 1995). Table V-13 shows the impact of the UMATA system.

Table V-13. Quantitative impact of the UMATA system

	Previous Centralized System	New Decentralized System	Difference %
Number of technical or professional staff	800	3500	3.38
Covered Municipalities	250	1040	3.16
Beneficiaries per technical staff	156	129	-0.17
Total cost per year	US$12,000,000	US$38,820,000	2.24
Yearly cost per beneficiary	US$96	US$86	-0.1
Beneficiaries	125,000	450,000	3

Source: Garfield, et.al, 1995

As the table shows, the UMATAs are providing free extension to some 450,000 small farmers, which represent 28% of the estimated total. However, Garfield et.al (1995) argue that the major challenge faced by the new system is quality rather than coverage. In fact, to assure the quality of more than 1,000 UMATA's is far from simple and the technical quality of the service runs at risk of deterioration. Despite the increasing aggregate resources devoted to the UMATA system, is not easy for each municipality to assure and maintain funds to accomplish all the tasks that the UMATAs are supposed to accomplish including environmental concerns. In addition, it has been the case that after the decentralization process the risk of political interference of the municipal government is strong. As a result, extension agents of the UMATAs are too often changed for political reasons, such as after municipal elections. In fact, improving quality and assuring continuity of the extension service is a real challenge for the municipal authorities in Colombia.

One of the greatest difficulties for developing countries to implement an incentive system for soil conservation is to guarantee funds and also to assure continuity of the program at least until the main goals have been achieved. Of course the availability of financial resources is a critical factor. Given the current fiscal rigor, it is not easy to find governments, which are willing to spend such resources. If governments are willing, it could be short term and temporary incentive programs (Ramirez, et.al, 1992).

Given that the Rionegro watershed provides water to produce approximately 30% of the total hydropower countrywide (Cornare, 1998), one could think that there should be a sort of compensation for those small farmers protecting the steep land in order to maintain the water availability for hydropower generation. Following this rationale, the national government issued the Law 99 of 1993. This law states that the hydropower companies located in any specific municipality must transfer 3% of their gross sales per year to the municipal budget. In 2003 the transfers to the municipalities located in the Rionegro watershed accounted for US$6.3 million (Interconección Eléctrica S.A, 2003). However, these transfers go to the general municipal budget and not necessarily to soil conservation programs. On the contrary, in most cases, the municipal budget is spent in the urban area because the majority of the population is located there. It would make more sense if at least a portion of the transfers made by the hydropower companies went to specific projects in each municipality in order to fund soil conservation activities and sustainable agriculture. There seem to be an opportunity to get financial resources to be addressed to erosion control through the promotion of more sustainable practices such as agroforestry. This choice has not been deeply explored and it is one of the main recommendations derived from this research.

The resources coming from the hydropower companies could be spent in hiring better-qualified extension agents for the UMATAs, wages for building terraces in farms with slopes greater than 20%, improving cropping techniques, and buying seeds, among other things. It could be also spent in subsides for planting trees as part of the agroforesry system to partially compensate the poor farmer's decision to embark in forest plantation projects. The main advantage of this proposed fund is that it overcomes the uncertainty for the continuity of funding since the Law 93 already guarantees the money and laws do not change as often as a temporary subsidy program. Rather than money, this a matter of efficient allocation of financial resources.

This chapter has presented the main results of an LP model that, despite of data limitations, shows the agroforestry and natural forest activities as the optimal allocation of land in order to reduce erosion and runoff, and improving life conditions since the net present value of revenues from agroforestry is higher than that of shifting cultivation. An incentive to make farmers willing to convert their lands has been proposed, based on the resources given by hydropower companies.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main results from this research show that the shifting cultivation scheme practiced in the Rionegro watershed generates the highest level of erosion for all land classes of 20%, 30%, 40% slopes, followed by agroforestry and natural forest. At the same time, runoff is also higher for shifting cultivation since the soils under this practice have been denuded from its original vegetation cover. Given the steepness of the land and the amount of precipitation in the study region it is predictable that erosion and runoff represent critical environmental effects that may compromise the sustainability of agriculture and also the welfare of the rural population living in this region unless some sustainable practices are implemented.

Slope is a key variable for all results. Thus, the higher the slope the more erosion and runoff are observed in the region as well as lower yields and organic carbon accumulation, particularly for shifting cultivation. Two main conclusions can be derived from the EPIC simulations. 1) The results are consistent with the main findings in the related literature in the humid tropics. 2) The most effective management practice against runoff and, soil and organic carbon losses are natural forest and agroforestry.

The economic analysis shows higher net present values of income for agroforestry comparing all slopes and activities. This is due to the inclusion of commercial trees such pine, which aggregate more income to the families in the region, as well as higher yields due to the soil protection exerted by *Sesbania* woody plants.

On the other hand, the results of the LP model, in terms of the optimal allocation of land among management practices depend upon the discount rates used and also upon the maximum erosion rates. Thus, the lower the discount rate and the lower the erosion rate the optimal land distribution favors natural forest for all classes of lands and also favors the conversion from shifting cultivation to agroforestry after twenty years. When the erosion rate is increased to tolerate more tons per hectare, the optimal allocation of land favors agroforestry for all land classes. When the discount rate gets higher, meaning more value to the present, and the erosion rate is higher, lands under shifting cultivation appears to be allocated under slopes of 20% and 40%.

Recommendations

A sustainable management system for land use in the Rionegro watershed must accomplish the following goals. 1) maintain the long-run biological and ecological integrity of natural resources. This means that soils must preserve the organic carbon content in order to guarantee soil productivity. 2) sustain a desirable level of support to farm and community well-being. 3) contribute to increasing quality of life.

Soil degradation, a consequence of land misuse, can be minimized if land is used for whatever it is capable of and by using practices of soil and crop management that are ecologically compatible. Pursuing sustainable agriculture in tropical countries like

Colombia assures not only the small farmer's survival, but also guarantee better life conditions, and strengthen rural development. The concern about hiring labor in the most erosive practices should be dissipated if the government is willing to implement policies that contribute to develop labor intense activities associated with less erosive practices. For example, agroforestry could be both soil protective and also labor intense if more value added activities are developed such as agroindustry and timber production. Long-term policies to reduce rural poverty such as better education and health must be implemented in order to developed more value added activities coupled with sustainable practices.

A system of incentives to promote soil conservation must be implemented. The fund proposed in this research would allow the small and poorest farmers in the study area to develop pilot agroforestry projects in order to increase their income. In doing so the extension service must be improved by hiring better qualified extension agents who are able to guide the process of gradually converting land from the most erosive practice to the less erosive.

Antioquia and Colombia in general are in great need of improving the databases related to the natural resource sector. Data limitation is a bottleneck for researchers and policy makers to do meaningful studies. In most cases data do not exist or when it exists there is an institutional weakness that makes the process of getting information unnecessarily complicated.

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APPENDIX

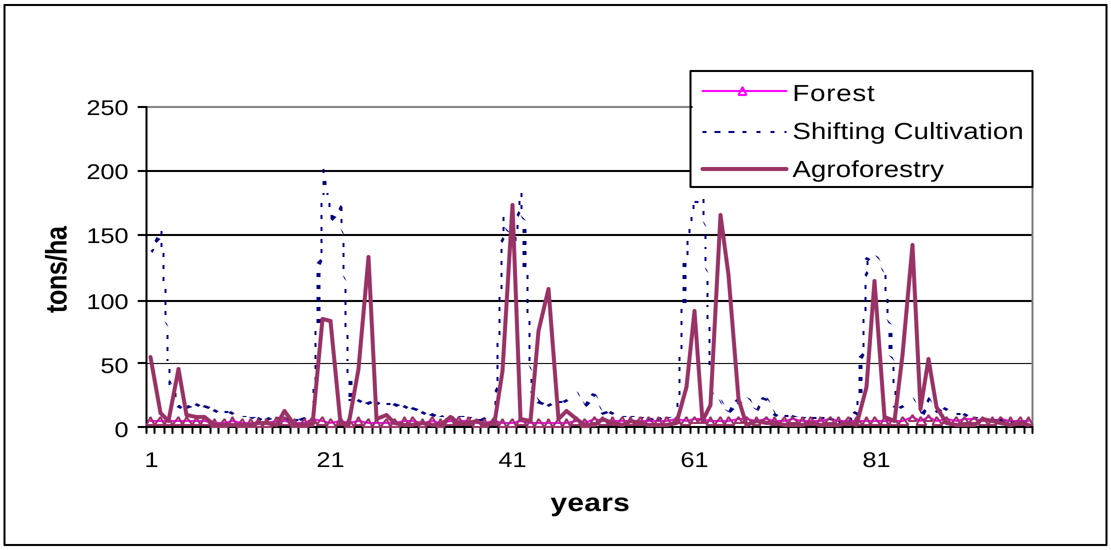

Figure A-1. Rionegro watershed. Erosion under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 30%

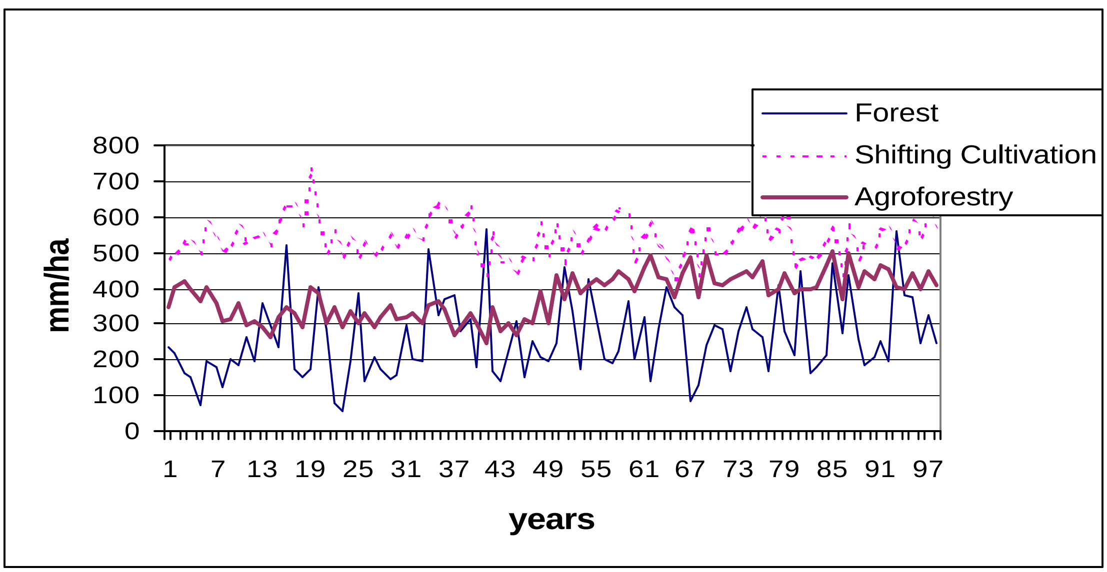

Figure A-2. Rionegro watershed. Runoff under forests, shifting cultivation, and agroforestry Soil type TE. Slope 30%

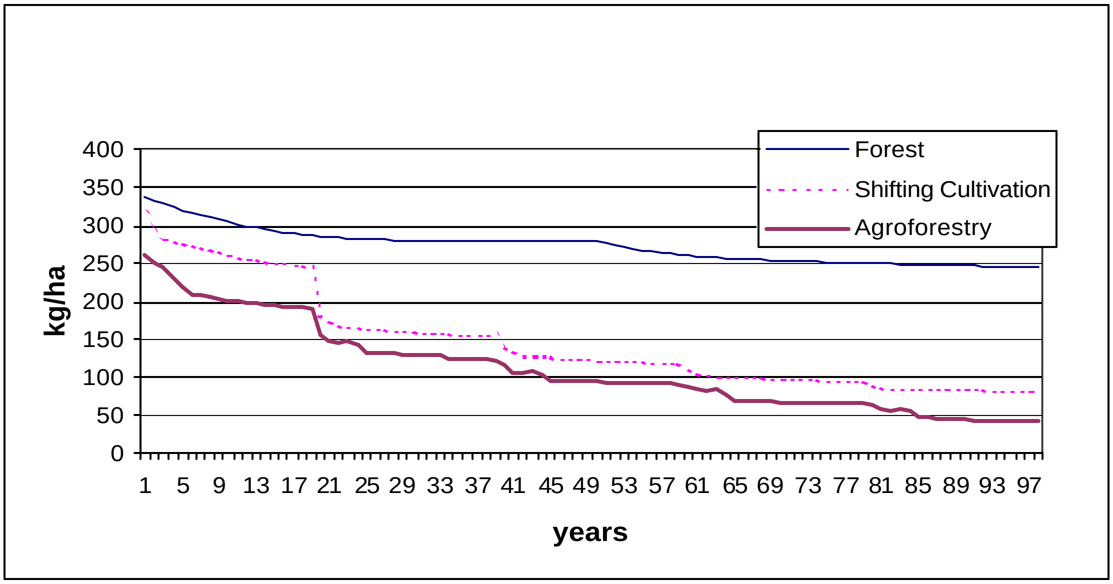

Figure A-3. Rionegro watershed. Organic carbon under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 30%

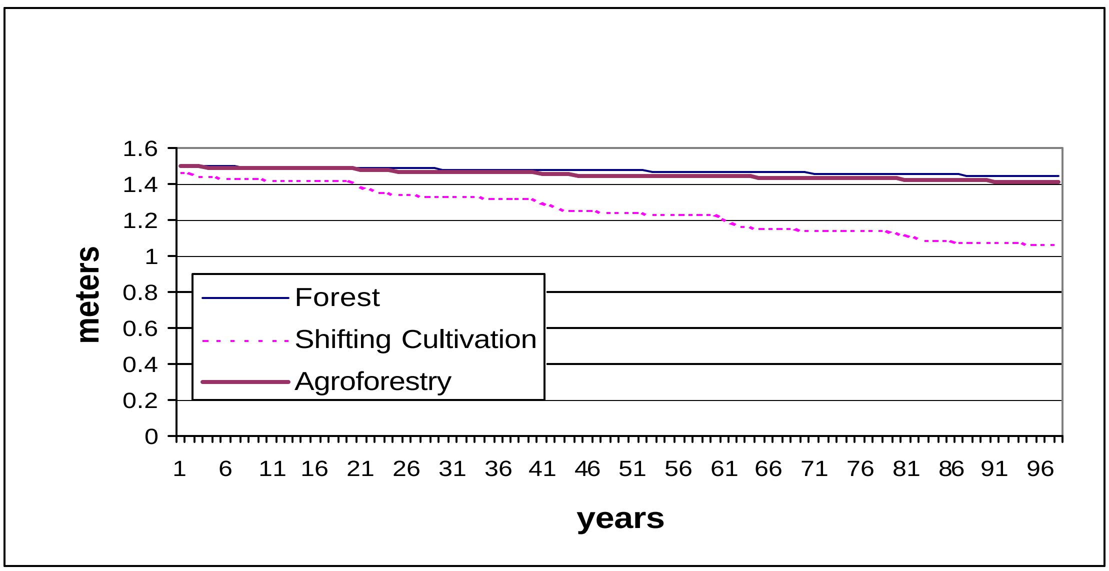

Figure A-4. Rionegro watershed. Soil depth under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 30%

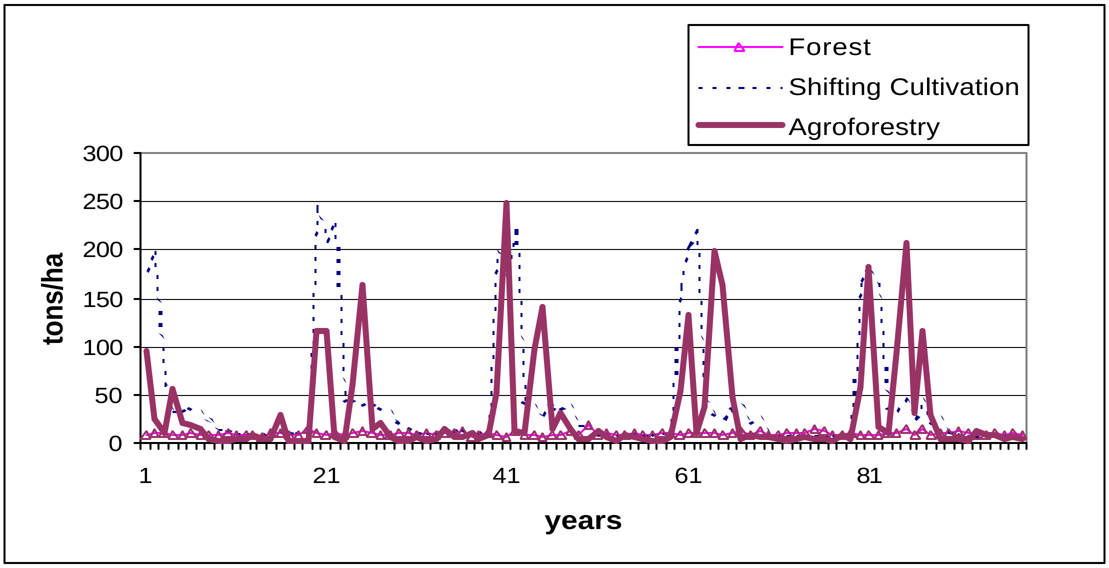

Figure A-5. Rionegro watershed. Erosion under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 40%

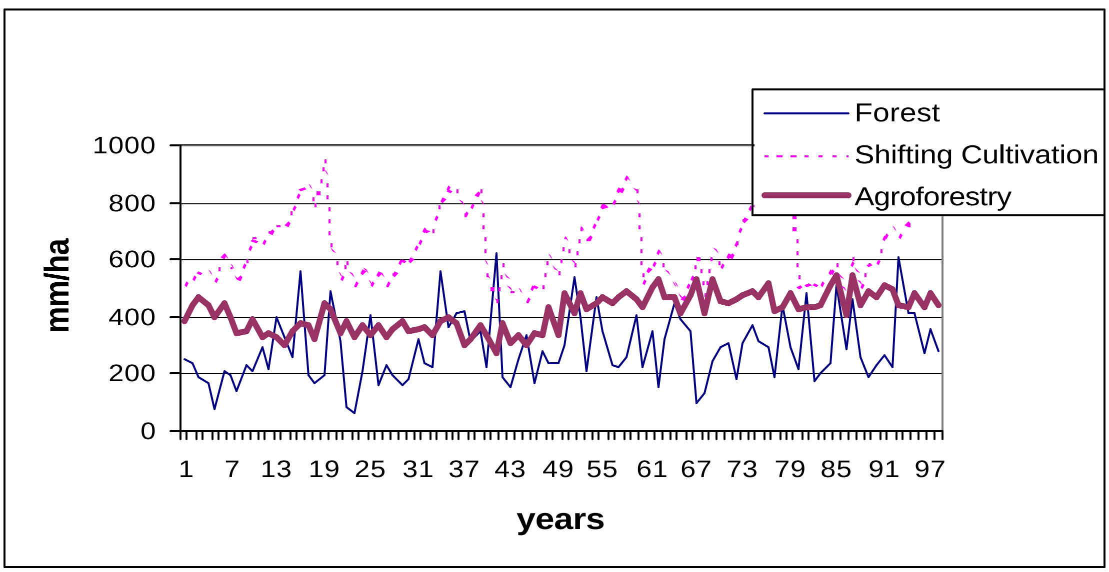

Figure A-6. Rionegro watershed. Runoff under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 40%

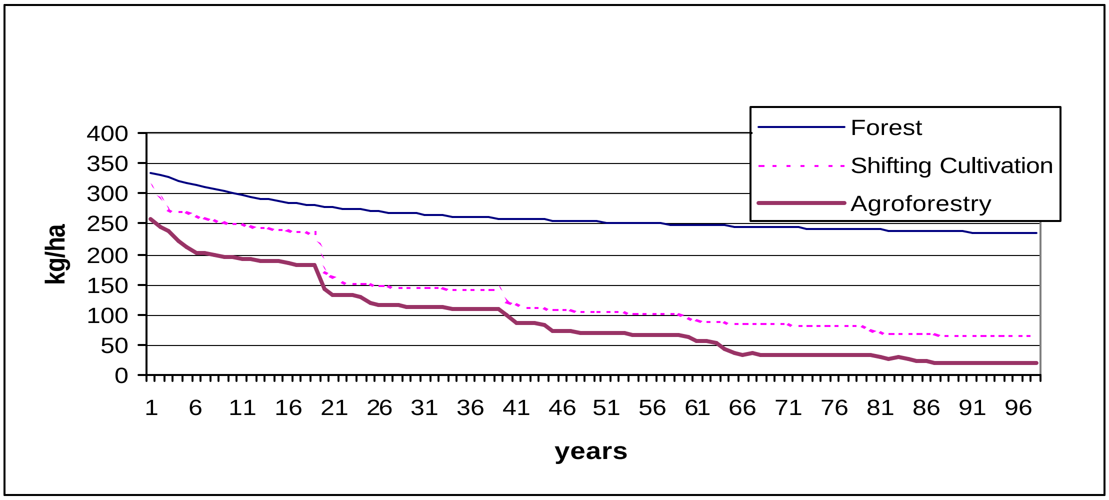

Figure A-7. Rionegro watershed. Organic carbon under forest,shifting cultivation, and agroforestry. Soil type TE. Slope 40%

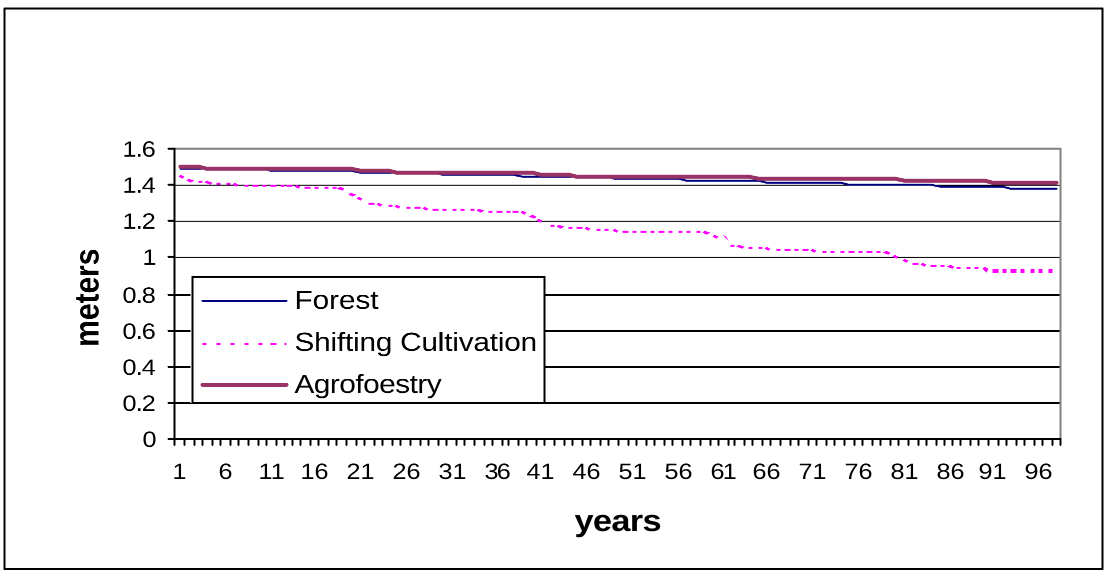

Figure A-8. Rionegro watershed. Soil depth under forest, shifting cultivation, and agroforestry. Soil type TE. Slope 40%

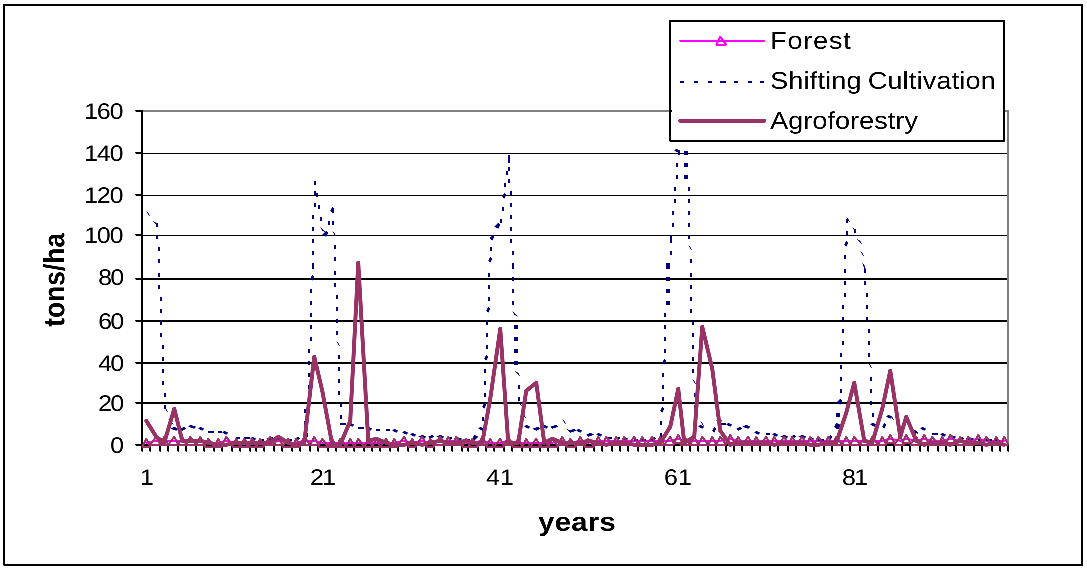

Figure A-9. **Rionegro watershed. Erosion under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 20%**

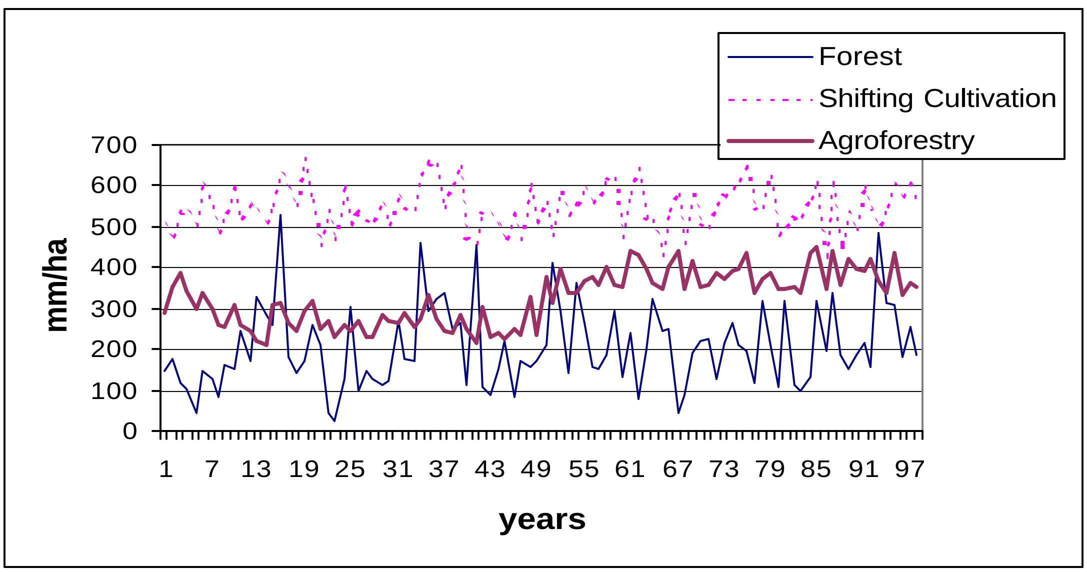

Figure A-10. **Rionegro watershed. Runoff under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 20%**

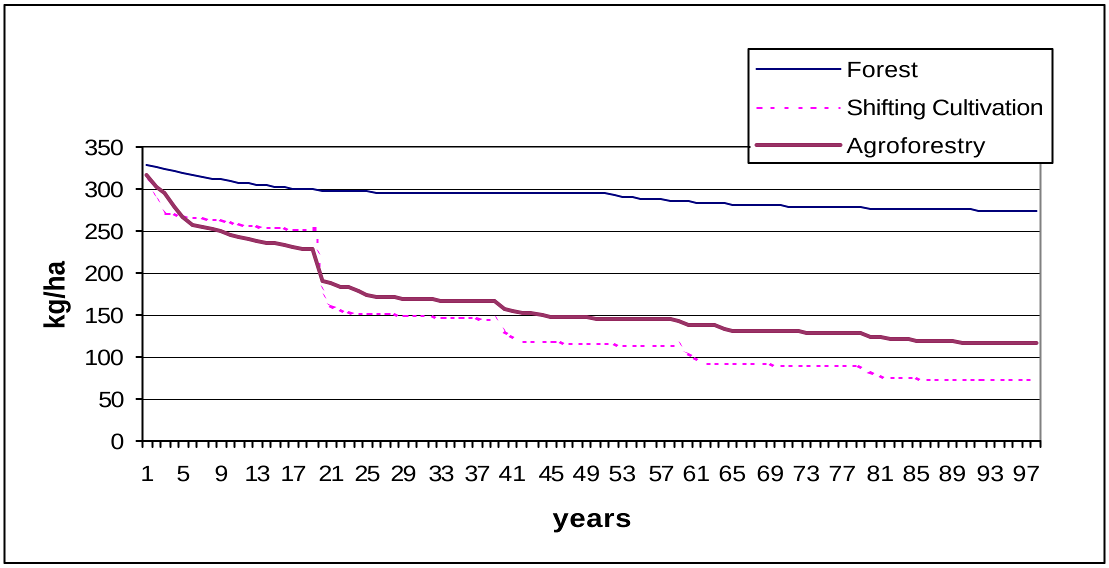

Figure A-11. Rionegro watershed. Organic carbon under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 20%

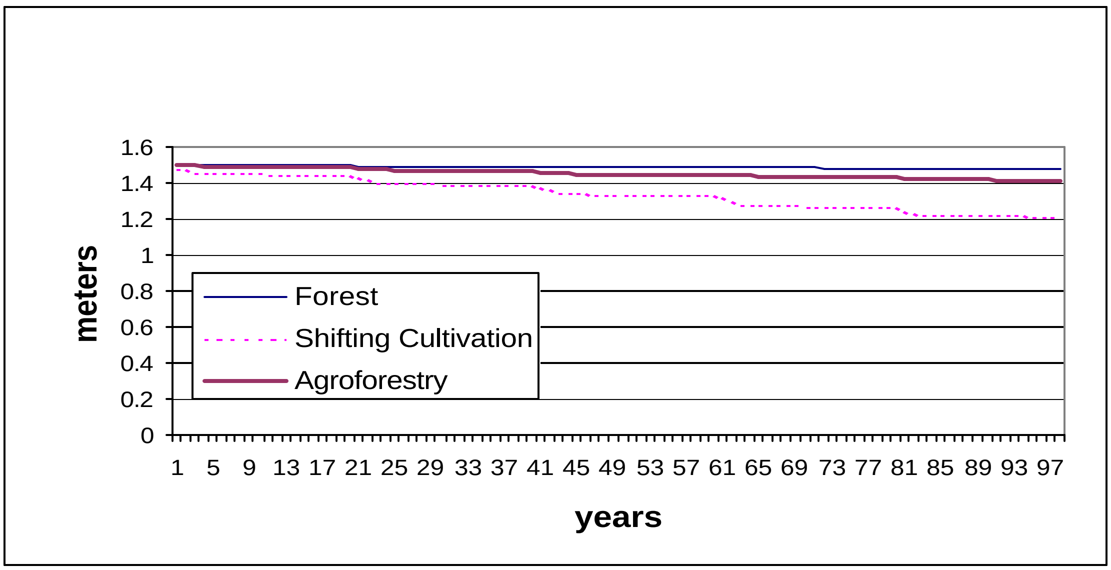

Figure A-12. Rionegro watershed. Soil depth under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 20%

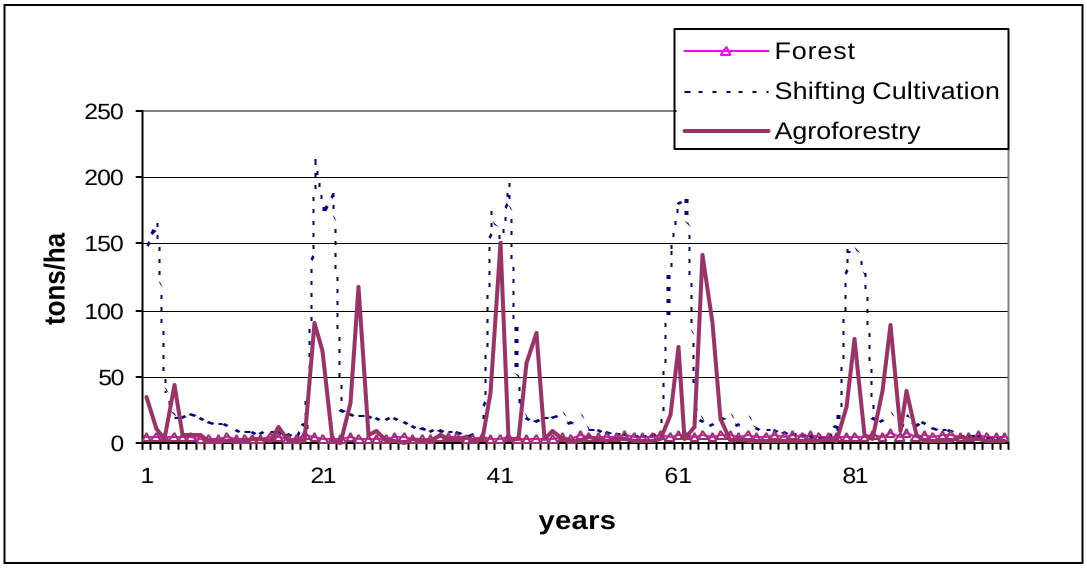

Figure A-13. Rionegro watershed. Erosion under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 30%

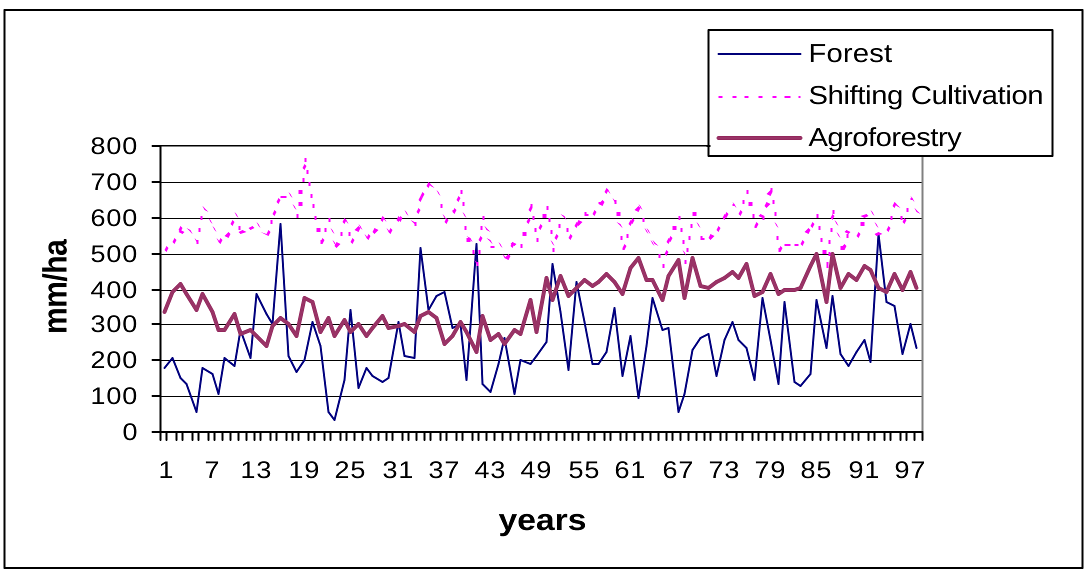

Figure A-14. Rionegro watershed. Runoff under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 30%

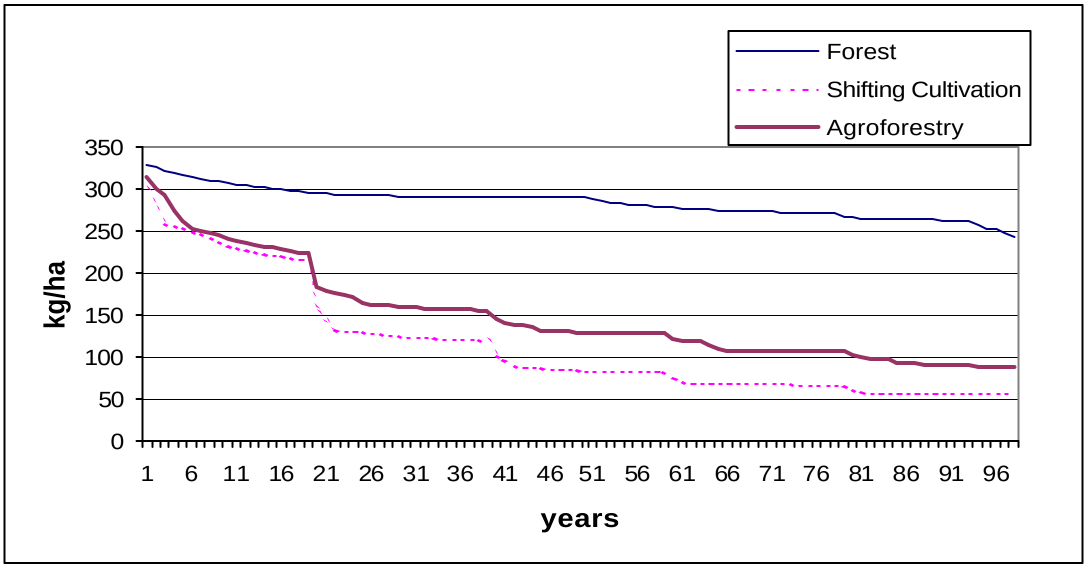

Figure A-15. Rionegro watershed. Organic Carbon under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 30%

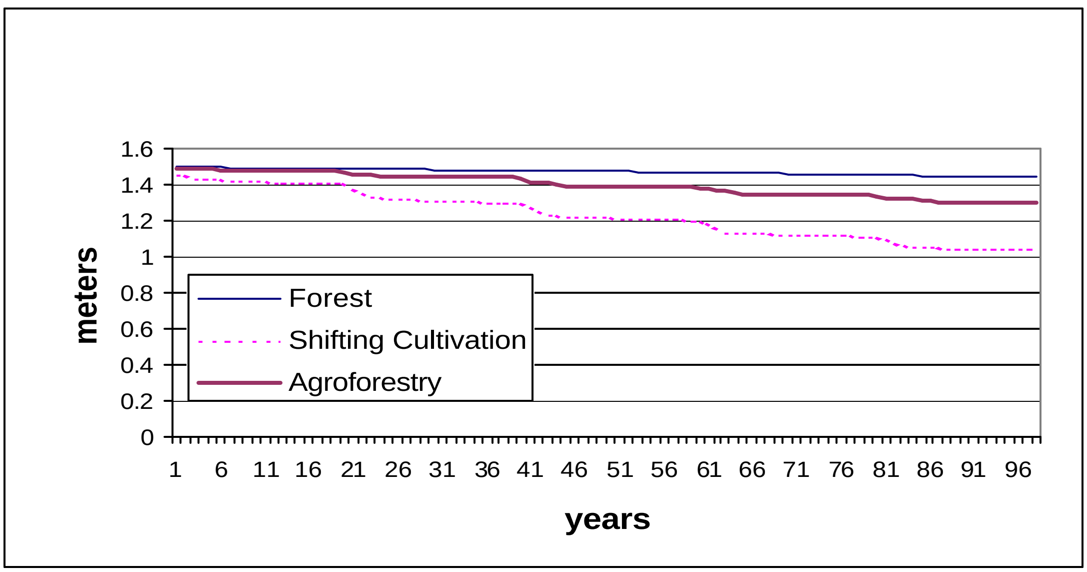

Figure A-16. Rionegro watershed. Soil depth under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 30%

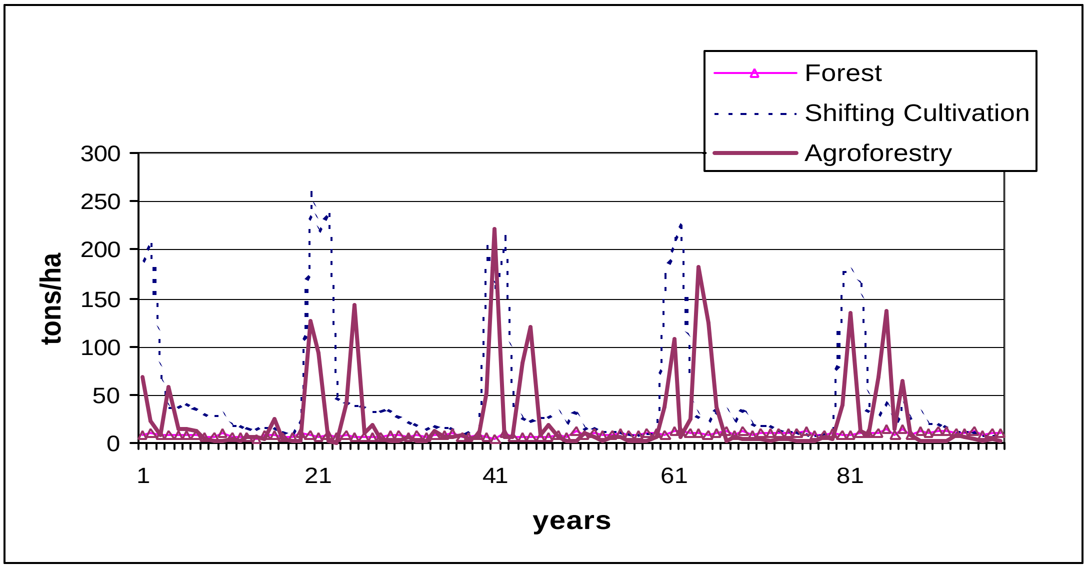

Figure A-17. Rionegro watershed. Erosion under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 40%

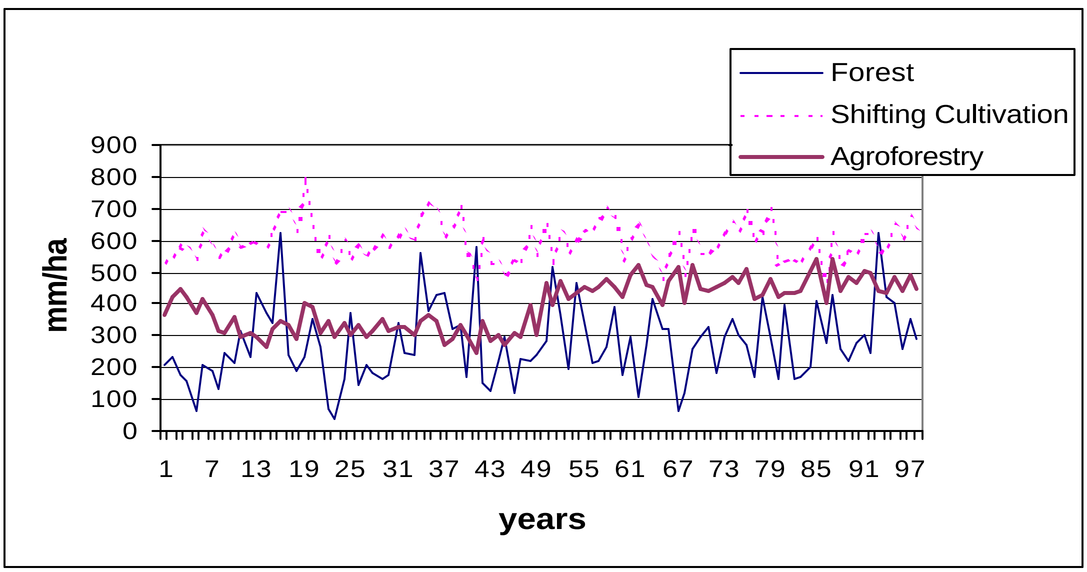

Figure A-18. Rionegro watershed. Runoff under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 40%

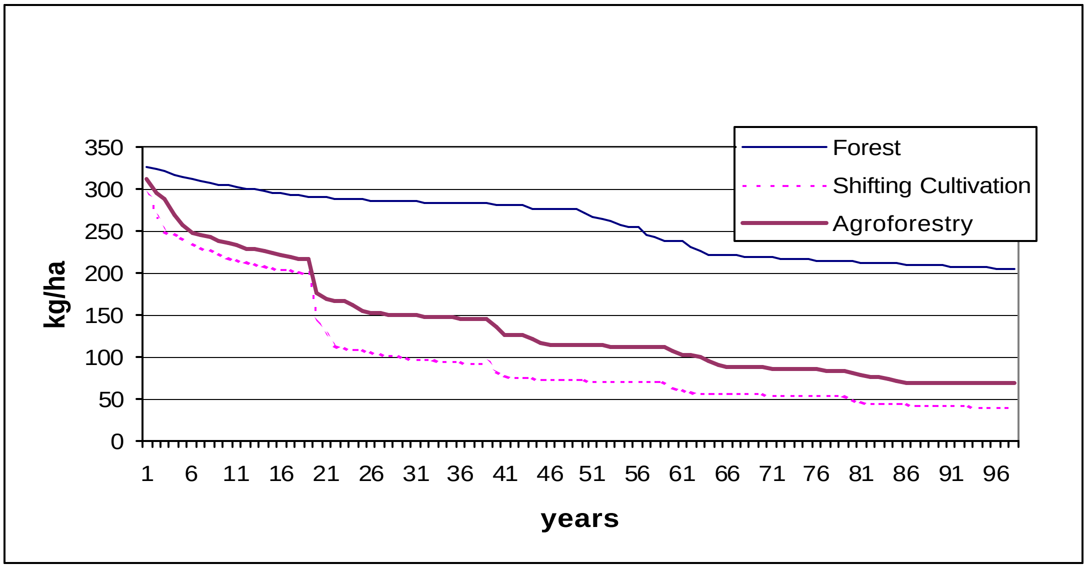

Figure A-19. Rionegro watershed. Organic carbon under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 40%

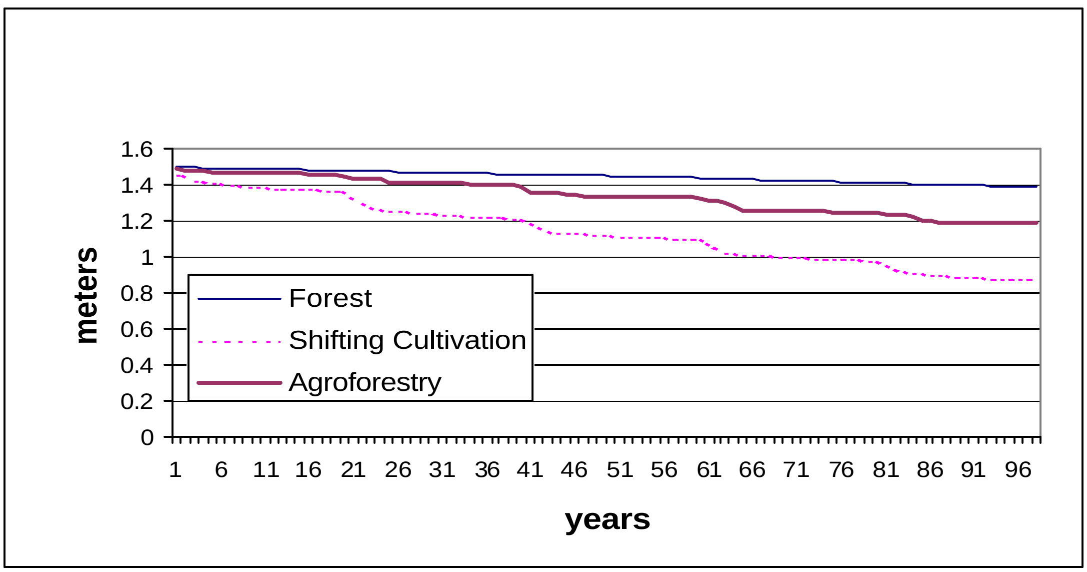

Figure A-20. Rionegro watershed. Soil depth under forest, shifting cultivation, and agroforestry. Soil type SV. Slope 40%

VITA

Mauricio Alviar

Candidate for the Degree of

Doctor of Philosophy

Thesis: ECONOMIC AND ENVIRONMENTAL EFFECTS OF LAND USE ON WATER YIELD AND SEDIMENT: A CASE STUDY IN COLOMBIA

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Medellín, Colombia, August 27, 1964. Raised in the same city in a family made up by my parents Jairo and Esther (q.e.p.d), my unforgettable aunt Lia, my brother Juan Fernando and my sisters Lia Isabel, Cecilia and María Victoria.

Education: Graduated from Colegio Fray Rafael de la Serna (High School), Medellín, Colombia, in December, 1981; received Bachelor degree in Economics from Universidad de Antioquia in August, 1989; completed requirements for the Master of Science degree at Duke University, May, 1995; attended the Ph.D. course in Natural Resource Economics at Gothenburg University in Sweden in May and June, 1998; participated in the International Conference on Conservation and Development, Quito (Ecuador) in May, 1999; completed the requirements for the degree of Doctor of Philosophy at Oklahoma State University in July 2004

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Name: Mauricio Alviar Date of Degree: July, 2004

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of the Study: ECONOMIC AND ENVIRONMENTAL EFFECTS OF LAND USE ON WATER YIELD AND SEDIMENT: A CASE STUDY IN COLOMBIA

Pages in Study: 152 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: This dissertation covers a set of watershed management problems faced by social planers in the eastern part of the province of Antioquia, (Colombia). This dissertation aims to shed light on the sustainable management practices in the Rionegro watershed of Antioquia by approaching different alternatives of land use and their economic and environmental effects on water yield and soil erosion. Natural forestry, shifting cultivation, and agroforestry are analyzed according to the physical, climatic, and economic characteristics of the watershed.

Findings and Conclusions: Using the Erosion Productivity Impact Calculator (EPIC) model, different simulations were performed in order to estimate the environmental effects of three main activities: natural forest, shifting cultivation, and agroforestry in terms of erosion, runoff, and organic carbon. Soil classes and different slopes were considered for simulating the environmental effects of land use. From the outcomes of EPIC, a linear programming model was developed to maximize the net present value of revenues derived from the agricultural activities. Erosion, runoff, labor, and land constraints were defined to estimate the model. Shifting cultivation appears to be the most erosive land practice. The less erosive land practice is natural forest followed by agroforestry. The dissertation recommends the implementation of an incentive system in order to encourage subsistence farmers to convert their lands from shifting cultivation to agroforestry.

Adviser's Approval Dr. Arthur L. Stoecker