Economic Value of the Carbon Sink Services of Tropical Secondary Forests and its Management Implications

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Abstract

This paper explores the economic feasibility secondary forest regeneration and conservation as an alternative to help address global warming. Detailed measurements of tropical secondary forests through time, in different ecological zones of Costa Rica, are used for estimating carbon storage models. The paper addresses key issues in the international discussion about cross- and within-country compensation for carbon storage services and illustrates a method to compute/predict their economic value through time under a variety of scenarios. The procedure is applicable to other developing countries where secondary forest growth is increasingly important.

Key Words: Tropical Forests, Carbon Sequestration, Global Warming, Activities Implemented Jointly.

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Traditionally, forests have been perceived as a source of timber, wood and other extractive products such as medicinal and ornamental plants. The importance of the ecological services provided by the forests has been neglected in the past. This perspective has changed considerably due to international and local initiatives that view forests as ecosystems that render both productive and service functions. An ecological service that has been internationally recognized is carbon sequestration. Plants capture CO_2 from the atmosphere through photosynthesis, fixing carbon (C) in their biomass and releasing oxygen (O_2). Forest ecosystems contain 20 to 100 times more carbon per unit area than agricultural ecosystems (Andrasko, 1990; Schroeder, et al., 1993).

The Intergovernmental Panel on Climate Change (IPCC) has discussed the possibility of using forests to mitigate the atmospheric concentration of greenhouse gases. The United Nations Framework Convention on Climate Change, a result of the Río Conference, was signed by 162 countries and ratified by 20 (Andersen, 1996). Most of them agreed in the Kyoto Protocol to substantially reduce their carbon dioxide (CO_2) emissions. “Activities Implemented Jointly” (AIJ) programs, introduced under the Kyoto Protocol, can help industrialized countries achieve emission reduction targets. AIJ involves cooperative government or private sector initiatives with the aim of reducing future emissions or sequestering CO_2 currently in the atmosphere. A country/ industry can achieve carbon mitigation credits by reducing its emissions through improved technologies or by financing initiatives that promote forest conservation or regeneration.

According to the IPCC, deforestation has been the cause of releasing 16,000 million metric tons of carbon (mtC) ($1tC=3.67tCO_2$) into the atmosphere, and 450 million hectares of forest would need to be planted to sequester the 29,000 million mtC that have accumulated in the atmosphere as a result of all past emissions. AIJ could be an important instrument for increasing forest areas and sequestering the CO_2 currently in the atmosphere, or at least slowing deforestation and land use change, which avoids additional emissions. Ecosystem studies have shown that dry biomass in tropical forests varies between 150 and 382 metric tons per hectare (mt/ha). Assuming a carbon to dry biomass ratio of 45 percent (Houghton, et al., 1991; Brown and Adger, 1993), their long-term carbon storage capacity would be between 67.5 and 171 mt/ha. Fearnside and Malheiros (1996) measured biomass levels of 52.8 mt/ha in five-year-old stands of Brazilian secondary forest, and of 196.6 mt/ha in 25-year-old stands.

Andersen (1996) estimated long-term carbon storage capacity at 140 mt/ha in mature primary forests, at 55 mt/ha in partially intervened forests, and at only ten mt/ha in pastureland. Calculations for primary forests in Costa Rica indicate biomass levels of between 167 and 283 mt/ha, and of between 152 and 237 mt/ha for secondary forests (Carranza, 1996). This is equivalent to 75.15 to127.3 and 68.4 to106.6 mtC/ha, respectively. These figures indicate that secondary forests might be important carbon sinks. However, they have been minimally studied in comparison to primary tropical forests.

This study estimates the magnitude and potential economic value of the carbon sequestration/storage service rendered by the naturally regenerating humid tropical secondary forest of Costa Rica, under a variety of scenarios. It identifies AIJ conditions under which the conservation of these forest areas would be economically attractive. The paper concludes that a modest but sustained increase in secondary forest areas in a small developing country like Costa Rica can generate significant economic benefits through AIJ agreements with industrialized countries and/or their domestic industries wanting to earn CO_2 mitigation credits.

Data, Methods and Procedures

Seven years of individual tree diameter measurements in experimental forests of the CATIE/PROSIBONA silvicultural management project are used to estimate a biomass accumulation model. Specifically, the data was collected from nine plots in four different humid tropical forest areas of Costa Rica, with stands between two and 44 years of age: The “Florencia”, “Tirimbina”, “Espaveles”, and the Ian D. Hutchinson experimental sites. The Ian D. Hutchinson site is in a 44-year-old secondary forest. The original forest was selectively harvested and then cut down to use the land for cattle ranching. A few years later, the site was abandoned. The site consists of 180 ha's of humid tropical forest (bh-T), according to Holdridge's life zone classification system. PROSIBONA started experimental studies at the site in 1987. It established experimental plots in 1988 and took the first diameter measurements when the forest was 34 years old. Follow-up measurements were obtained in 1989, 1990, 1991, 1993, 1994 and 1995.

The "Tirimbina" site is in a life zone classified as very humid premontane forest transition to basal (bmh-P) and very humid tropical forest (bmh-T), according to Holdridge's life-zone system. It has an extension of 29.16 ha's and contains four experimental plots. Its origins are traced to the abandonment of rice crops after a single year of farming. Diameter measurements were started in 1987, in two-, five-, 15-, and 25-year-old forest plots. Follow-up measurements were taken annually until 1992, and again in 1995. The "Espaveles" site is 20 ha's of primary (13.4 ha's) and secondary (6.6 ha's) forest, in a life zone classified as a humid premontane forest (bh-P) according to Holdridge. The site was deforested in 1937 and dedicated to rubber (*Hevea brasiliensis*) plantations in 1944. Other crops like plantain and pineapple were grown afterwards. Experimental studies on rice production were also conducted in the area, which was finally abandoned in 1954. PROSIBONA took the first measurements in 1988 when the secondary forest was 35 years old. Follow-up measurements were taken annually until 1992, and again in 1997.

The "Florencia" site is 32 ha's of secondary forest in a very humid tropical forest (bmh-T) life zone (Holdrige). The soils in this area have a low productivity. PROSIBONA started diameter measurements in 1993 when the forest was 27 years old. Follow-up measurements were taken in 1994, 1995 and 1998. Although trained professionals took the individual tree measurements, measurement errors are always possible, and represent a source of uncertainty in the analysis.

The Biomass Accumulation Model

Biomass accumulation is predicted for each individual tree using an equation estimated by Brown, Gillespi and Lugo (1989), with data from humid tropical forests:

$$(1) \qquad Yi = 13.675 - 6.1181\,Di + 0.8391\,Di^2 + ei$$

where *Yi* is the total biomass of the ith three, in kg of dry weight, *Di* is the tree's diameter at breast height (DAP) and *ei* is an error term. Equation (1) has a coefficient of multiple determination (R^2) of 90%. This high R^2 only means that equation (1) would be quite precise for predicting biomass based on diameter measurements in forests with a similar mix of species and growing conditions than those prevailing in the forest from which it was estimated. Using this equation to predict biomass in the forest sites included this study could involve substantial extrapolation uncertainty.

The biomass accumulation on each of the experimental plots at year-of-measurement *x*, which corresponds to a given forest age in that plot and site, is estimated by adding up the biomass predictions for all individual trees on the plot at year *x*, and transformed into per ha bases using the plot's area. The resulting data set consists of 50 biomass observations from forests from one to 44 years of age. This data set is used to estimate a non-linear model based on an adaptation of the forest-volume growth function proposed by Richards (1959), which is widely used because of its flexibility. It can accommodate a wide variety of growth rates following near-linear, curvilinear and s-shaped patterns, and it always ends on a plateau. The model is:

$$(2) \qquad Y(x) = a_S(1 - exp^{-bx})^c + e; \; s=1,2,3,4$$

where $Y(x)$ is biomass accumulation as a function of forest age (x), a_S estimates the maximum biomass accumulation capacity in each forest site *s* (1=Florencia, 2=Tirimbina, 3=Ian Hutchinson, 4=Espaveles), *b* is the biomass growth rate[1], and *c* does not have a particular biological interpretation. The error term is assumed to be an independently distributed normal random variable with zero mean and variances σ_S^2 (s=1,2,3,4), to account for differences in the variability of forest growth across sites. The model is estimated by using the Newton-Raphson algorithm (OPTMUM procedure) of GAUSS 386i to maximize the following log-likelihood function:

$$(3) \qquad LL = \sum_{t=1}^{50} -ln(\sigma_S) - 0.5\{[Y(x) - a_S(1 - exp^{-bx})^c]/\sigma_S\}^2$$

where σ_S equals σ_1, σ_2, σ_3, or σ_4 and a_S equals a_1, a_2, a_3 or a_4 depending on whether the biomass observation is from site 1, 2, 3 or 4. A factor of 0.45 is used to transform the model's biomass predictions to carbon. This factor does not differ substantially across humid tropical forest types (Houghton, et al., 1991; Brown and Adger, 1993). Thus, it is not likely a major source of error.

Valuing of Carbon Sink Services

When valuing carbon sink services, it is important to distinguish between the three different accounting philosophies reflected in current AIJ programs: carbon storage, carbon parking and carbon sequestration. Carbon storage relates to the forest capacity to maintain a certain amount of biomass per ha, which means that the carbon in it is not being released into the atmosphere. In this case, pricing refers to a one-time payment for forest conservation. Land-use change is permanently voided through, for example, the establishing of a national park. The value of the carbon storage service lies in avoiding potential future CO_2 emissions forever.

Carbon parking is less restrictive than carbon storage. Here, pricing refers to the principle applied in the recent agreements with Costa Rican landowners, which sanction land use changes during a limited 20-year period in return for an economic compensation of U.S.$200 per ha during the first five years of the agreement. Deforestation and land use change is at least forestalled, avoiding carbon emissions while the agreement is in force. Carbon sequestration refers to the removal of CO_2 currently in the atmosphere; i.e., the mitigation of past emissions. Carbon sequestration by forests is a function of their biomass growth rates. Marginal social damage costs refer to the economic value of the damage caused by the emission of an additional metric ton of carbon (mtC) into the atmosphere. Therefore, valuing carbon sink services at marginal social damage cost estimates is only conceptually correct in the case of carbon sequestration.

Fankhauser and Tol (1996), and Tol (1999) discuss the wide range of marginal social damage costs estimated by various authors, which average approximately U.S.$20/mtC. Abatement costs refer to the cost of maintaining and/or reducing carbon emissions to certain levels (for example, to those agreed in the

Kyoto constraint). In practice, marginal damage and abatement costs are not likely the same. Abatement costs are more representative of the anticipated market price of carbon, and could be more appropriate to value carbon sequestration.

Some developing countries have been able to negotiate international compensation for carbon parking services. For example, Costa Rica signed an AIJ agreement with the Norwegian government, receiving U.S.\$10/mtC parked in a specific forest area during a 20-year period. It has also issued 20-year carbon parking certificates that are being marketed internationally at the Chicago Mercantile Exchange [Costa Rican Office for Joint Implementation (OCIC[2]) (1995)].

Internally, Costa Rica's law, through the National Investment Fund for Forest Financing (FONAFIFO[3]), provides the same level of compensation to landowners for both carbon sequestration and carbon parking services [Executive Decree No.26967, Ministry of Natural Resources and Environment (MINAE) (1996)]. If sequestration were the prime objective of AIJ agreements, however, payments should mostly be made for regenerating forest areas during their years of growth. The payments should be based on marginal social damage or abatement costs. Payments could also be made for the conservation of older secondary forest areas through carbon parking or storage contracts to avoid land use change and the resulting CO_2 emissions.

Carbon storage agreements are rare, and reliable reference prices are not available. Under the forest owner perspective, they should entitle higher payment rates than parking, due to the uncertainty about future carbon, timber and land values. Parking contracts give owners the advantage of being able to periodically reassess whether to harvest or to engage in another contract. The risk premium that would be commanded for the higher degree of uncertainty associated with carbon storage would difficult to estimate. Under the correct risk premium, however, the decision-makers should be indifferent between a carbon parking and a carbon storage contract. Therefore, acceptance of a carbon parking contract at a given compensation rate would be equivalent to agreeing to a storage contract at a higher, risk-adjusted compensation level. In light of the former, the analysis will focus on carbon sequestration and parking only.

The economic analysis assumes that owners evaluate a large set of long-run forest land use alternatives during the first year that carbon parking/sequestration contracts are available (Table I). The more obvious alternatives are: to clear/harvest the forest and sell or devote the land to its most profitable alternative use; to enter the forest into a carbon sequestration contract; to enter the forest into a series of carbon parking contracts without harvests in between contracts; and to enter the forest into a series of carbon parking contracts with harvests in between contracts.

There are "mixed" alternatives that could also be economically desirable, such as entering the forest into one or more carbon parking contracts, with or without harvests in between contracts, then harvesting and switching into a carbon sequestration contract or selling or devoting the land to its most profitable alternative use. All alternatives involve the decision of whether to have a clearing/harvest before entering the first contract. This set of alternatives implies that forest areas that have been entered into one or more carbon parking contracts can be harvested and switched into a carbon sequestration agreement or sold once the last parking contract has expired. No other type of switching is allowed, since it would constitute a breach of contract. The payment rates for carbon sequestration are based on the previously discussed marginal damage and abatement costs estimates. Because of the variety of estimates available, three potential payment rates of U.S.$10/mtC, U.S.$25/mtC and U.S.$40/mtC sequestered are considered in the economic analysis. It is assumed that payments are made annually on the basis of the amount of carbon sequestered during that year.

As in the existing Costa Rican AIJ agreements and CTO initiatives, carbon-parking contracts are for 20-year periods. The 20-year carbon parking compensation rates of U.S.$5/mtC, U.S.$15/mtC U.S.$25/mtC used in the analysis are also based on these experiences. Payments to forest owners are made annually depending on the amount of carbon parked during that year. Equal payments are calculated by making their present value equal to the assumed up-front 20-year compensation received by the government, using a real social discount rate of five percent.

Given the formerly discussed payment rates and switching possibilities, forest owners must consider the age of their forests when entering the first contract in order to identify the land use alternative that will maximize long-term revenues. The problem is analyzed on a per-hectare basis by comparing the present value of the net revenues that would result from each of the possible alternatives. The net present value of clearing/harvesting the forest and devoting the land to its most profitable alternative use, is simply the opportunity cost of the land (*OCL*) plus the value of the harvest [*VH(x)*], if any, minus the cost of the clearing/harvesting [*CH(x)*]. Note that *OCL* is assumed to remain constant, in real terms, while *VH* and *CH* depend on the forest age (*x*).

Opportunity costs of between U.S.\$500/ha to U.S.\$1,000/ha have been reported for marginal agricultural lands such as those currently occupied by secondary forests in Costa Rica (Ramirez and Gómez, 1998). These two extremes are used to represent a low and a high *OCL* in the analysis. A harvest from a secondary forest that is less than 20 years old has little or no value in Costa Rica. For forest that are more than 20 years old, the value of the harvest (*VH*) is assumed to be U.S.\$3.5/mt of biomass. The cost of clearing/harvesting a forest (*CH*) is assumed at U.S.\$1/mt of biomass. The net present value (NPV) of entering one hectare of forest of initial age I into an irrevocable carbon sequestration contract, is calculated by:

$$(4) \qquad PVCSQ = \sum_{t=1}^{M} 0.45CSPt[a(1-exp^{-b(t+I)})^{c}-a(1-exp^{-b(t+I-1)})^{c}]/(1+i)^{t}$$

where $a(1-exp^{-b(x)})^{c}$ is evaluated at the maximum likelihood parameter estimates for *a*, *b* and *c* to obtain a prediction of forest biomass level at age *x*. *M*=200 years for the purpose of the analysis, 0.45 is the biomass-to-carbon conversion rate, *CSPt* is the annual payment for the carbon sequestration service in real U.S.\$/mtC, which in some scenarios will be allowed to change through time (*t*), and i is the real discount rate assumed. The NPV of entering a hectare of forest of age I into continuously renewing carbon-parking contracts with no harvests in between contracts and annual payments at the end of each year (*t*) is calculated by:

$$(5) \qquad PVCP = \sum_{t=1}^{M} 0.45CPPt\, a(1\text{-}exp^{-b(t+I)})^{c}/(1+i)^{t}$$

where *CPPt* is the annual payment for the carbon parking service in real U.S.\$/mtC, which in some scenarios will be allowed to change through time (*t*).

The NPV of entering one hectare of forest of age I into a series of continuously renewing carbon-parking contracts with total, extractive harvests at the end of each contract is given by:

$$(6) \qquad PVCPH = \sum_{t=1}^{20} 0.45CPPta(1\text{-}exp^{-b(t+I)})^{c}/(1+i)^{t} + \sum_{t=21}^{40} 0.45CPPta(1\text{-}exp^{-b(t-20)})^{c}/(1+i)^{t}$$

$$+\ldots+ \sum_{t=181}^{M} 0.45CPP_{t}a(1\text{-}exp^{-b(t-180)})^{c}/(1+i)^{t} + NVH(20)/\{(1+i)^{40}(1\text{-}exp^{-(20\ i)})\} + NVH(I+20)/(1+i)^{20}$$

where *NVH(x)* is the net value of the harvest, i.e. the value [*VH(x)*] minus the cost [*CH(x)*] of the harvest, for a forest if age *x*. The NPVs of the "mixed" alternatives are calculated by combining elements of the previous formulas. For example, the NPV of entering a forest of age I into one carbon parking contract, then harvest and sell or devote the land to its most profitable alternative use is given by:

$$(7) \qquad PV1CPHSL = \sum_{t=1}^{20} 0.45CPP_{t}\, a(1\text{-}exp^{-b(t+I)})^{c}/(1+i)^{t}\} + (NVH(I+20)+OLC)/(1+i)^{20}$$

The net present value of entering one hectare of forest of age I into one carbon parking contract, then harvesting and switching it into a carbon sequestration contract is given by:

$$(8) \qquad PV1CPHSQ = \sum_{t=1}^{20} 0.45CPP_{t}\, a(1\text{-}exp^{-b(t+I)})^{c}/(1+i)^{t}\} + NVH(I+20)/(1+i)^{20}$$

$$+ \sum_{t=21}^{M} 0.45CSP_{t}\, [a(1\text{-}exp^{-b(t-20)})^{c}\text{-}a(1\text{-}exp^{-b(t-21)})^{c}]/(1+i)^{t}$$

In all cases above, the net present value of the option of harvesting before entering into the first contract is obtained by evaluating the corresponding equation for I=0 and adding the net value of the harvest for a forest of age I (NVH(I)). Equations (4) through (8) and other similarly obtained equations are used to determine which of the alternatives in Table II would be preferred by the forest owners given their forests' current age (I), 11 different combinations of carbon sequestration and parking compensation rates, two *OCL* values ($500 and $1000), two alternative real discount rates of 5% and 10%, and three forest growth scenarios discussed below.

Due to the lack of detailed forest inventory data, five informed assumptions are necessary to extrapolate per hectare results to all of Costa Rica's humid secondary forests:

1. The best secondary forest cover estimates available are correct: 425 thousand ha's, of which 302 thousand (71%) are humid. Of the latter, 160 thousand (53%) are less than 15 years old and the remaining are more than 15 years old (Solórzano, et al., 1991).
2. Significant secondary forest growth started in the late 1940s (Solórzano, et al., 1991).
3. Within the 0-15 and the 16-50 year-old categories, the forest age distribution is homogeneous.
4. Secondary forest areas could potentially grow at the estimated 1984-94 rate of 12,800 ha/year (Kaimowitz, 1995; CORFOGA, 1995) for ten more years and at half that rate until 2110.
5. Seventy-one percent of the future growth in forest areas will be humid secondary forests; i.e., that the current humid-to-dry secondary forest proportion will be maintained.

The aggregate economic valuation results are contingent upon these assumptions. Another major source of uncertainty arises when extrapolating the carbon storage predictions from experimental plots to all of Costa Rica. As mentioned earlier, the experimental areas are located in the four main types of humid tropical secondary forestlands found in Costa Rica. However, the share of the total forest area growing in each of these types of forestlands is unknown. A sensitivity analysis is conducted to address this lack of information. Specifically, pessimistic (optimistic) scenario assumes that the slowest (fastest) of the four estimated forest growth models holds for all areas. The average scenario assumes that the average of the biomass accumulation levels predicted by the four models through time and the average of the maximum biomass accumulation capacity estimated for each of the four forest sites holds for all forest areas.

There is also uncertainty about the price to be paid per unit of carbon parked/sequestered. Thus, the effect of a range of possible compensation rates per unit of carbon parked/sequestered is evaluated through sensitivity analysis. The impact of two alternative real discount rates (5% and 10%) on the economic valuation results is also investigated.

The country-level situation is analyzed by assuming that at the initial year (2000) all existing forest areas are placed in the land use alternative that would maximize the flow of discounted net revenues to their owners, given the forests ages and expected rates of growth, the carbon parking and sequestration payment rates, the net value of the harvest, the opportunity cost of the land, and the real discount rate. Each year after 2000, owners of potentially additional secondary forest areas also place them in the net revenue-maximizing land use alternative.

This identifies the number of hectares of forests of different ages that would be standing under either a carbon parking or a carbon sequestration contract during any given year after 1999, and the number that has been dedicated to an alternative use, if any. Therefore, it allows for the calculation of the average amount of carbon being parked in all Costa Rican secondary forest areas through time, and of the aggregate revenues being received each year from carbon parking and carbon sequestration payments, forests harvests, and land sales, if any. All of the computations are conducted using matrices and matrix operations. The procedures, matrices, matrix operations and GAUSS programs utilized are available from the authors upon request.

Results

Biomass Accumulation

Table II presents the results from the estimation of the biomass accumulation model (equation 2). It has a coefficient of multiple determination (R^2) of 62.3%, which is excellent for a model estimated combining times-series and cross-sectional data (Judge, et al., 1985). The log-likelihood function reaches a maximum value of -166.44. The relatively small asymptotic standard errors of the parameters that estimate maximum biomass accumulation (a_1, a_2, a_3 and a_4) suggest that the secondary forests at the four sites reach different maximum biomass levels: 101.54 mt/ha in Florencia, 190.11 mt/ha in Tirimbina, 142.53 mt/ha in Ian Hutchinson, and 162.13 mt/ha in Espaveles (Table II and Figure 1). These variations are attributed to the different mix of species, soil quality and climate prevailing on each site.

The likelihood function for a restricted model where $a_1=a_2=a_3=a_4$ (RM I) only reaches a maximum value of –180.21. The $\chi^2_{(3)}$ test-statistic for Ho: $a_1=a_2=a_3=a_4$ vs. Ha: not all a_i's are equal (Judge, et al., 1985) has a value of 27.54, implying rejection of Ho at the 1% significance level. Individual $\chi^2_{(1)}$ test-statistics (not presented) indicate that none of the a_i's are equal to one another. The further restriction Ho: $\sigma_1=\sigma_2=\sigma_3=\sigma_4$, imposed in model III, is also rejected by a likelihood ratio test. Individual $\chi^2_{(1)}$ test-statistics (not presented) suggest that $\sigma_1\neq\sigma_2=\sigma_3$, $\sigma_1\neq\sigma_4$ and $\sigma_4\neq\sigma_2=\sigma_3$. Biomass level variability is only similar in sites 2 and 3.

Depending on the site, the unrestricted model forecasts that between 70% and 80% of the maximum biomass level is reached in 20 years, and between 85% and 95% is achieved during the first 30 years of forest growth. On average, these ecosystems are predicted to sequester approximately four mtC per ha-year during their first ten years of growth and nearly an additional one mtC/ha/year during the next ten years. After 40 years of forest growth, they can permanently store or park an average of 60 mtC per hectare. In comparison, preliminary estimates for artificial tropical forestry plantations indicated a carbon sequestration capacity of 7.7 mtC/year during the first 15-20 years of growth (Ramirez and Gómez, 1999). However, the establishment costs can exceed U.S.$1,000/ha. Mature tropical primary forests do not sequester significant amounts of carbon, but can store between 80 and 90 mtC/ha (Ramirez, et al., 1999).

Economic Valuation of Carbon Sink Services

Table III summarizes the results of the per hectare analysis for average growing forests (similar tables for slow and fast growing forests are available from the authors). There is a wide range of variation on the optimal, NPV maximizing alternative, depending on the assumed scenario. In several scenarios, especially those involving the higher discount rate, there are two optimal alternatives, one for forests entering contracts at younger ages and another for older forests. Only some of the alternatives evaluated ever appear as optimal. These can be classified into two groups depending on their implied long-term carbon storage levels. Alternatives (2), (3), (4), (5), (8), (12) and (13) all result in the highest possible long-term average carbon storage levels of 38.5 to 44mcC/ha (slow forest growth), 56.6 to 62.4mtC/ha (average growth) and 72.1 to 82.4 mtC/ha (fast growth). Alternative (1) produces zero carbon storage while alternatives (6), (14) and (15) result in very low long-term average carbon storage levels of under ten mtC/ha. Alternative (1), (2), (3) and (8) appear as optimal in more than 90% of the scenarios evaluated.

Alternative (1), which is to clear or harvest and sell the forest land at the assumed *OCL*, prevails in all of the scenarios involving the lower payment rates for carbon parking and sequestration (5/10) and a high discount rate. At these low payment rates, alternatives (12) and (13), which involve two parking and harvest cycles and then sequestration, are only preferred to (1) under fast growth and the lower *OCL* of U.S.$500/ha. Under slow forest growth, a high 10% discount rate and the higher *OCL* of U.S.$1000/ha, alternative (1) is optimal for all carbon payment rates evaluated. Under average forest growth and a high discount rate, the highest carbon sequestration payment rate is required to avoid alternative (1) or (6) (one parking contract, a harvest and then sell at the assumed *OCL*) in favor of alternatives (2) or (3).

Alternatives (2) (sequestration), (3) (clearing/harvest and then sequestration) and (8) (repeated carbon parking with no harvests) are preferable from the environmental standpoint because of their superior long-term average levels of carbon storage. Alternatives (2) and (3) are optimal at the intermediate payment rate for carbon sequestration (U.S.$25/mtC) under both discount rates, as long as the *OCL* is low. When the *OCL* is high, alternative (2) and (3) are also optimal at this carbon sequestration payment rate under average forest growth and a low discount rate, and under fast growth regardless of the discount rate.

Alternative (8) is optimal at the intermediate payment rate for carbon parking (U.S.$15/mtC per

20-year period) and the lower discount rate and *OCL*, under the three forest growth scenarios. Alternative (8) is also optimal under an *OCL* of U.S.$1,000 for average- and fast-growing forests, as long as the discount rate remains low. In short, the intermediate compensation rates for carbon sequestration/parking are sufficient to motivate secondary forest conservation under most realistic scenarios. However, the highest compensation rate for carbon sequestration (U.S.$40/mtC) is required under average forest growth if both the discount rate and the *OCL* are high, which is not an unlikely scenario. The present value of the net stream of income per hectare accruing to a forest owner from carbon payments, harvests and/or the clearing and sale of the land under the different scenarios and the corresponding optimal alternatives is also reported in Table III. If the optimal alternative does not involve clearing, harvesting or sale [such as alternative (2) and (8)], this is equivalent to the actualized value of the carbon payments. An average growing forest achieves a 200-year average carbon storage level of over 60 mtC when alternative (2), (3) or (8) are implemented.

Under average growth, a low carbon parking payment and an intermediate carbon sequestration payment rate (5/25), alternatives (2) or (3) are optimal, depending on the age of the forest when considering a contract. The NPV is U.S.$819 in the case of a new forest in a low *OCL* area and a 10% discount rate. This is also the actualized cost of securing the carbon sink service. At the 5% discount rate the cost increases to U.S.$1,049 because of the decreased time-value of money. Under this scenario, middle aged forests are cleared before entering the sequestration contract [i.e. alternative (3)]. Therefore, the payments for carbon sink services are the same in the case of new and middle aged forests, but the values reported in Table III are lower because they include the cost of the clearing. The payments are also the same for 30-year-old forests, although the value accruing to owners increases due to the income-generating harvest before entering the carbon sequestration contract, which is included in alternative (3).

The disadvantage of alternative (3), in the case of existing forest areas, is that it involves a clearing/harvest before entering the carbon sequestration contract, which could be controversial. Although this would be hard to enforce, banning the former leads to alternative (2), which is never optimal in forests that are one or more years old. Carbon sequestration is only attractive to forest owners if they can capture the large annual payments earned during the first few years of accelerated secondary forest growth. Under average forest growth but intermediate payment rates for both carbon sequestration and parking (15/25), alternative (8) is optimal at all forest ages, as long as the discount rate is low. The NPV is U.S.$1,057 in the case of a new forest, U.S.$1,360 for a 15 year-old forest, and U.S.$1,438 for a 30 year-old forest, regardless of the *OCL*. These are also the actualized costs of securing the carbon sink service, since there are no clearings/harvests involved. Although the long-term carbon storage levels would be similar, the costs are substantially higher for older forests that start with high biomass levels, due to the time-value of money effect. The same effect causes the costs to be lower (U.S.$720, U.S.$1,070 and U.S.$1,204, respectively) at the 10% discount rate. Alternative (8), however, is never optimal under a high *OCL* and discount rate.

An interesting combination of alternatives arises under payment rates that increase by constant amounts during the first 20 years from five to 25/mtC for parking and from ten to 40/mtC for sequestration, average and fast forest growth and a 10% discount rate. Alternative (4) (one parking contract, a harvest and a sequestration contract) is optimal for younger forests and alternative (5) (a harvest, one parking contract, a harvest and a sequestration contract) becomes optimal for forests that are 20 years old or older. As discussed before, these alternatives are among those achieving the highest average long-term carbon storage levels.

In general, the payment rate schedule that minimizes the cost of achieving a near- maximum level of long-term carbon storage is different depending on the prevailing scenario. However, secondary forest conservation and the corresponding carbon sink services can be secured through carbon sequestration or parking contracts, spending less than U.S.$1,500/ha under most scenarios. This implies long-term average levels of carbon storage of 40 to 80mtC per ha, depending on the rate of forest growth, and up-front unit costs of between U.S.$15 and U.S.$25 per mtC placed under long-term storage, depending on the prevailing scenario.

An estimated 300,000 hectares of humid tropical secondary forests exist in Costa Rica to date. The assumed maximum of one million hectares reached by 2110 would complete the process of recuperating all areas deforested from 1945 to 1980, during a dramatic expansion of the cattle-ranching frontier. Figure 2 shows the estimated amounts of carbon stored in these areas through time, by forests of all ages, under the main land use alternatives identified in the per hectare analysis: infinitely-renewing parking contracts [alternative (8)], which is equivalent to sequestration without an initial clearing or harvest [alternative (2)]; clearing or harvest and then sequestration [alternative (3)]; and alternative (4) (parking, harvest and sequestration) for younger forests combined with alternative (5) (harvest, parking, harvest and sequestration) for forests that are more than 19 years old. Alternative (8) only produces substantially higher storage amounts than alternative (3) during the first 20 years. Much larger long-term differences are caused by the assumed rate of forest growth. This means that it would be important to establish precise forest growth rates in areas where large-scale AIJ programs are implemented.

The results of the country-level analysis, which includes two pessimistic, three realistic and two optimistic scenarios, are presented in Table IV. Figure 3 shows the flow of payments that would be due for the carbon sink services provided by all of Costa Rica's humid tropical secondary forest areas (existing + assumed growth) under the three realistic scenarios.

Realistic scenario 1 refers to an intermediate carbon parking payment rate (U.S.$15/mtC) under low or intermediate carbon sequestration payment rates (U.S.$10 or U.S.$25/mtC) and a 5% discount rate, which triggers alternative (8) for both *OCLs* and all forest ages. Under this scenario, existing forest areas would store a long-term annual average of 19.5 million mtC, and the new areas would store 34.7 million mtC, for a total of 54.2 million mtC/year. The payments would start at U.S.$16 million/year in 2000 and increase at a decreasing rate reaching U.S.$132 million/year in 2120. The discounted value of this flow of payments is U.S.$1215.8 million, of which U.S.$406.5 million (33.5%) correspond to the already existing forest areas and U.S.$809.3 million (66.5%) accrue to the projected area growth (Table IV). These amounts represent the actualized cost of the AIJ program and the actualized value of the payments to forest owners.

Realistic scenario 2 refers to an intermediate carbon sequestration payment rate (U.S.$25/mtC) and low or intermediate carbon parking rates (U.S.$5 or U.S.$15/mtC), which, under a low *OCL* and a high real discount rate scenario trigger alternative (2) for new forests and (3) for all other forest ages. The payments start at a much higher level of U.S.$108 million/year in 2000 and decrease at a decreasing rate to less than U.S.$12 million/year by 2040. The two downward kinks in the curve are due to the decreases in new secondary forest areas to 6,400 and 0 hectares/year assumed after 2010 and 2110 respectively. The discounted value of this flow of annual payments is U.S.$1122.2 million, of which U.S.$316.7 million (28.2%) correspond to the already existing forest areas and U.S.$805.5 million (71.8%) accrue to the projected growth in forest areas. A small amount of harvest income is also obtained. Under this scenario, existing forest areas would store a long-term annual average of 18.8 million mtC, and the new areas would store 34.7 million mtC, for a total of 53.5 million mtC/year.

Realistic scenario 3 refers to payment rates that increase by constant amounts during the first 30 years from 5 to 25/mtC for parking and from 10 to 40/mtC for sequestration. Recall that under average and fast forest growth, a low *OCL* and a 10% discount rate, alternative (4) is optimal for younger forests and alternative (5) becomes optimal for forests that are 20 years old or older. In this case, the annual payments start at a very low level in 2000, but increase dramatically between 2020 and 2030 when the harvest and sequestration activities implied by both alternative (4) and (5) after an initial carbon parking contract begin to occur. The discounted value of this flow of payments is U.S.$1,243.5 million (U.S.$676.7 from sequestration contracts and U.S.$566.8 from parking contracts), of which U.S.$366.1 million (29.5%) correspond to the already existing forest areas and U.S.$877.4 million (70.5%) accrue to the assumed growth in forest areas. A more substantial amount of income from harvests (U.S.$157.3) is obtained in this case. Under this scenario, existing forest areas would store a long-term annual average of 18.1 million mtC, and the new areas would store 32.5 million mtC, for a total of 50.6 million mtC/year.

The pessimistic scenarios involve slow forest growth rates, a high 10% discount rate, an intermediate carbon sequestration payment rate (U.S.$25/mtC), the low *OCL*, and an intermediate or a high parking payment rate (U.S.$15 and U.S.$25/mtC). These are the worst conditions, from the forest owners' perspective, under which a significant amount of carbon storage would still take place. A total long-term annual average of 36.5 million mtC/year would be stored under the intermediate carbon parking payment rate, all of it through carbon sequestration contracts, at an actualized cost of U.S.$782.2 million. The high carbon parking payment rate triggers carbon parking contracts for existing forests that are more than one year old. The total long-term average storage is about the same, but is achieved at a much higher actualized cost of U.S.$999.1.

The optimistic scenarios involve fast forest growth rates, a low 5% discount rate, a high *OCL*, and either the highest carbon sequestration and parking payment rates (U.S.$25/mtC and U.S.$40/mtC) or increasing rate schedules starting at the intermediate values. These are the best conditions from the forest owners' perspective. The same total long-term annual average of 69.1 million mtC/year would be stored under both scenarios, all of it through carbon parking contracts, at an actualized cost of U.S.$2,584 million at the constant rates and U.S.$3,026.8 million at the increasing rates (Table IV).

Conclusions and Recommendations

Humid tropical secondary forests have a considerable potential for carbon sequestration and storage. Most of the carbon sequestration takes place during the first 20 years of growth. Compensation rates for carbon sequestration/parking within the range of what is being discussed/ negotiated in AIJ programs are sufficient to motivate secondary forest conservation under most realistic scenarios. The payment rate schedule that minimizes the cost of achieving a near maximum level of long-term carbon storage is different depending on the prevailing scenario. Carbon sequestration is only attractive to forest owners if they can capture the large annual payments earned during the first few years of accelerated secondary forest growth. However, the regeneration of large forest areas, the conservation of existing forest areas, and the corresponding carbon sink services can be secured through carbon sequestration or parking contracts, at a cost of between U.S.$500 and U.S.$1,500/ha, depending on the prevailing scenario. In contrast, the estimated net present value of the current incentives provided by the Costa Rican government for secondary forest regeneration/conservation is less than U.S.$200/ha.

Given the different rates of forest growth, secondary forest regeneration implies a permanent removal from the atmosphere of between 40 and 80mtC/ha, and the conservation of existing forest avoids future emissions in these amounts. The actualized costs are between U.S.$15 and U.S.$25 per mtC placed under long-term storage, depending on the scenario. An interesting set of very-low-cost alternatives which achieves the highest average long-term carbon storage levels arises under intermediate payment rates that increase by constant amounts during the first 30 years, but only for average and fast forest growth and a 10% discount rate.

Land in Costa Rica is scarce and expensive in relation to most other developing countries with much larger existing or potential tropical secondary forest areas. Thus, it is likely that at intermediate or even low carbon sequestration/parking payment rates the per-hectare economic value of the carbon sink service provided exceeds the opportunity cost of the land in most tropical humid regions of the world. Under adequately funded AIJ programs, forest conservation would be an economically sensible alternative in these areas, especially considering that forests render other environmental services that are also economically valuable.

Large long-term differences in the long-term annual average amount of carbon could be stored in the 300,000 hectares of existing and the 770,000 hectares of potential humid tropical secondary forest areas of Costa Rica are caused by the rate of forest growth. This means that it would be important to establish the precise growth rates in areas where large-scale AIJ programs are implemented. A long-term average of 54 million mtC would be stored under average forest growth conditions. About two thirds of this carbon would be net atmospheric uptake in the new forest areas projected in the analysis. The actualized economic value of the carbon storage services provided is estimated at about U.S.$1,200 million under realistic conditions.

Approximately one third of this value accrues to already existing forests. For comparison, Costa Rica’s gross domestic product (GDP) was estimated at U.S.$24 billion in 1999, while its trade balance stood at –U.S.$600 million. If a global carbon market eventually develops, promoting secondary forest regeneration and conservation can yield substantial economic benefits for developing countries. Costa Rica has a relatively diversified non-agricultural economy and one of the highest per-capita gross domestic products among developing countries. Even under these circumstances, receiving compensation for the carbon sink services of naturally regenerating secondary forest areas would represent a significant source of revenue for the economy.

The intertemporal distribution of the costs of an AIJ program, i.e. of the revenues received by forest owners through time, would vary greatly depending on the discount rate, *OCL*, and on the payment rate schedule adopted. Under two of the realistic country-level scenarios evaluated, which initially or eventually involve carbon sequestration contracts, between 22 and 36% of the total payments would be received during the first 25 years of the program, and between 45 and 54% would be received during the first 50 years. The third realistic scenario, which involves carbon parking contracts, delays nearly 90% of the payments until 2050-2200.

If carbon sequestration is one of the main objectives of a system of forest incentives, promoting secondary forest regeneration should be a priority over primary forest conservation. This is not the case in Costa Rica’s and most other developing countries’ incentive programs. The fact that secondary forest ecosystems in their earlier stages of development are very vulnerable to land-use change provides an additional argument for higher incentives. A comparative economic analysis of secondary forests vs.

artificial forestry plantations as carbon sequestration alternatives is recommended. A complete panorama of the AIJ alternatives for a developing country would also include mitigation measures in the energy and transport sectors. The cost effectiveness of carbon sequestration in secondary forests and plantations vs. measures to reduce CO_2 emissions adopting less energy-intensive technologies and fossil fuel substitutes need to be evaluated as well.

Finally, it is important to stress that cross-country payments for carbon storage services rendered by existing forests do not imply that certain countries have the right to emit all their stored carbon and should be compensated for not doing so. Countries in Annex B of the Kioto Protocol have a limited right to emit, but the seller can still trade as long as it makes sure that its commitments are meet some other way. Within-country incentives to forest conservation might also be justifiable to reduce the country's overall CO_2 emissions. Payments from industrialized to developing countries for net atmospheric carbon uptake is a globally accepted mechanism. The compensating country can use the sequestered carbon to offset its own emissions and comply with international conventions. For industrialized country governments/private sectors, this type of AIJ agreements may be less expensive than reducing internal emissions, at the margin.

Notes

[1] The growth rate is assumed constant across forest sites because data about the earlier stages of forest growth (first 25 years) is only available for the "Tirimbina" site.

[2] The OCIC was created in 1995 to direct and facilitate AIJ negotiations and to secure international funding for national forestry initiatives.

[3] FONAFIFO promotes natural forest regeneration, conservation, and management, and plantation forestry through payments for environmental services (PSA) to forest land owners.

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Table I. Long-run forest land use alternatives faced by forest owners during the first year that the carbon parking/sequestration contracts are available.

Number	**Description**
1	Clear or harvest and sell
2	Sequestration
3	Harvest – sequestration
4	Parking – harvest – sequestration
5	Harvest – parking – harvest – sequestration
6	Parking – harvest – sell
7	Harvest – parking – harvest – sell
8	Parking without harvests in between contracts
9	Harvest – parking without harvests in between contracts
10	Infinite parking with harvests in between contracts
11	Harvest – infinite parking with harvests in between contracts
12	Parking – harvest – parking – harvest – sequestration
13	Harvest – parking – harvest – parking- harvest – sequestration
14	Parking – harvest – parking – harvest – sell
15	Harvest – parking – harvest – parking – harvest – sell
16	Parking – parking – harvest – sequestration
17	Harvest – parking – parking – harvest – sequestration
18	Parking – parking – harvest – sell
19	Harvest – parking – parking – harvest – sell

Table II. Estimated biomass accumulation models.

	Full Model		Rest. Model I		Rest. Model II		Rest. Model III	
Parameter	Estimate	Std. Error	Estimate	Std. Error	Estimate	Std. Error	Estimate	Std. Error
b	0.041	0.024	0.174	0.064	0.172	0.062	0.181	0.076
c	0.481	0.303	0.918	0.417	0.912	0.408	0.930	0.470
a_1	101.54	2.29	144.26	2.44	144.46	2.38	142.37	4.75
a_2	190.11	1.36	144.26	2.44	144.46	2.38	142.37	4.75
a_3	142.53	1.37	144.26	2.44	144.46	2.38	142.37	4.75
a_4	162.13	1.77	144.26	2.44	144.46	2.38	142.37	4.75
σ_1	2.17	1.76	55.34	22.71	55.52	22.78	26.42	2.64
σ_2	23.18	1.26	25.09	3.05	24.71	2.71	26.42	2.64
σ_3	18.10	1.33	22.83	6.27	24.71	2.71	26.42	2.64
σ_4	5.85	1.33	5.46	1.74	5.48	1.76	26.42	2.64
R^2	0.623		0.380		0.380		0.382	
MVLF	166.44		180.21		180.25		188.70	
Likelihood Ratio Test			Full vs. Rest. I	27.54	Rest. I vs. Rest. II	0.08	Rest. II vs. Rest III	16.90
Level of Significance				1%		Not Sig. at 10%		1%

Notes: All parameter estimates in the restricted models are statistically different from zero at the 1% level. MVLF refers to the maximum value reached by the concentrated log-likelihood function.

Table III: Optimal alternatives and corresponding present values under the different scenarios evaluated (average growing forests).

OCL		**Assumed Carbon Parking/Sequestration Payment Rate ($/mtC) (growth = average, i = 5%)**										
		5/10	**5/25**	**5/40**	**15/10**	**15/25**	**15/40**	**25/10**	**25/25**	**25/40**	**INC1**	**INC2**
500	**PV_0**	500(1)	1049(2)	1678(2)	1057(8)	1057(8)	1678(2)	1762(8)	1762(8)	1762(8)	1397(8)	2101(8)
	PV_{15}	577(6)	946(3)	1575(3)	1360(8)	1360(8)	1575(3)	2267(8)	2267(8)	2267(8)	1648(8)	2555(8)
	PV_{30}	819(1)	1368(3)	1997(3)	1483(8)	1483(8)	1997(3)	2471(8)	2471(8)	2471(8)	1757(8)	2746(8)
1000	**PV_0**	1000(1)	1049(2)	1678(2)	1057(8)	1057(8)	1678(2)	1762(8)	1762(8)	1762(8)	1397(8)	2101(8)
	PV_{15}	898(1)	946(3)	1575(3)	1360(8)	1360(8)	1575(3)	2267(8)	2267(8)	2267(8)	1648(8)	2555(8)
	PV_{30}	1319(1)	1368(3)	1997(3)	1483(8)	1483(8)	1997(3)	2471(8)	2471(8)	2471(8)	1757(8)	2746(8)
OCL		**Assumed Carbon Parking/Sequestration Payment Rate ($/mtC) (i = 10%)**										
		5/10	**5/25**	**5/40**	**15/10**	**15/25**	**15/40**	**25/10**	**25/25**	**25/40**	**INC1**	**INC2**
500	**PV_0**	500(1)	819(2)	1310(2)	500(1)	819(2)	1310(2)	720(8)	819(2)	1310(2)	529(4)	979(2)
	PV_{15}	398(1)	716(3)	1207(3)	655(6)	716(3)	1207(3)	1070(8)	1070(8)	1207(3)	664(4)	1092(4)
	PV_{30}	819(1)	1138(3)	1629(3)	819(1)	1138(3)	1629(3)	1204(8)	1204(8)	1629(3)	848(5)	1298(3)
1000	**PV_0**	1000(1)	1000(1)	1310(2)	1000(1)	1000(1)	1310(2)	1000(1)	1000(1)	1310(2)	1000(1)	1000(1)
	PV_{15}	898(1)	898(1)	1207(3)	898(1)	898(1)	1207(3)	1084(6)	1084(6)	1207(3)	898(1)	1092(4)
	PV_{30}	1319(1)	1319(1)	1629(3)	1319(1)	1319(1)	1629(3)	1319(1)	1319(1)	1629(3)	1319(1)	1319(1)

Notes: *OLC* stands for the assumed opportunity cost of the land; i is the real interest rate; INC1 refers to payment rates that increase by constant amounts during the first 20 years from 5 to 25/mtC for parking and from 10 to 40/mtC for sequestration; INC2 indicates payment rates that increase from 15 to 35/mtC for parking and from 25 to 55/mtC for sequestration; PV_0, PV_{15} and PV_{30} refer to the maximum present value of the net income per hectare originated from carbon parking and/or sequestration payments, harvest(s), and/or the clearing and selling of the forest land, given initial forest ages of 0, 15 and 20 years, respectively. The long-term land use alternative that would produce that maximum net present value is identified in parenthesis.

Table IV. Pessimistic, realistic and optimistic scenarios analyzed at the country level and results of the analysis.

Scenario	**Rate of Forest Growth**	**OCL $/ha**	**Parking Payment Rate ($/mtC)**	**Sequestration Payment Rate ($/mtC)**	**Discount rate %**	**Optimizing Alternatives (forest ages)**
Pessimistic1	Slow	500	15	25	10	2(0), 3(>0)
Pessimistic2	Slow	500	25	25	10	2(0), 3(1), 8(>1)
Realistic1	Average	500 or 1000	15	10 or 25	5	8 (all ages)
Realistic2	Average	500	5 or 15	25	10	2(0), 3(>0)
Realistic3	Average	500	5-25	10-40	10	4(0-20), 5(>20)
Optimistic1	Fast	1000	25	40	5	8 (all ages)
Optimistic2	Fast	1000	15-35	25-55	5	8 (all ages)

Scenario	**Long-Term Average Quantity of Carbon Stored (million mt)**		**Discounted Value of Payments and Net Income form Harvest(s) (million U.S. dollars)**									
			Sequestration			**Parking**				**Harvest**		**Total**
	Old	New	Total	Old	New	Total	Old	New	Total	Old	New	Total	
Pessimistic1	12.8	23.7	36.5	215.7	548.6	764.3	0	0	0	17.9	0	17.9	782.2
Pessimistic2	23.6	13.3	36.9	15.2	548.6	563.8	435.5	0	435.5	0	0	0	999.1
Realistic1	19.5	34.7	54.2	0	0	0	406.5	809.3	1215.8	0	0	0	1215.8
Realistic2	18.8	34.7	53.5	316.7	805.5	1122.2	0	0	0	26.3	0	26.3	1148.5
Realistic3	18.1	32.5	50.6	191.0	485.7	676.7	175.1	391.7	566.8	74.0	83.3	157.3	1400.8
Optimistic1	24.9	44.2	69.1	0	0	0	864.0	1720.0	2584.0	0	0	0	2584.0
Optimistic2	24.9	44.2	69.1	0	0	0	976.6	2050.2	3026.8	0	0	0	3026.8

Note: A real social discount rate of 5% is used in all cases to allow for comparisons.

Figure 1: Predictions of Biomass Accumulation Model

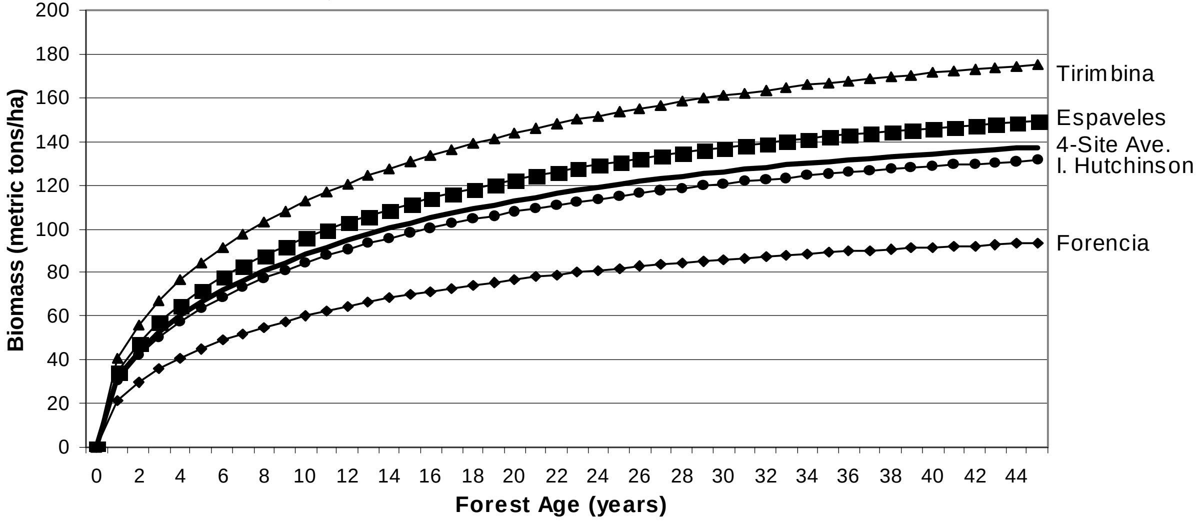

Figure 2: Carbon Stored in Costa Rica's Humid Secondary Forest Areas through Time under 3 Land Use Alternatives and the Slow, Avearge and Fast Forest Growth Rates

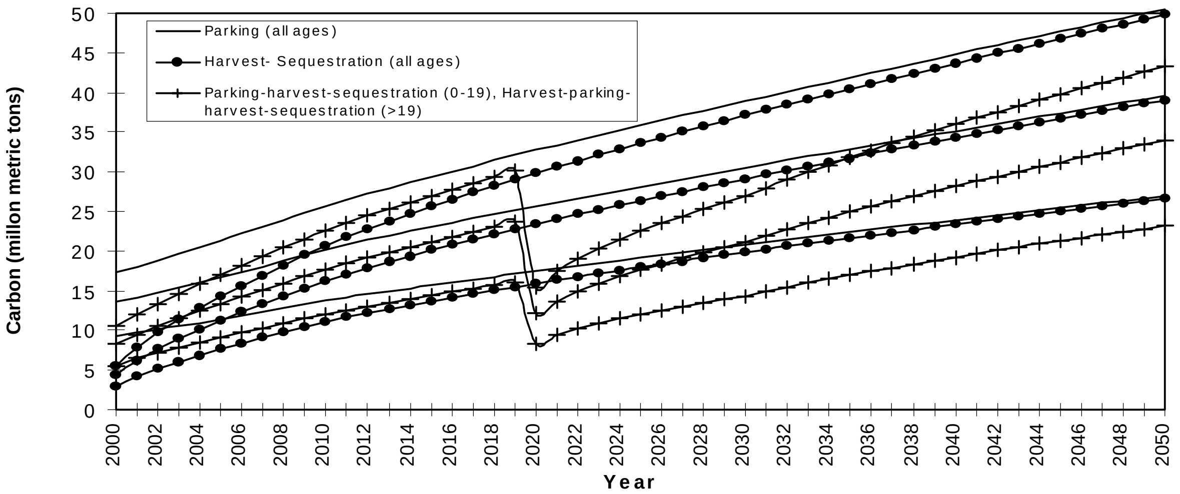

Figure 3: Annual Payments for Carbon Sequestration and/or Parking Services under 3 Realistic Scenarios