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Assessing the Potential for Carbon Sequestration at Three Forest Fire Restoration Sites in Mexico

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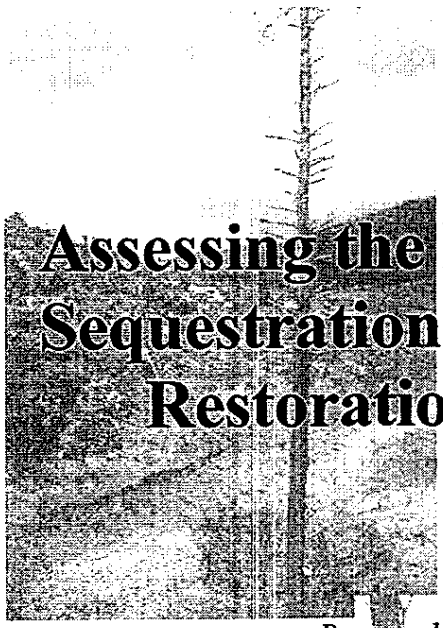

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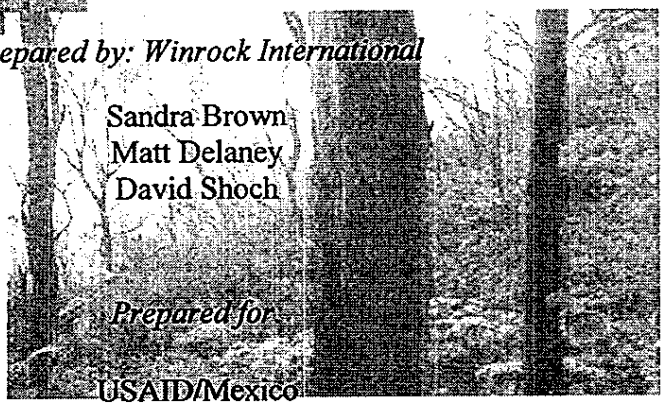

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Executive Summary

In 1998, Mexico experienced some of the worst forest fires in its history with more than 200,000 hectares (ha) burned over a seven-month period. USAID/Mexico and SEMARNAP are collaborating to address the damages resulting from these fires, and their implications for global climate change. As part of this collaboration, in September and October of 2000 Winrock International conducted visits at three sites affected by the 1998 wildfires (Reserva de la Biósfera Mariposa Monarca in the State of Michoacán, the Sierra de Arteaga in the State of Coahuila, and the Reserva El Ocote in the State of Chiapas) to assess their potential to capture and retain carbon. Reforestation activities are underway at these three sites as a first step to restore the forests in the areas. These three areas are subject to different levels of threat from fire and all are subject to other threats and pressures (Table 1).

Table 1
Summary of threats to carbon stocks in the project areas

Threats	Project areas		
	Reserva El Ocote	Reserva Mariposa Monarca	Sierra de Arteaga
Fire	low	moderate	high
Land use change	high	moderate	low
Logging	moderate	high	low

Wild fires in the Sierra de Arteaga were severe and almost all standing trees (90 percent +) were killed in a 5,000-hectare area. PRONARE is conducting a reforestation effort in the burned forest with mixed success. The potential carbon sequestered over 30 years from the planned reforestation effort ranges from 17.5 to 93 t C/ha (Table 2), with the range of estimates varying with survivorship of planted trees (40 to 100 percent surviving) and growth rates (0.6 to 0.8 cm/yr). Without reforestation and natural regeneration by mattoral vegetation, the amount of carbon sequestered varies from 6.5 t C/ha (15 year fire cycle) to 27 t C/ha (no fire during the 30 year period). The total net amount of carbon that could be sequestered (with restoration activities minus natural regeneration) would range from –10 (low growth rate and low survivorship) to 89 t C/ha. Over the whole project area of about 5,000 ha, this is equivalent to 50,000 to 452,000 tons of carbon (t C).

For the Reserva El Ocote, forest fires affected about 23,000 ha of forests in 1998, and damage caused about 30 to 80 percent of standing trees to be killed. Natural regeneration witnessed in the burned areas was considered sufficient to restore forest carbon. Although the area was aerially seeded there was little evidence that these seeds had germinated and

the burned areas were dominated by early pioneer species. Protection of the burned areas to allow for natural regeneration and prevention of deforestation would sequester and retain 110 to 113 t C/ha in vegetation and an additional 8 t C/ha in soil (Table 2). Protection of an assumed total deforestation of 3,600 to 3,900 ha of burned forest areas followed by natural regrowth over the 30 year period could generate 424,000 to 468,000 t C. In addition to capturing carbon from restoration efforts in Reserva El Ocote, there are other activities that could generate carbon benefits. The largest threat to carbon stocks is conversion of forestland to agriculture and pasture. Protection of unburned forests of varying ages from conversion to agriculture or pasture could result in 137 to 199 t C/ha being sequestered and retained. The total carbon benefits would be 530,000 to 774,000 tons after 30 years. Reforestation efforts targeted to degraded lands in the reserve could also sequester 19 to 137 t C/ha depending upon growth and survival rates of the planted trees, or from 123,000 to 893,000 t C over 30 years on an area of 6,500 ha.

Table 2
Summary of the ranges of carbon sequestered and/or retained in different projects after 30 years. Estimates are the difference between the with- and without-project scenarios, estimated on a per hectare basis and total over proposed project area

Project	Net amount sequestered or retained		
	Reserva El Ocote	Sierra de Arteaga	Mariposa
Reforestation and/or protect burned lands: • **t C/ha** • **total over area-1000 t C**	110 to 113 424 to 468	-10 to 89 -50 to 452	30 3

Approximately 4,300 ha of the Reserva Mariposa Monarca were affected by wildfires. The majority of the wildfires that burned through the area were surface fires, burning only the surface litter and understory plants and juvenile trees, and in most cases did not affect mature trees. There was at least one area of about 100 ha where the fire impacts were more severe, and crowns of trees were affected. However, prior to the wildfires the property had been subject to timber harvesting which removed most of the mature trees. Slash was left behind and when the wildfire burned through it affected the remaining juvenile trees (2 to 4 m in height). Reforestation of the small burned area would likely sequester about 60 to 90 t C/ha over 30 years, depending on growth rates of planted trees. Accounting for natural regeneration, which is likely to reach the same value over 50 to 70 years, the net amount of carbon sequestered through reforestation over 30 years is likely on the order of 30 t C/ha or 3,000 tons in the 100 ha (the difference between reforestation and natural regeneration). Tree planting in the other burned areas is likely to sequester little to no new carbon because the canopy is closed and the planted species are shade

intolerant. In fact such planting could increase the risk of a more serious fire in the future because the planted trees could become a "fire ladder" in the future and create a crown fire.

Several pilot projects designed to sequester and/or retain carbon in forests are already in some stages of implementation throughout tropical and temperate forests. Based on the IPCC Special Report on Land Use, Land-Use Change, and Forestry, these pilot projects are projected to sequester and/or retain 4 to 328 t C/ha over varying project lives (30 to 100 years); the estimates produced in this study for Mexico are about in the mid-range of these.

Key data gaps for the three areas include expected survival rates of planted trees, growth rates of planted or naturally regenerating trees, effect of slope and aspect on survival and growth rates, types and area of forest strata (e.g., slope, aspect, fire intensity), and fire history.

Given the uncertainties that influence the estimates of potential carbon sequestered, a carbon measuring and monitoring system will need to be implemented if a project is to occur in the future. Baseline development, identification, and measurement of relevant carbon pools, and design of a sampling strategy are some of the key issues that must be addressed in the creation of a carbon monitoring system. In addition, a quality assurance and control program should be developed to ensure reliability of data and offset calculations. For Sierra de Arteaga and Reserva El Ocote, the relevant carbon pools to be measured and monitored are live trees, understory vegetation, litter, roots, and new dead wood. Soil carbon is unlikely to produce a carbon benefit except in areas likely to be converted to agriculture, as in the Reserva El Ocote.

Any potential carbon sequestration project for these sites will have to address complex issues and uncertainties if accurate and precise estimates are to be made. Long-term monitoring (30 years) of land-use change patterns, growth and survivorship of trees, and success of fire management programs would be conducted to quantify the success of project activities.

1. Introduction

In the spring of 1998, Mexico experienced some of their worst forest fires in history. Over the course of seven months, more than 200,000 hectares (ha) were burned. To respond to this disaster the Government of Mexico (GOM), through the Secretariat of Environment, Natural Resources, and Fisheries (SEMARNAP), developed a *National Restoration Program* (Programa Nacional de Restauración Ecológica y Contra el Cambio de Uso del Suelo por Incendios Forestales) whose purpose is to restore and to prevent land-use change in the affected areas. Under this program, 85 sites located in 21 states throughout Mexico were selected. These 85 sites represent a total of 188,289 hectares to be restored, and these were officially decreed as Ecological Restoration Sites on 23 September 1998.

USAID/Mexico and SEMARNAP are collaborating in an attempt to identify issues related to both the forest fires and global climate change. One outcome of this collaboration is the development of a project to assess the amount of carbon potentially sequestered or avoided from being emitted (i.e. retain existing stocks of carbon) by restoring some of the burned areas. Specifically, the purpose of this report is to assess the technical and methodological issues affecting the potential of burned sites to sequester and/or retain carbon, including the measurement of carbon at restoration sites, and the amount of carbon that would have existed or been emitted without restoration activities. The project focused on the following three sites affected by the forest fires in 1998:

1. Sierra de Arteaga in the State of Coahuila (temperate pine forest);

2. Reserva El Ocote, in the State of Chiapas (tropical forest); and

3. Reserva de la Biosfera Mariposa Monarca in the State of Michoacan (temperate pine/fir-forest).

These sites were selected based on several criteria: 1. all suffered some loss of biomass due to the forest fires of 1998, 2. they face human pressure for conversion (i.e., land use change), 3. they are considered an important area where land-use change pressures need to be addressed and mitigated, and 4. they face risks from future forest fires. The fact that two of the sites have been decreed as natural reserves by the GOM (i.e., Reserva de la Biósfera Monarca and Reserva El Ocote) does not preclude them from facing the pressures mentioned above and therefore meet the criteria for site selection.

1.1 Objectives of the Study

The primary objective of this study is to identify the carbon sequestration or retention potential at the three identified sites. Specifically, the study addresses the technical and methodological issues of estimating the carbon sequestration and/or retention potential as well as estimates the carbon benefits that may accrue with restoration activities. The specific objectives are:

1. Calculate a statistically and technically valid estimate, based on existing data, of the amount of carbon that will be captured or retained during forest restoration at the three identified sites;

2. Identify and address the methodological and technical issues surrounding the calculation of actual with and without-project carbon baselines; and

3. Design a carbon measuring and monitoring system that could be used in the long term to verify the carbon sequestration or retention potential of the three sites.

1.2 Organization of the report

In this report, we present the results of the study organized around each of the three sites separately. For each site we will describe the physical setting, the effects of the fires, other pressures they are subject too, the restoration activities and their success to date, carbon stocks and their rates of accumulation, the potential net amount of carbon sequestered or retained through implementation of project activities, and data gaps and uncertainties in the analyses. The last section of the report will describe the carbon measuring and monitoring system needed to verify the potential carbon benefits from the restoration activities.

2. Sierra de Arteaga

2.1 Physical setting and human pressures

The Sierra de Arteaga area is part of the larger Sierra Madre Occidental. PRONARE has focused its restoration efforts on a 5,099 hectare area in the Sierra Las Alanzas and the Sierra de Coahuilon, both part of the Sierra de Arteaga. Elevations in this area range from 1,700 to 3,500 meters above sea level. Most of the study area contains steep slopes of from 30 to 45 degrees. Average annual rainfall is 600 to 700 millimeters, with approximately 30 days of frost per year (Delegacion Federal en el Estado de Coahuila, 1999).

Plant community distribution in the Sierra de Arteaga is most notably associated with elevation and aspect. On south-facing slopes, the driest zones of the Sierra, grows a low (to 4 meters) plant community called *matorral*. This community is composed primarily of evergreen shrubs of the following genera: *Crataegus, Ceanothus, Quercus, Rhus, Cercocarpus,* and *Arbutus*. In older stands, occasional emergent trees are found, like *Pinus greggii* and *Cupressus* sp. Matorral stands of 20 to 30 years in age (post-fire) display nearly complete shrub cover with few to no emergent trees. On more moist, north-facing slopes, there are two common forest communities. From 2,300 to 3,300 meters above sea level occur dense forests of mixed conifers (*oyameles*) including *Pseudotsuga flahaulti, Abies vejarii, Picea mexicana,* and *Pinus ayacahuite*, in addition to occasional pure stands of *Populus tremuloides.* At lower elevations, from 1,700 to 2,600 meters above sea level, on north-facing slopes is a sparser community of widely-spaced *Pinus cembroides,* and *Pinus greggii,* with scattered evergreen matorral shrubs (Delegacion Federal en el Estado de Coahuila, 1999). Many species in Sierra de Arteaga display fire-tolerant or fire-adapted characteristics; *Populus tremuloides* (abundant root sprouting after fire), *Pinus greggii* (serotinous cones), and *Pinus ayacahuite* (vascular tissue is below ground in early growth stages; "grass stage").

Land ownership in the restoration area is distributed among three ejidos (Mesa de las Tablas, Potrero de Abrego, and Santa Rita) and numerous smaller private parcels. In this area there are approximately 540 people (13 communities), whose household economies depend on the production of apples and potatoes, as well as cattle ranching (Delegacion Federal en el Estado de Coahuila, 1999). Population density is low, roughly 10 ha per person.

2.2 Effects of the fires

Severe forest fires burned four distinct areas of the Sierra de Arteaga in 1998. PRONARE is presently engaged in reforesting the largest of these areas that were severely burned by two contiguous forest fires in 1998. One of the fires originated from a poorly guarded campfire in an area of newly constructed vacation homes. Almost all trees (90 percent+) were killed in the area of the burn. Salvage logging operations removed dead wood from 38 percent of this area, extracting on average 19.7 m^3 /ha.

2.3 Restoration activities

To date, 4,027,330 native conifers (*Pinus pseudostrobus, P. cembroides, P. greggii, P. ayacahuite, Cupressus lindleyii, and Pseudotsuga spp.*) have been planted over 2,674 hectares. Spacing varied but averaged 4 x 4 meters. Weighted average survival of plantings after one year (1998 to 1999) was 44.6 percent, and ranged from 17.5 percent to 72 percent. The majority of areas planted (95 percent) are within ejido lands, while only about half of the burned area is within ejido lands. Survival was greatest in the small private landholdings, where people showed a greater commitment to maintaining the planted trees due to easier access and heightened sense of ownership, and where the planting was carried out with more substantial technical involvement from PRONARE (the ejido areas were planted by the army). Ejido lands planted by the army did not have a high survival rate. Often 3 to 4 seedlings were placed in each hole, and survivorship was low.

Land tenure is likely to have a marked impact on the amount of carbon sequestered by the reforestation activities in this area because of its impact on survivorship of the planted trees. The ejido lands, comprising about half of the burned area, are more remote with limited access and survivorship of the trees planted appears to be low; low survivorship will result in low quantities of carbon being sequestered (see below for more details). Reforestation on the private lands, on the other hand, shows higher survival rates, which will ultimately lead to higher amounts of carbon sequestered. These differences in survivorship rates and the impact on the carbon sequestered are captured by the different scenarios that we produce in the next section.

Fires are an ongoing risk to this area, and it was indicated that the forests would be better protected with improved fire surveillance and fire prevention techniques. Since 1998, 4.6 kilometers of fire-breaks have been cut in the area. Fire-breaks were installed by removing all trees leaving only a small understory of herbaceous vegetation. Response time for forest fire fighting (procurement of radios, monitoring from fire towers) has also

improved recently, and SEMARNAP has mounted a fire-prevention campaign in the region.

2.4 Potential amount of carbon sequestered or retained

The potential to capture carbon in the Sierra de Arteaga is high and is a good candidate for a carbon project. Carbon can be sequestered via reforestation of burned areas and retained through improved fire management in the area. To calculate the potential amount of carbon sequestered from reforestation and fire protection activities, several variables were considered. We assumed that without the reforestation activities (without-project case), the area would undergo natural succession into matorral vegetation. During the field visits matorral vegetation was colonizing many of the areas affected by wildfires and in one area that was burned by a forest fire in 1978, matorral vegetation was well established and virtually no mature trees were visible, but some scattered small trees were present indicating that trees will establish eventually but slowly and if fire does not spread through the area again. With reforestation (with-project case) and fire prevention a forest could become established over time instead of matorral vegetation To calculate the potential carbon sequestered, two basic questions need to be answered: 1. what is the likely carbon content of the planted forest and 2. what is the carbon content of the matorral vegetation? Subtracting these two quantities from each other will provide an estimate of the net amount of carbon sequestered per ha due to the restoration activities.

Several factors influence the potential carbon content of the planted forest, for example: the density of planting, survival rate, and rate of growth of the trees. SEMARNAP and PRONARE are currently targeting a density of 622 trees/ha (4 m x 4 m spacing). For the carbon sequestration calculations, three different survival rates (100 percent, 70 percent, and 40 percent) were used. These reflect the differences in land ownership as discussed above in the previous section. Data on growth rates of the trees in the area were unavailable and two growth rates based on values taken from the literature, and age and diameter of trees measured in the field were used. The likely biomass-carbon content of the planted trees was estimated using two regression equations from the literature (biomass is estimated based on tree diameters). For the other carbon components of the planted forest (roots, litter, understory) values were taken from the literature or from data collected in the field. We also assumed that some fire prevention activities would take place in the reforested area such as reduction of fuel loads by periodic controlled burns. The effect of controlled burns in our model was to assume that no significant understory and litter layer would accumulate (see Table 3 for assumptions).

For the without-project case calculations, we estimated the biomass-carbon content of matorral vegetation using literature values and from our observations in the field. We

assumed that the matorral would colonize areas affected by fires and accumulate biomass-carbon for about 20 years before scattered trees would invade and become established. From information gathered during the site visit, the fire return cycle in this area is of the order of 10 to 30 years. Without the project, we assumed that fires would occur in the matorral vegetation at years 15 and 25, and that all vegetation would be burned. We also simulated a scenario in which no fire occurred during the 30 year period.

On north slopes it would be expected that trees would grow faster and that their survival rates would be higher and that fire damage may be less than on south slopes. To estimate the effect of slope on the total carbon sequestered by reforesting the whole area of about 5,000 ha, we made one combination of the various scenarios that we present below to reflect a 50/50 division of the project area into north and south slopes.

Other factors that influence the carbon calculations are the length of the project. In our experience, carbon projects are usually 20 to 30 years but they can be longer or shorter depending on the activity. All the assumptions used in estimating the potential amount of carbon sequestered are listed below (Table 3).

Table 3
Assumptions used to estimate the amount of carbon sequestered by reforestation in Sierra de Arteaga

Component	Assumption and/or estimation method
Restored forests	
Project life	30 years
Total area of project	5,099 ha
Survival rates of plantings: 100 percent 70 percent 40 percent	 622 trees/ha 435 trees/ha 249 trees/ha
Growth rates of planted surviving trees Pines/fir Pines/fir	 0.6 cm/yr. 0.8 cm/yr.
Biomass of trees at 30 yr. Pines/fir—0.6 cm yr^{-1} Pines/fir—0.8 cm yr^{-1}	Based on biomass regression equations for pines/fir from Brown and Schroeder (1999) 102 kg/tree (assume linear growth) 227 kg/tree (assume linear growth)
Root biomass	Calculated from aboveground biomass using equation in Cairns et. al (1997)
Litter and understory	Burned every few years to reduce fuel loads, carbon is thus recycled
Dead wood	50 percent of dead wood produced is also burned Assume dead wood remaining is 50 percent of 7 percent of aboveground biomass
Matorral	
Components included	Aboveground, roots, and fine and coarse litter
Source of data (biomass units) -Schlesinger (1991) -- 22 yr old -Cairns et al. (2000)—unknown age -Estimate from observations at site visit for a 20 yr old stand	 107 t/ha 14.2 t/ha 34.5 t/ha—used for the scenarios
Growth rate	Assume after age 20, vegetation reaches steady state and trees invade; rate of biomass accumulation increases at an additional rate of 1 t C ha^{-1} yr^{-1} until age 30 years
Fire cycle	Assume 15 and 25 year cycle and no fire during the 30 year period

A total of 18 scenarios were developed taking into account uncertainties in growth rates, survivorship, and frequency of fire in the matorral. Table 4 summarizes the estimated quantities of carbon sequestered in the reforested area under different assumptions of

survival rates of planted trees and growth rates on both a per ha basis and for the total project area. The values for north and south slopes assume a 50/50 split of the area and use the lowest survival rate and slower growth for the south slopes and use the highest survival rate and faster growth rate for the north slopes. Survival rates of the planted trees clearly have an important effect on the amount of carbon sequestered by the reforestation program. The low survival rates that we observed in the ejido lands show that about half as much carbon would be sequestered there as on the private lands where survival rates of the planted trees were higher—up to 70 percent or more. Rates as low as 17 percent that were reported in some areas would reduce the amount sequestered to less than 10 t C/ha, although this would be partially offset by a higher natural regeneration of other native vegetation such as matorral. With low survival rates and slower growth rates, the reforestation activities (17.5 t C/ha) barely surpass the natural regeneration by matorral vegetation with a longer fire return cycle (13 t C/ha); at survival rates less than 40 percent, natural regeneration would most likely surpass reforestation activities with respect to carbon sequestration.

Table 4
Summary of amounts of carbon sequestered (per hectare and total stock) by reforestation activities, over an assumed project life of 30 years, in Sierra de Arteaga (area of project is assumed to be 5,099 ha)

Survival rate of planted trees	Growth rates		Growth rates	
	0.6 cm/yr (t C/ha)	0.8 cm/yr (t C/ha)	0.6 cm/yr (1000 t C)	0.8 cm/yr (1000 t C)
• 100 percent	43	93	217	474
• 70 percent	30	66	154	334
• 40 percent	17.5	38	89	194
	Carbon stock (t C/ha)		Total carbon (1000 t C)	
Aspect (assume 50-50 split)[1]				
• South slopes	17.5		45	
• North slopes	66		167	
Natural succession				
• Matorral--average C[2]				
– no fire	27		139	
– 15 yr fire	6.5		33	
– 25 yr fire	9.8		50	

[1]Assume the 40 percent survival and 0.6 cm/yr growth for south and 70 percent survival and 0.8 cm/yr growth for north slopes

[2]The average carbon stock of the matorral over the 30 year period due to fires reducing the stock periodically.

Growth rates are uncertain but they have a marked impact on the rates of carbon accumulation. A difference of 0.2 cm/yr in growth results in more than double the amount of carbon sequestered for a given survival rate. If the growth rate was only 0.5 cm/yr, the amount of carbon sequestered at the end of 30 years with 100 percent survival would be 23 t C/ha. Clearly, the growth rates that can be achieved in this area will greatly influence the amount of carbon sequestered.

Combining the carbon stock estimates in Table 4 with the area of the proposed project and accounting for carbon emissions from burning of the matorral on the various assumed fire cycles results in the net amounts of carbon sequestered summarized in Table 5. We present results with no consideration for differences in growth and survival due to aspect and with consideration for differences due to aspect. Figure 1 illustrates the time course of the amount of carbon accumulating over the length of the project for selected scenarios.

Table 5
Summary of the net amounts of carbon sequestered on 5,099 ha of land over a 30 year period in Sierra de Arteaga. The net amount is based on the difference between the with- (reforestation) and without-project (natural succession) scenarios

Scenario (fire frequency and survival)	With project (1000 t C)		Without project (1000 t C)	With – without project (1000 t C)	
	0.6 cm/yr growth	**0.8 cm/yr growth**		**0.6 cm/yr growth**	**0.8 cm/yr growth**
No consideration for aspect					
25 year fire					
• 100 percent	217	474	22	195	452
• 70 percent	154	334	22	132	312
• 40 percent	89	194	22	67	172
15 year fire					
• 100 percent	217	474	66	151	408
• 70 percent	154	334	66	88	268
• 40 percent	89	194	66	23	128
No fire					
• 100 percent	217	474	139	78	335
• 70 percent	154	334	139	15	195
• 40 percent	89	194	139	-50	55
50-50 split of area into south and north aspect					
25 year fire	212		22	190	
15 year fire	212		66	146	
No fire	212		139	73	

The net amount of carbon sequestered ranges from 50,000 to 452,000 t C (or –10 to 89 t C/ha) over the 30 year period. The negative value is for 40 percent survival, slow growth rate and no fire during the 30 year period in the matorral vegetation. Given the average survival rates of planted trees was about 40 percent based on the data gathered from the site visit and that the fire return cycle is about 10 to 30 years, the likely range of the net amount of carbon sequestered, assuming no effect of aspect, is estimated to be 23,000 to 172,000 t C, or 4.5 to 34 t C/ha. With consideration for differences due to aspect, this range could be 146,000 to 190,000 t C or 29 to 37 t C/ha.

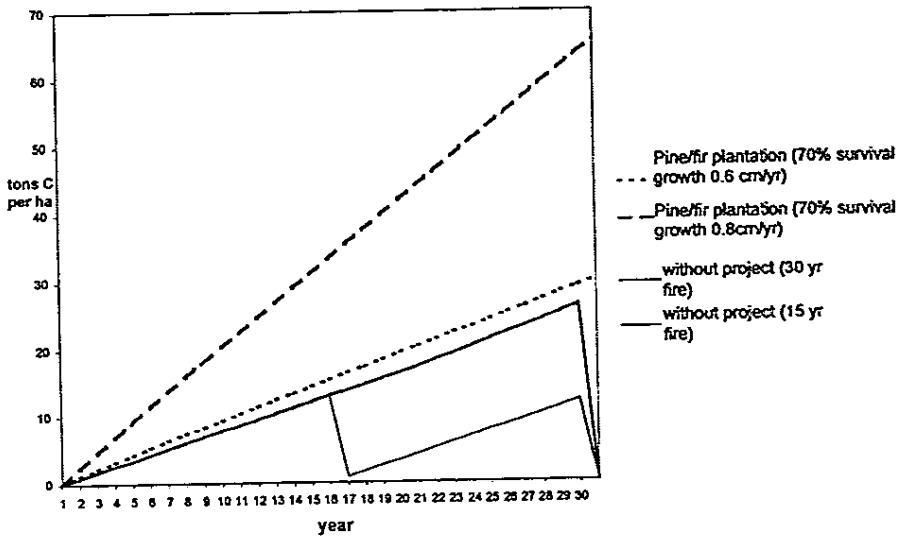

Figure 1 Potential carbon sequestered for selected scenarios in Sierra de Arteaga

2.5 Data gaps and uncertainties

The range of carbon offsets predicted for the area indicates a level of uncertainty and the presence of data gaps for variables involved in the project calculations.

- One important data gap is more specific information on growth rates of planted trees. Small differences in growth rates can have marked effects on the amount of carbon sequestered (e.g., the increase from 0.6 to 0.8 cm/year can double the amount of carbon sequestered).

- The different scenarios clearly indicate how important the survival rates are in the estimated amount of carbon that could potentially be sequestered. Survival rates are something that can be managed as part of the project, although land tenure also have an effect.

- The types of fire management that could be implemented, and their relative effectiveness, are also an important data gap, both within the reforested area and in naturally regenerating areas.

- Information on disturbance regimes, such as periodicity of fires, will also need to be quantified to improve estimates of carbon sequestration.

- The total number of lands suitable for planting is currently assumed to be 5,099 ha, but as the site visit indicated, north-facing slopes support trees more easily than south-facing slopes. It is possible that without the project, north-facing slopes could naturally regenerate into a forest over time, while south-facing slopes are more likely to support matorral vegetation. Because of the impact of north versus south aspect slopes on the amount of carbon sequestered, data are needed on the area of north and south-facing slopes within the 5,099 ha area to improve the carbon sequestration estimates in the region.

3. Reserva El Ocote

3.1 Physical setting and human pressures

The El Ocote Reserve was established as a federal reserve in 1982 with an initial area of 48,200 ha; the same area was decreed a state reserve in 1972 (Gobierno del estado de Chiapas. 1972). Recently, 52,088 ha were added to the Reserve as two biological corridors to the east and west of the original reserve boundary; Corredor Biológico Sierra El Francés and Corredor Biológico Chimalapas respectively. The Reserve currently occupies an area of 100,288 ha. Of this area, 40,200 ha correspond to the core zone, and 60,088 ha correspond to the buffer zone. All land within the buffer zone is divided among ejidos and privately owned parcels. Most of this area, at least 50 percent as of 1994, is used for cultivation or grazing (Vásquez Sanchez et al., 1996).

Elevations within the Reserve range from 300 to 1500 meters above sea level. Annual rainfall averages between 2000 and 2200 millimeters. The El Ocote Reserve includes significant areas of steep slopes (6 percent) and dissected karstic terrain (30.7 percent) (García-Gil et al, 1996). Over 60 percent (about 65,000 ha) of the Reserve area is covered by tropical broad-leaved forest in different stages of succession. Representative canopy species include *Brosimum alicastrum*, *Vatairea lundellii*, and *Schizolobium parahybum*. As of 1996, only 306 ha of mature forest (over 25 meters in height) remained in the Reserve, all of it within the buffer zone and threatened by land use conversion.

Approximately 8,100 people live within the Reserve (*mestizos* and indigenous *tzotziles*, *tzeltales*, and *zoques*), and over 150,000 people live in the area of influence around the Reserve. The population growth rate within the Reserve is 3.6 percent, well above the national average of 2 percent (Vásquez Sanchez et al., 1996). The recently constructed highway from Tuxtla Gutierrez to Cosoleacaque, which passes close to the eastern and northern boundaries of the Reserve, has facilitated immigration to the region and increased pressure for agricultural conversion particularly near Sierra El Francés. The deforestation rate, calculated for the entire Reserve for the period from approximately 1975 to 1990, is 0.6 percent per year. Most of the conversion has been from forest to agriculture or grazing in the Reserve's buffer zone, on productive soils at elevations of from 300 to 600 meters above sea level. The deforestation rate for the buffer zone alone is considerably higher, around 2 percent per year (calculated from data from March and Flamenco, 1996).

Household economies in the region of the Reserve depend on, in order of importance: livestock, maize agriculture, coffee production, timber harvesting, fishing, production of

chili, bananas, and citrus. Most land holders have from 20 to 35 hectares, with 54 percent dedicated to grazing, 24 percent to maize agriculture, and 22 percent to shade-grown coffee, on average (Vásquez Sanchez et al., 1996).

3.2 Effects of the fires

Multiple forest fires affected 23,000 ha of the El Ocote Reserve in 1998. This included 11,000 ha within the core zone and 12,000 ha within the buffer zone (Figure 2). These forest fires resulted both from isolated lightning strikes and human activities including slash and burn agriculture and the practice of burning grazing land to stimulate emergence of new shoots for livestock. Forest fires in this region are infrequent but have occurred within the Reserve in recent history. Reserve staff are familiar with an area affected by a severe burn in the 1970's, and two minor burns occurred in 1991 and 1997 (SEMARNAP 1999). The most severe damage resulting from the 1998 fires occurred in steep areas over 1,200 meters, which had thin soils and were more vulnerable to desiccating winds. Damage estimates for burned areas ranged from 30 to 80 percent of trees killed.

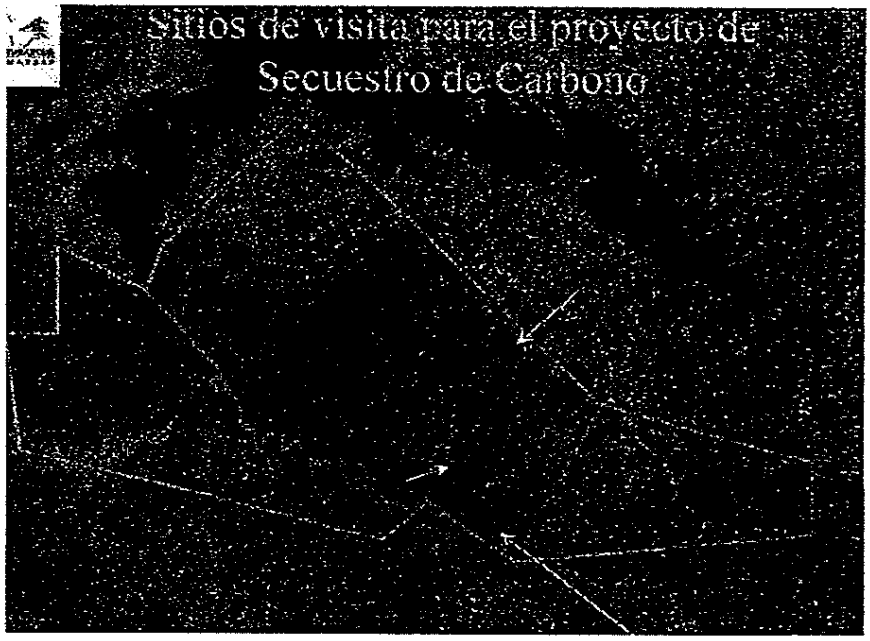

Figure 2 Areas burned (displayed in green) in the El Ocote Reserve 1998

Despite the damage from wildfires, natural regeneration witnessed in these areas after two years was abundant and considered sufficient to ensure restored forest growth

(Figure 3). Dominant species in these regenerating areas included *Belotia* mexicana, *Heliocarpus donnell-smithii, Cecropia peltata, Solanum rugosum, Guettarda combsii,* and bamboo. Some trees (*Cecropia peltata*) were over five meters tall only two years after the 1998 wildfires. It is unlikely that a reforestation activity in these areas would surpass natural regeneration in restoring forest growth and sequestering carbon. For this reason, there is little potential for tree planting to accumulate additional carbon. To demonstrate improved carbon sequestration, we recommend directing reforestation efforts to areas where natural regeneration is impeded (see Section 3.4.3).

Figure 3 Two-year old regeneration with remnant burned trees in a severely burned area of the El Ocote Reserve

Forests that were burned in the Reserve provided an incentive for people to move into the area and many of these lands, particularly in the buffer zone and near points of access (like the highway), are currently being converted to agriculture, despite the rough terrain and steep slopes.

3.3 Restoration and protection activities

Restoration activities in the El Ocote Reserve have been underway since 1998. To date, 106,025 trees have been planted in 170 ha of the core and buffer areas of the Reserve. In addition, 135 kilometers of fire breaks were cut in the Reserve in 1999 (PRONARE 2000). A program is also underway to improve productivity on existing cultivated and pasture lands bordering the Reserve.

3.4 Potential amount of carbon sequestered or retained

The El Ocote Reserve offers a wide range of opportunities to sequester and retain carbon. Pressure to convert forested lands to agriculture is currently high and is likely to remain

so, or increase, in light of the high rate of population increase recorded in the region. Castillo et al. (1998), observed increasing annual deforestation rates within the Reserve over the period 1972 to 1995; rates increased from 0.33 percent to 1.39 percent over 23 years. In particular, the burned forests in the Reserve face considerable pressure from agricultural colonization. Although converted lands may support maize agriculture for only two to three years, many of these areas will undergo permanent conversion; old milpas are frequently relegated to grazing land (Vásquez Sanchez et al., 1996). Retention of carbon in existing biomass could be easily demonstrated by protecting these forests where conversion threats are highest. Protection would also allow burned forests to regrow over time, allowing for additional carbon to be sequestered. Forest protection will require concomitant measures to secure productivity on existing cultivated lands and discourage expansion of the agricultural frontier. SEMARNAP is implementing such a strategy via their "Sedentarización de la Milpa" program. The expansion of pasture lands can further be controlled by installing fire breaks around existing pastures to effectively contain annual burning activities.

Additional carbon benefits could be obtained from other activities in the El Ocote Reserve: 1. protection of intact forests from being converted to agriculture and pastures, 2. reforestation of existing savannah/pasture lands, and 3. introduction of reduced impact logging practices. Based on data collected on land-use change pressures in the region, we estimate that approximately 6,000 ha of advanced secondary forests are in danger of being converted to agriculture or pastures over the next 30 years. In addition, there are currently 65,000 ha of savannah/pasture and degraded lands in the Reserve and there is a potential to establish tree plantations in some of these areas (approximately 6,500 ha).

3.4.1 Protection of burned forest lands in the El Ocote Reserve

Table 6 presents our assumptions used to estimate the amount of carbon sequestered and retained by protecting burned forests in Reserva El Ocote. Based on data collected on the site visit, we assumed that without protection, burned forests are under risk of conversion to agriculture and pastures during the next several decades. For the without-project case, we estimated the likely rate of deforestation in the absence of any protection. We assumed a fixed area deforested each year (120 ha), or increasing by 10 ha/yr every 10 years (scenarios 2 and 4 in Table 6.). This is based on a deforestation rate of 2 percent of the initial area of protection (calculated from data from March and Flamenco, 1996). We consider this to be a conservative projection of potential deforestation in the Reserve; this assumes a 6 percent annual deforestation rate by year 30, while current trends suggest a value far exceeding this, 13 percent by year 30 (calculated from data from Castillo et al, 1998). In our calculations, we also considered that 24 percent of the deforested lands would be converted to row crop agriculture (Vásquez Sanchez et al., 1996). We assume

all conversion to agriculture was permanent; we did not account for shifting cultivation practices.

Initial carbon stocks of burned forest were calculated from transects installed during the site visit (32 t C/ha). We assumed forest soil carbon content to be 84 t C/ha in the top 40 cm (from DeJong et al., 1998). The next step in the calculations is to estimate the likely rate of biomass-carbon accumulation over time. We assumed that following disturbance, these burned forests are actively growing and are likely to accumulate carbon at a higher rate than older forests; we estimate 3 t C/ha.yr accumulated per year for the first 20 years, then 2 t C/ha.yr from years 21 to 30 based on data in Brown and Lugo 1990. The carbon content of agricultural crops was assumed to be 3 or 5 t C/ha based on field experience and the literature. We also accounted for likely loses of carbon in soils as land is converted to agriculture. The literature suggests that after a forest is converted to agriculture, 40 percent of the soil carbon oxidizes after 5 years of cultivation (Detwiler 1986). Applying that rate to the estimated forest soil carbon content, the total amount of soil carbon released to the atmosphere was calculated (Table 6). Finally, we assumed that protecting the burned forests from deforestation also allowed these forests to accumulate carbon over time. Thus there are two sources of carbon benefits from this activity—the retained carbon on site by preventing deforestation of the burned lands, and the carbon sequestered in the recovering forests due to their protection.

Table 6
Assumptions used to estimate the amount of carbon sequestered and retained by protecting burned forests in the El Ocote Reserve

Scenario	Deforestation[1] (ha/year)	Rate of carbon accumulation[2] (t C/ha/yr)	Initial carbon stock of aboveground biomass (tC/ha)	Carbon content of agriculture crop (t C/ha)	Loss of soil carbon due to cultivation[3] (tC/ha for 5 yr)
1	120	3 and 2	32	5	6.7
2	120,130,140	3 and 2	32	5	6.7
3	120	3 and 2	32	3	6.7
4	120,130,140	3 and 2	32	3	6.7

[1]Rate of deforestation is 2 to 4 percent per year (either 120 ha for 30 years or 120 ha for years 1 to 10, 130 for years 11 to 20, and 140 ha/year for years 21 to 30).

[2]Rate of carbon accumulation (regrowth) variable (3 for first 20 years, then 2 for years 20 to 30).

[3]Rate of soil loss is 40 percent of stock over 5 years of cultivation (Detwiler 1986); carbon stock in soil to 40 cm is 84 t C/ha (estimated from DeJong et al. 1998). No soil carbon is lost if converted to pasture.

A summary of four possible scenarios is given in Table 7; we did not vary the soil carbon in these scenarios because of its relatively small effect on the overall total carbon benefits. The amount of carbon sequestered and retained ranges from 110 to 113 t C/ha in the vegetation over the 30 year period, with an additional (on average) 8 t C/ha in the soil. An example of the accrual of carbon benefits for one scenario is shown in Figure 4. The amount of carbon sequestered and retained starts off slow but then increases significantly over time with the maximum benefits accruing at the end of 30 years as expected. The total net amount sequestered and retained, after accounting for the replacement crop and pasture vegetation, ranges from 424,000 to 468,000 t C. If instead of permanent conversion the land was used for shifting cultivation, the average amount of carbon sequestered and retained would be lower than what we obtain here because the carbon stocks on average would be lower.

Table 7
Net[1] amount of carbon sequestered and retained by protection of burned forests in the El Ocote Reserve over 30 years

Scenario	Total area deforested (ha)	Carbon sequestered and retained (t C/ha)	Carbon retained in soil[2] (t C/ha)	Total carbon (t C/ha)	Total sequestered and retained (1000 t C)	Total retained in soil (1000t C)	Total sequestered and retained (1000t C)
1	3,600	110	8	118	397.2	27.1	424.3
2	3,900	111	8	119	431.8	29.2	461.0
3	3,600	112	8	120	404.4	27.1	431.5
4	3,900	113	8	121	439.0	29.2	468.2

[1]Net quantity is the difference between the with protection activities and without-project activities

[2]The quantity of soil carbon retained is weighted over the whole area of lands protected from deforestation; on agriculture lands alone, this value would be 31 t C/ha.

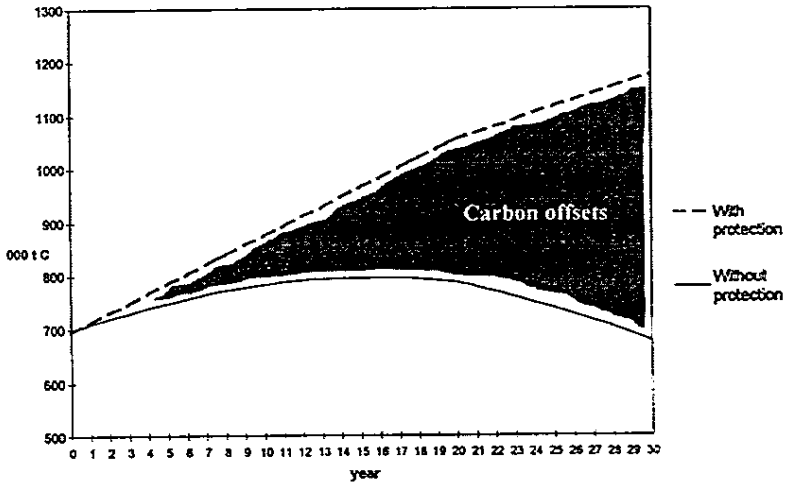

Figure 4 Growth of carbon stocks for the with and without project scenarios for protection of burned areas in the El Ocote Reserve

3.4.2 Protection of forested areas in the El Ocote buffer zone

Table 8 presents our assumptions used to estimate the amount of carbon sequestered by protecting secondary, unburned forests in the Reserva El Ocote. From literature sources we estimated the likely carbon standing stocks of secondary forest (in aboveground biomass) to be 90 to 136 tons of C per ha (DeJong et al. 1998, and Brown 1997). We qualify this as a conservative assumption, as aboveground biomass-carbon may approach 187 to 214 tons of C per ha (De Jong et al. 1998, National Forest Inventory 1996, and Delaney et. al 2000). Due to their more advanced state of regeneration, the estimated rate of regrowth, 1 to 2.5 t C/ha/yr, was assumed to be lower than in the burned areas. Deforestation, conversion to agriculture, and soil carbon losses were calculated using the same assumptions as those used above.

Table 8
Assumptions used to estimate the amount of carbon sequestered and retained by protecting secondary forests in the El Ocote Reserve

Scenario	Deforestation[1] (ha/year)	Rate ofcarbon accumulation (t C/ha.yr)	Initial carbon stock of aboveground biomass- (tC/ha)	Carbon content in agriculture crops (t C/ha)	Loss of soil carbon due to cultivation[2] (tC/ha for 5 yr)
5	120	2	136	5	6.7
6	120,130,140	2	136	5	6.7
7	120	1	136	5	6.7
8	120,130,140	1	136	5	6.7
9	120	2	136	3	6.7
10	120,130,140	2	136	3	6.7
11	120	2.5	90	5	6.7
12	120,130,140	1.5	90	5	6.7

[1]Rate of deforestation is 2 to 4 percent per year (either 120 ha for 30 years or 120 ha for years 1 to 10, 130 for years 11 to 20, and 140 ha/year for years 21 to 30).

[2]Rate of soil loss is 40 percent of stock over 5 years (Detwiler 1986); carbon stock in soil to 40 cm is 84 t C/ha (estimated from DeJong et al. 1998). No soil carbon is lost if converted to pasture.

Because the initial carbon stocks are higher in these scenarios than in those used for the protection of burned forests, the final quantities of carbon sequestered and retained are significantly higher 129 to 191 C/ha in vegetation alone (Table 9). The net amount of carbon sequestered or retained for protection of 3,600 to 3,900 ha of secondary forests is 530,000 to 774,000 t C.

Table 9
Net[1] amount of carbon sequestered and retained by protection of secondary forests in the El Ocote Reserve over 30 years

Scenario	Total area deforested (ha)	Carbon sequestered and retained (t C/ha)	Carbon retained in soil[2] (t C/ha)	Total carbon (t C/ha)	Total sequestered and retained (1000 t C)	Total retained in soil (1000t C)	Total sequestered or retained (1000t C)
5	3,600	189	8	197	680.4	27.1	707.5
6	3,900	189	8	197	737.1	29.2	766.3
7	3,600	160	8	168	576.0	27.1	603.1
8	3,900	160	8	168	624.0	29.2	653.2
9	3,600	191	8	199	687.6	27.1	714.7
10	3,900	191	8	199	744.9	29.2	774.1
11	3,600	158	8	166	567.0	27.1	594.1
12	3,900	129	8	137	501.2	29.2	530.4

[1]Net quantity is the difference between the with protection activities and without-project activities

[2]The quantity of soil carbon retained is weighted over the whole area of lands protected from deforestation; on agriculture lands alone, this value would be 31 t C/ha.

3.4.3 Reforestation of degraded lands in the El Ocote Reserve

Within the El Ocote Reserve are significant areas that have been converted to permanent grasslands and savannah due to historic and current grazing of livestock. Currently over 30 percent of the land in the Reserve is pasture/savannah, or about 30,000 hectares (Garcia-Gil et al. 1996). We recommend directing reforestation to degraded lands within the Reserve buffer zone, where, due to history of repeated disturbance (burning, grazing), and alteration of soil properties (compaction from grazing), natural forest succession (to a tall forest) has been impeded. In the buffer zone, less carbon intensive ecosystems have been induced, like grasslands and savannahs with scattered shrubs of *Byrsonima crassifolia* and *Acacia pennatula*. These areas offer unambiguous opportunities to restore forest biomass through planting activities.

One carbon sequestration strategy could be to require landholders within the Reserve buffer zone to relegate one-fifth of their grazing land to tree plantings (6,500 ha total). The conversion of current grazing lands to tree plantations will also require an intervention to improve remaining pasture to support more intensive grazing. The carbon sequestration estimates used in this analysis are based on data from mahogany plantations (Mayhew and Newton 1998). Mahogany is a good candidate because it is a native, high-value species and is already a significant component of reforestation in the Reserve. Growth estimates used in the calculations are conservative and may actually surpass one centimeter (diameter at breast height) per year. In the without-project case we assumed

that the land would have remained as mixed pasture/savannah. For the with-project case, the assumption is that the 6,500 ha of lands are planted with mahogany (Table 10).

Table 10
Assumptions used in estimating the amount of carbon sequestered by planting mahogany on pasture/savannah lands in the El Ocote Reserve

Tree plantings	
Project life	30 years
Total area of project Survival rates of plantings: 100 percent 70 percent 40 percent	6,500 ha 500 trees per ha 350 trees per ha 200 trees per ha
Growth rates of surviving trees Mahogany Mahogany	 0.65 cm per yr. 0.87 cm per yr.
Biomass of trees at 30 yr. Mahogany—0.65 cm per yr Mahogany—0.87 cm per yr	Based on biomass regression equations for tropical trees in moist climate from Brown et al (1989) 220 kg/tree (assume linear growth) 454 kg/tree (assume linear growth)
Root biomass	Calculated from aboveground biomass using equation in Cairns et. al 1997
Litter and understory	4.1 percent of aboveground biomass from Delaney et al. (2000)
Dead wood	Assume all dead wood produced in the reforestation areas is gathered for consumption as fuelwood by the local population
Permanent pasture/savannah	
Components included	Above ground, roots, and fine and coarse litter
Source of data (biomass units)	
Cairns et al. (2000)—unknown age	22 t per ha

Using the above assumptions we calculated the potential carbon content in the mahogany plantations to be 30 to 148 t C/ha at the end of 30 years (Table 11). The net amount sequestered is estimated to range from 123,000 to 893,000 t C. The amount of potential carbon benefits is dependent on the rate of survivorship and growth rates of trees (Figure 5) with the greatest number of benefits occurring when both variables are high.

Table 11
Summary of amounts of carbon sequestered in the El Ocote Reserve assuming different survivorship and growth rates of mahogany plantations

	Total C content over 30 years (t C/ha)		Net C sequestered over 30 years
	With project	Without project	(t C/ha)
Growth rate 0.65 cm per yr			
100 percent	73.2	11	62.2
70 percent	51.7	11	40.7
40 percent	30.0	11	19.0
Growth rate 0.87 cm per yr			
100 percent	148.4	11	137.4
70 percent	104.8	11	93.8
40 percent	60.7	11	49.7

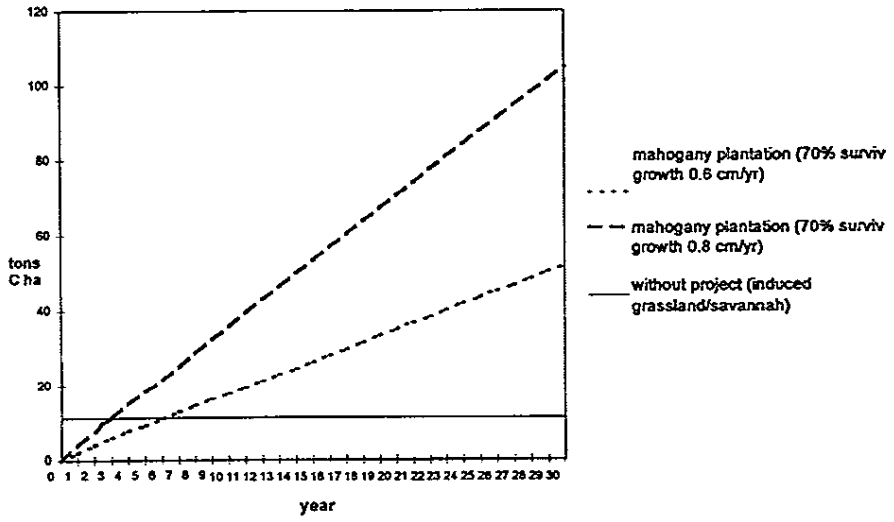

Figure 5 Potential carbon sequestered in mahogany plantations (with project) versus grassland/savannah (without project) in the El Ocote Reserve

3.4.4 Improved timber management practices in the Corredor Biológico Chimalapas

A fourth source of potential carbon offsets is through improved timber management in the 30,000 ha Corredor Biológico Chimalapas. Local demand for commercial timber species (primarily *Swietenia macrophylla*, *Cederela odorata*) ranges from 1,000 to 1,400 cubic meters per year from the El Ocote Reserve, which harbors the only significant remaining forests in the region. If stocking density is 10 m^3 per ha in the El Ocote forests, this would be approximately 100 to 140 hectares logged per year. Most of the wood harvested is used in furniture construction by local carpentry workshops. Within the Reserve, the Chimalapas biological corridor, part of which is included in the Reserve core zone, attracts the bulk of illicit timber harvest activities. Unplanned commercial timber harvest activities can result in significant residual damage. Based on our experience measuring logging impacts in Bolivia, unplanned commercial timber harvest activities frequently result in significant residual damage to the forest, which may contribute to greater emissions of carbon by increasing decomposition of dead wood. Excessive amounts of logging slash left behind by inefficient harvest operations may also increase the risk of forest fires, though this has yet to be quantified (Cochrane and Schulze, 1999). Reduced impact logging practices can minimize residual harvest damage by as much as 50 percent (Holmes et al., 1999). The introduction of reduced impact logging practices can certainly improve retention of forest carbon, but requires a considerable cost and effort to enforce and monitor. These costs, which are likely to exceed returns from the limited credits generated, may preclude reduced impact logging practices as a source of carbon credits.

3.5 Data gaps and uncertainties

The projections of carbon sequestered from the above activities have a degree of uncertainty associated with them.

- A large source of uncertainty and the variables that strongly influence the projected amounts of carbon sequestered and retained are the initial carbon stocks in the burned area (and secondary unburned areas) and the rates of regrowth of the regenerating forests. Although we did a rapid appraisal of the existing carbon stocks in the burned area, the sample was relatively small and it may vary more than is reflected by our data.

- Growth rates of trees and survival of seedlings are estimated at this point but would have to be quantified over time to confirm which scenario is most realistic.

- In addition, data would have to be collected to project the rate of deforestation into the future. The deforestation rates we use are based on data for the period from 1972 to 1995 but a complete analysis would require an estimate based on current data (1995 to 2000), as well as information on the success of programs designed to discourage land use change within the reserve.

- Quantitative information is also needed on the success of fire prevention programs (e.g. firebreaks) and how their implementation may affect carbon stocks directly, and indirectly by facilitating land use change.

4. Reserva de la Biosfera Mariposa Monarca

4.1 Physical setting and human pressures

The Reserva de la Biosfera Mariposa Monarca (Reserve) consists of five sanctuaries (Cerro Altamirano, Sierra Chincua, Sierra el Campanario, Cerros Chivati-Huacal, and Cerro Pelon), covering approximately 16,000 ha (Figure 6). Of the 16,000 ha in the Reserve approximately 4,000 ha make up the core zone, the remaining area is considered a buffer zone. There are more than 10 communities around the Reserve with a population of approximately 50,000. The majority of the land (80 percent) is owned by ejidos who practice forest management in most cases.

The area is a mixture of topography from relatively flat areas to mountainous regions of more than 3,000 meters (m) in altitude. Temperature ranges between 6.5 and 22 degrees Celsius with precipitation of about 1,000 mm per year (Peralta, 1998). Vegetation in the area is classified as temperate pine/fir forest. Trees species found in the area are mostly *Pinus spp.*, which reach 20 to 30 m in height. Other common tree species are *Quercus*, *Salix*, and *Alnus*.

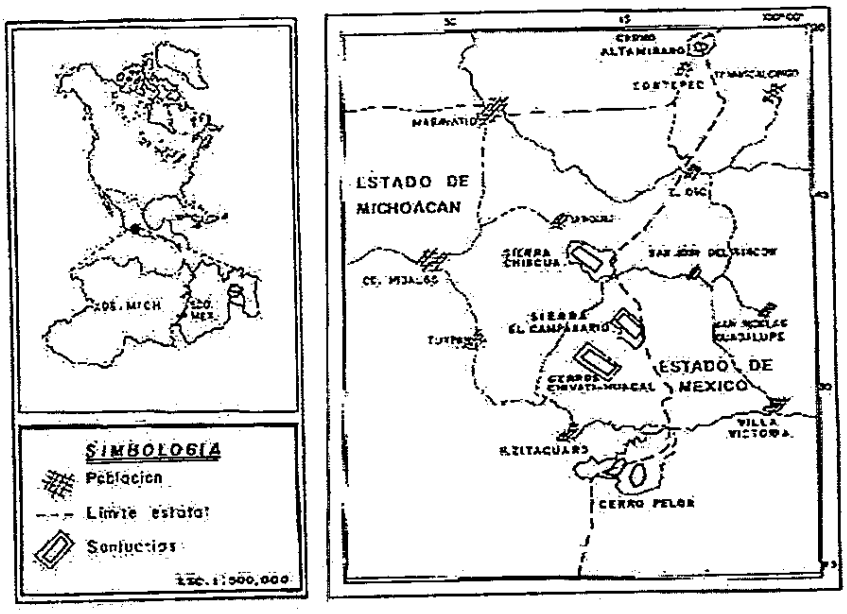

Figure 6 Map of the Reserva Mariposa Monarca

Winrock International, officials from SEMARNAP and USAID/Mexico visited the Reserve for two days in early October to assess the areas potential as a carbon project. Four transects were installed to measure standing carbon stocks in areas effected by wildfires. During the site visits, it appeared that illegal logging and over-harvesting were greater threats to the integrity of the Reserve rather than wildfires. SEMARNAP did not provide estimates of the amount of timber lost each year as a result of illegal harvesting, but in every area visited there was evidence of illegal logging (Figure 7).

Figure 7 Example of illegal timber harvesting in the Reserva Mariposa Monarca

In addition to illegal logging pressures in the Reserve many of the ejido timber lands were not well managed. We did not measure the efficiency of the logging operations in the area, but the portion of the commercially valuable timber extracted appeared low in comparison to the amount of the crown and slash left behind. Reduced-impact logging is not practiced in this region, and SEMARNAP is having limited success in halting illegal logging and improving forestry extraction practices.

4.2 Effects of the fires

Approximately 4,300 ha of the Reserve were affected by wildfires. No data were available on how the fires were distributed between the core and buffer areas of the Reserve. The majority of the wildfires that burned through the area were surface fires and did not affect mature trees. There was at least one area of about 100 ha in size (near San Cristobal) where the fire impacts were more severe, and crowns of trees were affected. However, prior to the wildfires the property had been subject to timber harvesting which removed most of the mature trees. Slash was left behind and when the wildfire burned

through it affected the remaining juvenile trees (2 to 4 m in height). In all other sites visited and from data provided by SEMARNAP it appears that the majority of wildfires were surface fires that burned the understory vegetation but left the forest intact (Figure 8).

Figure 8 Forest affected by wildfires in Sierra Chincua near Ejido Calabozo

4.3 Restoration activities

In the past, following timber harvesting no new trees were planted, but following the 1998 wildfires some areas have been replanted. To date, 328 ha have been reforested, but this activity could be classified as "enrichment plantings" in mature forest stands where only the understory vegetation was affected by wildfires. Species planted are mostly *Pinus* spp. Survivorship has ranged from 24 percent to 66 percent and is likely to decrease because the seedlings of most pine species are shade intolerant; the seedlings have been planted under closed canopy areas which provide insufficient light for development.

The fact that the extent of the damage to the forests from wildfires in this area was slight suggests that the fuel load before the fire was low. This suggests that light surface fires may burn through this area on a relatively regular basis. Replanting trees under the canopy could increase the chance that future fires would be more severe. If the seedlings grow into understory trees, these could serve as a "fire ladder" in future fires allowing the fire to reach the canopy and become a more damaging crown fire.

4.4 Potential amount of carbon sequestered or retained

Four transects (point quarter method for rapid appraisal) for measuring trees were installed in two different areas. Specifically, two transects were installed in the severely burned property near San Cristobal and two additional transects were installed in a mature forest stand in the Sierra Chincua property. Results demonstrate a wide difference in carbon content in the two areas (Table 12). The forest experiencing only a surface fire had approximately 189 t C/ha in live trees and 15 t C/ha in dead wood. In contrast the severely burned area had practically no carbon in live trees and about 16 t C/ha in dead wood—this value for dead wood is relatively low and confirms that most of the slash was consumed in the fire. For an unburned area in the region, Ordóñez (2000) obtained a range of 103 to 129 t C/ha in live trees based on more intensive sampling effort than ours during the site visit. Although Ordóñez's values are lower than our estimate, it is likely indicative of the range of biomass carbon in the area.

Table 12
Carbon content of aboveground biomass and dead wood for four transects measured by Winrock International as well as one value obtained from the literature

Location	GPS coordinates*	Aboveground biomass carbon t C/ha	Dead wood t C/ha
Sierra Chincua, near Ejido "Calabozo"—mature forest	N 2056220.0 E 281024.0 msl: 339 m	189	15
Cerro Pelon, near San Cristobal—burned	N 2162481.7 E 362869.8 msl: 2,869 m	3	16
Jacuaro, Ejido San Pedro‡		103 to 129	n/a

*GPS coordinates are in UTM, using the WGS-84 datum

‡From: Ordóñez (2000).

The results from the transects and observations in the field demonstrate that the potential to capture carbon in the burned areas in the Reserve is low because fire damage was not severe and only the surface layer was burned, including litter, understory, and seedlings. The area offers little opportunity for sequestering carbon and in our opinion it is not a good candidate for a carbon sequestration project. Only the one small area near San Cristobal was severely burned. In all other areas visited during the site visit, there appeared to be no significant impact on the carbon content of the forest as a result of the fires. The majority of the reforestation efforts are occurring in mature stands of pine and fir, and are not likely to have a major impact on the amount of carbon sequestered or

conserved over the long term. The presence of large areas of mature forest suggest that these forests have not succumbed to past fires and may be adapted to the local fire frequency.

In the severely burned area near San Cristobal, reforestation activities will probably result in a faster rate of carbon accumulation than by natural regeneration. As SEMARNAP officials pointed out, because of the high logging pressure in that area followed by the wildfires, there were not many mature trees in the area to act as seed sources. Natural regeneration could take 50 to 70 years for forests in this area to reach maturity, but with reforestation the amount of time required to reach a closed forest might decrease to 30 years or so. Over the 30 year period, the forest could accumulate about 60 to 90 t C/ha depending on species survival and growth rates (based on the data analyses for Sierra de Arteaga). Accounting for natural regeneration, which is likely to reach the same value over 50 to 70 years, the net amount of carbon sequestered through reforestation over 30 years is likely on the order of 3,000 tons of carbon in the 100 ha (the difference between reforestation and natural regeneration).

4.5 Data gaps and uncertainties

- One key piece of data missing from this area is the past history of fires and the extent of their damage. Given the presence of stands of mature trees suggests that the fire history has been such that it maintains a low fuel load, although this needs to be confirmed. If this is the case, then enrichment planting of trees in the understory of the forests could exacerbate the severity of future fires by providing "fire ladders" to the forest canopy. Further information is needed on this issue before whole scale replanting is implemented.

- Although we have recommended that the Reserve does not appear to be a good candidate for a restoration project for carbon sequestration, there are possibilities of sequestering or retaining carbon via improved forest management and/or halting illegal logging in the area. As evaluating these additional activities were not the focus or our site visit, we have insufficient information to evaluate other options. However, based on studies for forests of the eastern US, changes in forest management (e.g., less intensive harvesting through a more selective cut, improved felling to reduce damage to the residual stand) provide only small additional carbon on the land, about 1 to 3 t C/ha.yr. Such projects also produce significant challenges such a leakage and baselines; measuring the additional carbon is less of a challenge. However, halting logging in the reserve is a complex task; it is not clear if the illegally extracted timber is used for direct use (e.g.

fuelwood) or as a source of income. If illegal logging were halted in the Reserve through the addition of park guards and increased vigilance, it is possible that people currently exploiting the forest illegally would move to other forested areas outside the Reserve. This would result in a leakage problem for any proposed carbon project. To avoid this possibility, any carbon project that was created would have to consider an alternative for the people currently illegally using the forest resources inside the Reserve. Establishment of community wood plantations is one possible mechanism to meet human needs and avoid any leakage.

- The practices of the ejido owners are diverse, with some practicing sound forest management but others on adjacent properties using more intensive and destructive harvesting practices. In the community of Francisco Serrato, harvesting records over the last two years indicate extraction of pine and oak was high, averaging 24 m^3/ha, whereas in other communities extracted timber volumes are much lower. Poor logging practices may also increase the chances for a severe fire in the future. One possibility to reduce potential future catastrophic fires is through improved slash management via controlled burns.

4.6 Potential interventions in the Reserva Mariposa to increase carbon sequestered

- Based on the above information, there is little potential to increase carbon sequestration through the tree replanting activities currently underway to address wildfire impacts.

- Given the presence of many old forest stands and that the fires in this area were mostly surface fires, the forests in this area appear to be adapted to the fire frequency existing in the area. There may be some potential for improved slash management after harvesting, especially in the fire season, to reduce the risk of spread of surface fires.

- There appears to be an opportunity for a wider adoption of improved forest management to maintain more carbon on the land.

- Illegal logging is clearly a major pressure on the forests in this area, and is likely to be difficult to contain in the short run; further data need to be collected as to the cause of the illegal logging (e.g., source of fuel or timber for sale) and an investigation as to the possibility of establishing community wood plantations in areas closer to the surrounding towns.

5. Summary of Carbon Analyses

Below are classifications of risks for the three project sites (Table 13.), and potential net carbon accumulation quantified for projects areas expressed as tons of carbon sequestered or retained on a per ha and total area basis, over a 30-year period (Table 14).

Table 13
Summary of threats to carbon stocks in the study sites

Threats	Project sites		
	Reserva El Ocote	Sierra de Arteaga	Reserva Mariposa Monarca
Fire	low	high	moderate
Land use change	high	low	moderate
Logging	moderate	low	high

Table 14
Summary of the ranges of carbon sequestered and/or retained in different projects after 30 years. Estimates are the difference between the with- and without-project scenarios, estimated on a per hectare basis and total area basis

Project	Net amount sequestered or retained		
	Reserva El Ocote	Sierra de Arteaga	Mariposa
Reforestation and/or protect burned lands			
• **t C/ha**	110 to 113[1]	-10 to 89	30
• **total over area-1000 t C**	424 to 468	-50 to 452	3
Other activities			
Protection of advanced secondary forest		—	—
• **t C/ha**	129 to191		
• **total over area-1000 t C**	530 to 774		
Reforestation of degraded lands with mahogany		—	—
• **t C/ha**	19 to 137		
• **total over area-1000 t C**	124 to 893		

[1]Retention of carbon in soil is an additional 8 t C/ha

Several pilot projects designed to sequester and/or retain carbon in forests are already in some stages of implementation throughout tropical and temperate forest regions. Based on the IPCC Special Report on Land Use, Land-Use Change, and Forestry (Brown et al. 2000), these pilot projects are projected to sequester and/or retain 4 to 328 t C/ha over varying project lives (30 to 100 years) (Table 15). The estimates produced in this study for Mexico are about in the mid-range of the value for the pilot projects. On a total carbon basis, taking into consideration the area of the project, the carbon benefits from the restoration of the Mexican wildfire area are small, less than one million tons carbon. The areas involved in the pilot project phase encompass area of tens of thousand to hundreds of thousands hectares.

Table 15
Cost and carbon benefit examples of land-use change and forestry pilot projects in some level of implementation (from Brown et al. 2000). Cost estimates were obtained by dividing undiscounted costs and investment by estimated carbon benefits

Project type (number of projects)	Land Area (Mha)	Total carbon benefits (Mt C)	Costs ($/t C)	Carbon benefits (t C/ha)
Emissions avoidance:				
Forest protection (7)	2.8	41 to 48	0.1–15	4–252
Improved forest management (3)	0.06	5.3	0.3 –8	41–102
Carbon sequestration:				
Reforestation and afforestation (7)	0.10	10	1 –28	26 –328
Agroforestry (2)	0.2	10.5–10.8	0.2–10	26–56
Multi-component and community forestry (2)	0.35	9.7	0.2 –15	0.2–129

When considering implementing a carbon sequestration/retention project, cost is a key factor to take into account. The lack of other human pressures in the Sierra de Arteaga area makes the issue of baselines and leakage relatively simple to address. Furthermore, the relatively high rates of carbon sequestration that are achievable in this area and the relative ease of measuring and monitoring the carbon stocks might suggest that this project is a good candidate for a carbon project. However, the costs to implement this project could be high. First, high survival rates are key to realizing the potential and the more inaccessible ejido lands have poor survival rates. Significant costs could be expended in improving the survival rates in these lands. Fire is also a problem in this area and once again to realize the carbon potential, a significant amount of effort would need

to be expended to prevent devastating fires such as those experienced in 1998. Several fire prevention activities would need to be implemented to protect the carbon stocks in these forests including controlled burns to reduce fuel loads, construction of fire breaks, and a system for extinguishing fires if started; these are all costly tasks, particularly in the more remote areas of this region.

In El Ocote, recurring fires are likely to be less of a problem, especially if some of the practices of the land owners could be controlled. This area also has a high potential for sequestering and retaining carbon in a fairly inexpensive manner. Natural regeneration is occurring and forests are growing back well. In fact, seeding this area at this time is not recommended, but rather line or interplanting might be considered at a later date to introduce the desired species under the canopy of the young secondary forest. However, problems exist in this area with developing baselines and the potential for leakage might be high, factors that all increase the cost if implementing such projects.

Overall, it is likely that a carbon project in the El Ocote area will be less costly to implement than in Sierra de Arteaga because of the faster growth rates, the lack of need of planting (a costly operation), and the lack of need to implement major fire prevention strategies. Baseline development for El Ocote may present more problems, but they are not insurmountable. Further, policy may suggest that robust generic baselines for a region by project type could be developed which would reduce the cost significantly. Introduction of improved agricultural techniques to stabilize crop production on existing lands would lessen the potential impacts of leakage.

The projects and carbon potential scenarios that we have presented here are not easily replicated elsewhere. One cannot simply multiply the carbon sequestration amounts obtained here by areas of other burned regions. As we have shown, several factors strongly influence the amount of carbon sequestered including growth rates, survival rates, fire history, and human pressures. What can be replicated are the methods and approaches that we have used in this analysis. By demonstrating which key variables have the greatest impact on the estimated quantities of carbon, we have shown for future similar studies where the emphasis needs to be placed on data collection and information needs.

6. Design of the Carbon Measuring and Monitoring System

As discussed above, of the three sites analyzed in this study, only two offer any significant potential for sequestering or retaining carbon on the land: Reserva El Ocote and Sierra de Arteaga. Although there are several elements of a carbon measuring and monitoring plan that will be the same for both areas, there are also differences. The differences are mainly due to the nature of the measuring and monitoring activities needed to develop the without-project baseline. The details of the type of baselines, the activities leading to increased carbon on the land, and the potential amount of carbon sequestered or retained for these two projects have been described above.

Land-use change and forestry projects are generally easier to quantify and monitor than national inventories due to clearly defined boundaries, ability to stratify the area, sampling efficiency, and selective accounting. Techniques and methods for measuring individual carbon pools in LUCF (Land-Use Change and Forestry) projects are well established, and are based on commonly accepted principles of forest inventory, soil sampling, and ecological surveys (MacDicken 1997; Pinard and Putz 1996,1997). Designing a carbon measuring and monitoring system involves several steps that were outlined in the proposal; here we provide more details for each step for these two project areas.

- *Evaluate methods for baseline development, select a strategy for developing the appropriate baseline, and obtain data for the development of such a baseline*

The quantification of a without-project baseline for these type of projects is difficult because it means projecting how the land would be used by humans, recover from fire without interventions, and/or future fire frequencies. In the case of averting forest conversion to agriculture or pasture, the greatest challenge is to project rates of land-use change, that are influenced by local socioeconomic and cultural conditions, accessibility, and political factors. In the case of forest recovery after fires, the challenge it to predict how the land would have recovered through natural succession. And, in the case of changing forest harvesting practices, the challenge is to project how forest harvesting may change through time regardless of the project. For the latter two examples, nearby proxy areas can be used for data collection to help develop the without-project baselines.

For El Ocote, where averting conversion of the burned areas to pasture or slash and burn cultivation is likely to be the main focus, spatially explicit models that incorporate changes in human demographics, accessibility indices (e.g. road networks), biophysical

conditions of the land, cultural practices, and socioeconomic and political factors offer a promising method for baseline development. Regional, generic baselines that take into consideration some of the aforementioned factors offer another promising approach. However, the development of such approaches is still in its infancy, and instead in this report and analysis we relied on simple trend analysis based on past and current land-use change or harvesting practices. The lack of robust baselines for the project area, like many similar projects, is a cause for large uncertainty in the potential carbon benefits from El Ocote.

For Sierra de Arteaga, the development of a without-project baseline appears to be less problematic with respect to land-use change. From our site visit and data analysis, there appear to be few other human pressures in this area; recurring fires appear to be the main risk to the project. For this project, the potential net amount of carbon sequestered from the restoration activities will be the difference between the reforested areas, which is likely to develop into a closed forest (assuming implementation of fire prevention activities and controlled burns to maintain low levels of organic fuels), and mattoral vegetation, a persistent vegetation type after fire. To develop a credible baseline for the Sierra de Arteaga project, a proxy area of similar characteristics (e.g., slopes, aspects, and fire damage) to the project area should be identified and carbon measured as in the project area (details are given below). An analysis of past fire frequencies is also needed to help project future fire events. The carbon measurements in the proxy area should be targeted to same level of precision as in the project area to produce valid estimates of the quantity of carbon sequestered by the project.

- *Evaluate the project area and classify the project area lands into appropriate strata*

The quantification of carbon is especially challenging in the two project areas because there are several different land-cover types (strata) resulting from the fire, presence of human activities, and a variety of aspect, slope, and soil classes. To carry out a measuring and monitoring plan efficiently, the initial stratification of a project area is critical. The initial stratification guides all of the measuring and monitoring activities that occur over a project's lifetime. Stratifying the project area enables it to be sampled more efficiently because it reduces the variation within a stratum. For example, if there is one stratum designated "intensively burned" but within that area there are north and south aspects of different degrees of slope, the variation in rates of recovery and planting success may be high, and require many more plots than if the area was stratified into a few different strata. By stratifying such a heterogeneous area into more homogeneous strata, variation in field measurements can be reduced thus resulting in more precise carbon estimates.

However, there are trade-offs between the number of strata selected and sampling intensity—a balance needs to be developed between number of strata, sampling intensity, desired precision level, and cost. Furthermore, the areal extent of the project area has little effect on the sampling intensity.

Once the area of the project has been decided (about 5,000 ha for Sierra de Arteaga and uncertain for Reserva El Ocote), the first step is to stratify the area into relatively homogeneous units. Satellite imagery, aerial photos, topography maps, vegetation maps, soil maps, local knowledge, land-use history, and fire damage maps are useful sources for accomplishing this step. We suggest that the decisions for determining the number of strata be based on how all the factors are likely to influence carbon stocks and rates of regrowth in the project area rather than on plant community types for example. Clearly aspect is a key factor in Sierra de Arteaga and fire intensity in both areas. Based on experience, one should target no more than about six strata. The strata should be mapped and their areas determined.

- *Identification of the relevant carbon pools*

Criteria to consider in the selection of carbon pools to measure and monitor are the type of project, the size of the pool, their rate of change, their direction of change, cost to measure, and attainable accuracy and precision (MacDicken 1997).

The amount of carbon sequestered or retained from a project for all pools measured (pools 1 to n) are:

$= {}_{1}^{n}$ (carbon in $pool_1$ for with-project case – carbon in $pool_1$ for without-project case)

It is clear that for some pools the difference will be positive (e.g. stopping deforestation or lengthening forest rotation will have more carbon in trees on average [with-project] than conversion of forests to agriculture or shorter rotation [without-project]), but for others it will be negative (e.g. dead wood pool in an averted logging project will be less than the dead wood pool in a conventional logging practice). Basically, an accounting system may be used that includes all pools anticipated to exhibit a negative change (i.e. those pools that are smaller in the with-project case than in the without-project case) and selection of pools anticipated to give a positive change (i.e. those pools that are larger in the with-project case than in the without-project case) as a result of the project. Only pools that are measured and monitored should be incorporated into the calculation of carbon sequestered or retained. Here we discuss which pools should be measured monitored for the project areas based on these criteria.

For **Sierra de Arteaga**, carbon will be sequestered in:

- Live trees (minimum diameter of 2.5 cm)
- Understory—shrubs
- Roots
- Fine litter layer
- "New" standing and lying dead wood as trees die, fall, and shed branches

Because of the restoration work, it is expected that live biomass will accumulate more rapidly (both from planted trees and from increased naturally regenerating trees as a result of improved environment), forest litter will build up more quickly and to perhaps higher levels, and more "new" dead wood will be produced in these areas than in non-restored sites. Some carbon could accumulate in the soil over and above that which accumulates in the natural regeneration areas, however this depends on the severity of the fire and how much soil carbon was lost as a result of the fire. We recommend that the soil pool NOT be measured as the changes if any are likely to be small and the cost to detect such a small change will be high. The forest fires likely created dead wood that is emitting carbon as it decomposes. Based on our field measurements, the quantity of dead wood was rather small (about 10 t C ha^{-1} in severely burned areas) indicating most was burned in the fire. We assumed that the amount of dead wood in the with- and without-project areas would be the same and the initial amount of this component does not need to be measured.

It is recommended for the Sierra de Arteaga project area that procedures be implemented to reduce the risk of severe fires. One procedure to reduce this risk is through fuel management via controlled burns to reduce the organic fuel loads such as litter and dead wood. Although carbon will likely be sequestered in litter and dead wood, this could be periodically reduced through fire control procedures. As the carbon will be recycled periodically through controlled fires, there would be little net carbon accumulation in these two components and it might be more cost efficient <u>not</u> to measure them as part of the carbon sequestration plan. A final decision would depend on the management plans for reducing fire risk.

For **Reserva El Ocote,** we recommend that the following carbon pools be included:

- Live tree biomass (minimum diameter of 2.5 cm)

- Palms (if present)
- Understory if appears to be an important component
- Standing dead and lying dead coarse woody debris
- Fine litter if it appears to be an important component
- Roots
- Soil carbon for areas likely to be converted to permanent agriculture

Although the activities for sequestering and retaining carbon suggested for El Ocote are somewhat complex, the carbon stocks in the above pools will for the most part contribute significant amounts of carbon, though sometimes at different stages of recovery. During early stages of regrowth and recovery, understory plants can contain significant amounts of carbon (up to 10-20 percent of the carbon stocks aboveground), but as the canopy closes, the carbon in understory often decreases to less than 5 percent of the carbon in trees. Thus in the cases where the understory contributes little carbon it may not be cost efficient to measure it. Palms are a common component of many moist tropical forests and they can contain significant quantities of carbon and cost efficient methods are available for measuring them. The quantity of dead wood after the fire in this area is large (sampling one badly burned transect resulted in an estimate of 80 ton C ha^{-1}), and through time it will build up as the forest recovers and is protected from further human disturbance.

Measuring changes in soil carbon can be expensive because of the sampling intensity needed to detect often small changes against a background of large pools. However in many cases it is not necessary to measure this pool. For example, fire often does not reduce the soil carbon significantly and restoration activities are likely to have only a small effect on rebuilding this pool. Conversion of tropical forests to pastures has been shown to result in little to no loss of soil carbon (Brown and Lugo 1990, Lugo and Brown 1993) and thus activities to avoid conversion of forests to pastures would not result in carbon savings from the soil. Likewise for slash and burn cultivation, the short time period for cultivation (2-3 year) followed by a fallow period of 20 years or more would have no net effect on reducing soil carbon. The only activity that significantly affects soil carbon is conversion of forests to permanent cultivation—this generally results in a loss of soil carbon in the top 40 cm of up to 40 percent of the initial stocks over a time period of about 10 years (Detwiler 1986). Thus activities designed to reduce permanent

conversion to cultivated crops would retain significant amounts of soil carbon. Thus for these activities, we recommend that soil carbon be measured.

- *Number of measurement plots and design of sampling strategy*

For measuring forest carbon, the use of fixed-area permanent plots (a series of nested plots where forests are composed of trees of small- to large-diameter classes) is recommended; this approach is generally considered as the statistically superior means for evaluating changes in forest characteristics, including carbon pools. Within these plots, all the carbon pools can be measured or estimated. Methods are well established and tested for determining the number, size, and distribution of permanent plots (i.e., sampling design) for maximizing the precision for a given monitoring cost (MacDicken 1997) to achieve a given precision level.

The total error in measuring a given carbon pool is based on sampling error (the variation among sampling units, e.g., the number of plots, within the population of interest), measurement error (error in measuring the parameter of interest e.g. stem diameter and soil carbon.) and regression error when appropriate (e.g., error resulting from conversion of tree diameter to biomass based on a regression equation). Sampling error is usually the largest source of error (Phillips et al. 2000) and increased precision generally comes at increasing cost of inventorying because of the time and cost involved in establishing the appropriate number and distribution of permanent plots.

The number of permanent sample plots needed for the projects depends upon the variability of the carbon stocks and the desired precision level for the carbon estimates. The more precise one desires the estimates to be the more plots will be needed, and thus the more costly the measurements. For example, for the Noel Kempff project in Bolivia (an area of about 640,000 ha with six forest strata and based only on the sampling error, 452 plots were needed to be within 5 percent of the mean with 95 percent confidence (at a cost of about US$110K), 81 plots to be within 10 percent of the mean (at a cost of about US$20K), 14 plots to be within 20 percent of the mean (at a cost of about US$3K), and 4 plots to be within 30 percent of the mean (at a cost of about US$1K) (Powell 1999).

For designing the measuring and monitoring plan for the projects, the following steps are recommended:

- Obtain a measure of the variability of the carbon stocks, usually in the trees only, of each strata identified. This involves establishing about 15 or so plots in each strata and collecting data on trees and converting this to biomass carbon for each plot.

- The data are then analyzed to obtain the mean and standard deviation of the mean; this information is then used to estimate the number of sample plots needed to be within the desired precision level. For example for an area of one strata only:

    - Typical coefficients of variation (CV= standard deviation divided by the mean) of aboveground biomass carbon in forests ranges from 40to 70 percent

    - The number of sample plots needed to be within 10 percent of the mean for forests with these CVs ranges from 61 with a CV of 40 percent to 188 with a CV of 70 percent

For an area of multiple strata, the calculations are basically similar, but the variation and area of each strata are considered simultaneously; Winrock has developed software to estimate the number of plots for each strata in this situation (MacDicken 1997).

- Once the number of plots needed for each strata are estimated by the above methods, it is recommended that the actual number be increased by about 5 to 10 percent to allow for other sources of error and for the inability to locate or the destruction of plots in future inventories.

- Using the vegetation map, a systematic design, with a random start, is recommended. This means that transects lines are laid out across each strata on the map with the number of plots needed to sample a given strata located on the map. The geographical coordinates of the start of each transect should be noted, and the distance between each plot estimated. This map will serve as the basis for the installation of the permanent plots.

- Although every attempt should be made to follow the pre-established sampling design, field constraints often make this extremely challenging, particularly in rugged and fairly inaccessible areas; in this case adjustments can be made but they should be kept to a minimum.

Initial plot measurements in Sierra de Arteaga: The number of permanent plots to be installed in the Sierra de Arteaga project should be based on the variation in tree biomass carbon in existing stands of forest not burned in 1998. As the goal is to restore forest cover to the burned area, most of the carbon sequestered will occur in the later years of the project when the replanted areas become established. Thus, the precision levels should be based on the expected carbon stocks at the end of about 30 years. We recommend that the strata identified in the project area be located in existing forests

outside the burned area, and that the preliminary plots and data collection be performed in this area.

Initial plot measurements in Reserva El Ocote: The number of permanent plots to be installed in the El Ocote project should also be based on the variation in tree biomass carbon in unburned forests of the area located in strata similar to those found in the specific project area. What specific forest classes should be measured depends on the project activities, but they should include mature forests and late secondary forests.

- *Identification of appropriate methods for measuring the relevant carbon pools.*

The details of the methods for measuring all the relevant carbon pools identified above are given in MacDicken (1997). These methods have been tested in a several ongoing pilot projects in Belize, Brazil, and the USA. All these measurements are based on the establishment of fixed area nested plots. Strict adherence to these methods will ensure credible field measurements for estimating carbon quantities sequestered or retained. Additional details for each of the two project sites are as follows:

Sierra de Arteaga—As this is to be a reforestation project, in the early years there will be few trees to measure. However, the design of the plots will ensure that the procedures are in place for future monitoring when seedling will grow and move into the diameter classes covered by the nested plots. During the first one or two measuring events, the small 1 m radius plot will most likely be the only one used for trees. However for the other components (e.g. understory and dead wood), use of the larger nested plots will be required.

Reserva El Ocote—For this project area, depending on the activities, plots will be established in young recovering forests, secondary forests, and mature forests. As above, for the young recovering forests, during the first one or two measuring events only the small radius plots will be used for trees whereas the larger plots will be used for the other components.

- *Regression equations for converting tree measurements to biomass carbon*

All tree measurements will need to be converted to biomass carbon. The usual way is to use biomass regression equations. Below in Table 16 is a list of existing biomass regression equations suitable for use in these projects. These have been used extensively by other Winrock projects and some (palms and *Cecropia* spp.) were developed specifically for a given project. We recommend that these be used for the two projects here. New ones may have to be developed based on presence of any unique species

groups (e.g., other pioneers, mattoral woody species). The SOPs contain the method typically used for accomplishing this. Furthermore, it is advisable to check the accuracy of any given equations by harvesting two to three trees and determining their biomass. The carbon content is assumed to be 50 percent of the vegetation biomass.

Table 16
Regression equations used to estimate aboveground biomass of trees

Biome/Species group	Equation[1]	dbh and height range	R^2	Source
Tropical/*Cecropia* spp.	$y=12.764 + 0.2588*(D)^{2.0515}$	1 to 40 cm	0.91	Winrock International, unpublished
Tropical/palm *Euterpe precatoria*& *Phenakospermun guianensis*	$y=6.666 +12.826*(H^{0.5})*LN(H)$	1 to 33 m	0.75	Winrock International, unpublished
Tropical/ palm *Attalea phalerata* *Chryophylla* sp. Cohune	$y = 23.487 + 41.851*(LN(H))^2$ $y = 0.182 + 0.498 *H + 0.049 (H)^2$ $y = 10.856 + 176.76*H - 6.898 (H)^2$	1 to 11 m 0.45 to 10 m 0.5 to 13.3 m	0.62 0.94 0.94	Winrock International, unpublished
Tropical/palm *Astrocaryum mexicanum*	$y = EXP[3.627 + 0.577 LN(D^2H)] \times 1.02/1000$	unknown	0.73	Hughes et al., 1999
Temperate/Pine spp.	y=[0.887+(10486*(D^2.84))]/[(D^2.84)+376907]	0.6 to 56.1 cm	0.98	Brown and Schroeder 1999
Temperate/Spruce to Fir	y=[0.357+(34185*(D^2.47))]/[(D^2.47)+425676]	2.9 to 71.6cm	0.98	Brown and Schroeder 1999
Temperate/Genera hardwoods	y=0.5 + ((25000 * (D^2.5) / ((D^2.5) + 246872)	1.3 to 85.1 cm	0.99	Schroeder et al., 1997
Temperate/ General softwoods	y= [0.5 + (15000 * (D^2.7))]/ [(D^2.7) + 364946]	2.5 to 71.6 cm	0.98	Schroeder et al., 1997
Tropical moist	$y = EXP [-2.289 + 2.649LN(D) - 0.021(ln(D))^2]$	5 to 148	0.98	Revised from Brown 1997
Tropical dry	Y = EXP(-1.996+2.32*LN(D))	5 to 40 cm	0.89	Brown 1997

[1]y= biomass per tree in kg; D = dbh; and H = height; EXP = "e" raised to the quantity in brackets

Measuring biomass of roots is very time consuming and no standard methods exist. We recommend the use of a general root biomass regression equation based on an extensive database for upland forests of the world (Table 17; Cairns et al., 1997). There were no differences in the relationship of root biomass to aboveground biomass between

hardwoods and conifers and the data base was pooled. This means that these equations can be used for both groups of species.

Table 17
Regression equations for estimating root biomass (y in t/ha) from aboveground biomass (x in t/ha) for temperate and tropical forests

Biome	Equation	Number of data points	Adjusted r^2
Temperate	Y = Exp[-1.059 + 0.884 *LN(X) + 0.284]	151	0.84
Tropical	Y = Exp[-1.059 + 0.884 * LN(X)]	151	0.84

- *Frequency of monitoring events*

As both of the projects are interested in the amount of carbon being sequestered and/or retained as the forests regrow, relatively frequent monitoring will need to take place. During the first 15 years of a 30 year project, we recommend that the plots be re-measured every 5 years. For the remaining 15 years, one needs to determine if this frequency is warranted, e.g., if rates of carbon accumulation slow down one might want to monitor on a longer time interval (about 7 to 8 years), with a final monitoring at the end of the project period. Future international policy decisions regarding land-use change and forestry projects may require longer monitoring periods that would have to be taken into consideration at the end of the operational life of the project.

- *Development of a quality control/quality assurance plan*

To develop a reliable baseline and a measurement and monitoring plan for both the initial and future measurements, steps must be taken to control for errors in sampling and analysis. To accomplish this and to ensure the quality and credibility of the estimates of the quantities of carbon sequestered and/or retained, we recommend that a quality assurance and quality control (QA/QC) plan be formulated and implemented. This plan should include formal procedures to verify the without-project baselines, and methods to verify the procedures for collecting field data; the techniques to enter and analyze data; calculate the amounts of carbon sequestered and/or retained; and the inclusions of standard operating procedures for all aspects of the field and laboratory activities. We have found the following procedures are useful to accomplish these tasks:

- After the field data have been collected, a small team led by an one of field crew experts, revisit about 15 percent of the plots to verify that the plots were established correctly and that the trees were measured correctly, including the location of the dbh measurements. New field sheets are used and compared

against the original one. Any errors are corrected, and a record of the number of plots with wrong measurements recorded to enable an error estimate to be made.

- The data analysis software should have checks built into it to highlight potential errors in data entry (Winrock has developed such a software application and it is at present in the testing stage).

- Two people enter data from about 15 percent of the field sheets into the data analysis software which can then be compared to check for potential errors

- About 15 percent of the plant and litter subsamples collected for drying should be done in replicate

- A subsample of the dried plant, litter, and soil materials should be weighed again by another person

- Analysis of soil samples for carbon should include standards and replicates in every batch analyzed in the laboratory

- Use common sense when reviewing the results of the data analysis and carbon calculations to make sure that they fit within the realm of reality; compare results when possible with other similar types of projects.

- Use sensitivity analysis in the carbon calculations for uncertain variables.

As part of the QA/QC plan, a third party verification of baseline assumptions, data collection and analyses, and carbon calculations is also recommended.

- *Development of a plan for archiving and storing data*

Because of the relatively long-term nature of these projects, data archiving (maintenance and storage) will be an important component of the work. We propose that this should take several forms and copies of all data should be provided to each participating group: 1. paper copies of the field measurement sheets, laboratory data sheets, and data analyses will be placed in folders; 2. electronic copies of all data sheets, data analyses, and models (excel spreadsheets); 3. electronic copies of the final estimate of the amount of carbon sequestered and/or retained; 4. any GIS products; and 5. a hard and electronic copy of the measuring and monitoring reports. All of these data records should be kept in a dedicated and safe place.

All the electronic data should be copied onto durable media such as CDs. We recommend that given the time frame over which this project will take place and the pace of production of updated versions of software and new hardware for storing data, that the electronic copies of the data and report be updated periodically by the chief project manager.

- *Promising new technologies being developed to increase the cost efficiency of carbon monitoring*

Remotely sensing can provide a useful means for monitoring land-use change and forestry projects, and a range of remote data collection technologies are now available ranging from satellite imagery to aerial photo-imagery from low flying airplanes. However, none of these have yet been shown to measure forest biomass carbon to acceptable levels of accuracy and precision suitable for projects. A promising advance in this area couples dual-camera digital videos (wide-angle and zoom) with a pulse laser profiler, data recorders, and differential GPS (geographical positioning system) mounted on a single engine plane (Winrock International and Dana Slaymaker are developing such an approach which is presently in the testing stage; Slaymaker 1999). This system is able to produce indices of crown density and area, number of stems per unit area, canopy and individual tree height (from the pulse laser), a combination of which is expected to correlate highly with aboveground forest biomass. The plane flies aerial transects across the project area at know altitudes capturing 200 m wide georeferenced strips and a resolution of 50 cm with the wide-angle camera, and a 20 m wide georeferenced strips and a 3 cm resolution with the zoom camera. The plane also flies at higher altitudes above ground using 70 mm film to collect stereo images; these images are used to create 3-D models of the terrain. From analysis of these two sets of data, individual crowns, species types, tree height, and the presence of large emergent trees can readily be interpreted. This type of system will be especially useful for monitoring projects related to arresting or modifying logging and monitoring for small-scale human disturbance in protected forests as the presence and extent of forest gaps can readily be observed. Routine collection (every 5 years or so) of dual-camera videography data such as described here, initially calibrated with field measured data on carbon pools, over the life of the project will be crucial for monitoring both the with-project activities and proxy without-project cases.

Another promising advance in remote monitoring of forest biomass and thus carbon is a scanning lidar (a pulsed laser), a relatively new type of sensor which explicitly measures canopy height. NASA planned to include this sensor in one of its first Earth System Science Pathfinder program missions to be launched in late 2000, however budgetary

issues have placed this mission in jeopardy (more information at: www.inform.umd.edu/geog/vcl). The mission is planned to collect data from 25 m wide footprints continuously over land between 67 N and S and would provide three measures: canopy top height, vertical distribution of canopy elements, and surface topography below the vegetation canopy. This sensor will be able to monitor 98 percent of the earth's closed canopy forests. To date, variations of the airborne lidar have been tested over several forest types and the tests have shown its ability to successfully measure canopy height for conifer forests of the Pacific Northwest USA (Means et al., 1999), deciduous forests in Maryland, USA (Lefsky et al., 1999), and various aged secondary and mature tropical forests in Costa Rica (B. Peterson and J. B. Drake, University of Maryland 1999, pers. comm.). In the conifer forests of the Pacific Northwest, very high correlations were obtained with the sensor data and height, basal area, and total biomass (Means et al., 1999).

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