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UNCERTAINTY IN LAND-USE CHANGE AND FORESTRY SECTOR MITIGATION OPTIONS FOR GLOBAL WARMING: PLANTATION SILVICULTURE VERSUS AVOIDED DEFORESTATION

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ABSTRACT

How land-use change and forestry sector options can be used to mitigate global warming will depend on a variety of pending decisions regarding interpretation of the Kyoto Protocol, including treatment of uncertainty. In tropical forest countries, the allocation of effort between plantation silviculture and reduction of deforestation would be influenced by the stringency of requirements regarding certainty. Slowing deforestation offers much greater potential benefits, but the certainty associated with these is much lower than in the case of plantations. In the Brazilian case, deforestation avoidance could produce carbon benefits worth 6-45 times as much as the destructive ranching and logging uses to which the forest is now being converted. Capturing the potential value of carbon benefits from avoided deforestation will depend on increasing our understanding of the deforestation process and consequent ability to reduce the uncertainty associated with the effects of deforestation-avoidance measures. It will also depend on whether carbon credits are defined in terms of a maximum level of uncertainty.

KEYWORDS: Carbon, Global warming, Kyoto Protocol, Uncertainty, Climate change, Mitigation

1. INTRODUCTION

The danger of global warming caused by increased atmospheric concentrations of gases such as carbon dioxide (CO_2) gives urgency to finding ways to reduce greenhouse gas emissions and/or enhance flows of atmospheric carbon to biomass and other "sinks." The United Nations Framework Convention on Climate Change (UN-FCCC) was negotiated in 1992 for this purpose, and has since been supplemented by the December 1997 Kyoto Protocol [1]. The Kyoto Protocol establishes emissions limits for countries that are members of Annex B of the Protocol (similar to Annex I of the UN-FCCC), which currently includes most of the industrialized countries. The Protocol also establishes a variety of ways in which these commitments can be met. These include undertaking mitigation projects in non-Annex B countries under the Clean Development Mechanism (CDM) defined in Article 12 of the Protocol [2], and emissions trading defined in Article 17. The uncertainty of estimates of emissions and uptakes is likely to affect the amount of credit or debit that would be assigned to a global warming mitigation project or to a country under the Kyoto Protocol. Decisions have not yet been made on how these issues will be handled. It is hoped that the conceptual discussion that follows will contribute to understanding the consequences of different possible decisions in this area.

The most pressing question regarding sinks in the land-use change and forestry (LUCF) sector is whether avoided deforestation can be made a viable mitigation option under the Kyoto Protocol, particularly in the context of the CDM. The CDM (Article 12) applies only to countries that have not joined Annex B of the Protocol, and therefore do not have limitations on their national emissions. At present, all countries with substantial areas of tropical forests fall into the "non-Annex B" category, making them eligible for CDM projects but ineligible for other provisions for carbon credit under the Protocol, such as Joint Implementation (under Article 6) and emissions trading (under Article 17). At some time in the future, tropical forest countries may find it in their interests to join Annex B in order to capture major potential financial benefits from carbon credits traded under Article 17 that could be achieved by slowing deforestation [3].

The CDM is expected to come into effect before other "flexibility mechanisms" (provisions under the Protocol allowing Annex B countries to meet some or all of their commitments through activities in other countries). This is because the CDM includes a "banking" provision through which carbon credit can be earned as early as 2000 and later applied to offset emissions of Annex B countries during the Protocol's first commitment period (2008-2012). Decisions are still pending as to what, if any, LUCF activities will be eligible for credit under the CDM. Decisions will probably await completion in May 2000 of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Land-Use Change and Forestry. Decisions on these matters are likely to be taken at the Sixth Conference of the Parties (COP-6) of the UN-FCCC, to be held in November 2000.

Because the CDM is project based, many potential LUCF projects could be subject to "leakage," or loss of their benefits for global climate by effects beyond a given project's geographical, temporal or subject area boundaries. For example, if a forest reserve is set up to protect carbon, people who would otherwise have been clearing in that area may simply move to some other part of the forest to continue clearing.

The problem of uncertainty in establishing causality (attribution) is substantial in the case of deforestation reduction projects due to high potential for leakage (in the case of reserve protection) and to poor understanding of the social processes leading to deforestation (in the case of policy initiatives). This problem is likely to reduce substantially the carbon benefit that can be claimed under the CDM (Article 12) and in many cases under Joint Implementation (Article 6), but has much less potential effect on the credit that could be obtained under emissions trading (Article 17) should tropical forest countries join Annex B of the Protocol. This is because emissions trading is based on accounting at the national level, rather than at the project level, making any leakage that occurs within national borders irrelevant and making it unnecessary to show why a given reduction in emissions has occurred. This assumes that Article 3.7 (the "Australia clause") of the Protocol is interpreted to include deforestation as a form of land-use change to be counted in the 1990 baseline for countries that, like most tropical forest countries, had net emissions from land-use change in 1990 [4, pp. 318-319].

Table 1 gives an idea of the magnitude of potential gains to tropical countries such as Brazil. The average sale price of forested land in Brazilian Amazonia represents the net present value (i.e., discounted profits) that could be obtained from current land uses in the region, namely selling the timber and deforesting land for cattle pasture. At the US$ 5-35 per metric ton of carbon (t C) currently used by the United States government in planning its future expenses to meet its Kyoto commitments through "flexibility mechanisms" such as the CDM, the value of maintaining the same hectare's stock of carbon out of the atmosphere would be 6-45 times the average 1998 sale price of forested land in Amazonia (see [5]). The carbon prices used in this calculation refer to tons of carbon of immediately achieved fossil fuel emissions reduction, which has the same effect as avoided deforestation in the case of countries like Brazil with large areas of remaining forest [6]. Devaluation of the Brazilian Real by 40% in 1999 makes the contrast between land prices and carbon value even greater today.

Brazil's 1990 net committed emissions of 267×10^6 t C from Amazonian deforestation ([7], updated from [8]) would be worth US$ 1.3-9.3 billion. An estimated 2.4×10^9 t C is emitted globally each year from tropical deforestation and related land-use changes such as shifting cultivation and clearing of non-forest vegetation, calculated as the annual average net committed emissions over the 1981-1990 period [9]. At the US$ 5-35/t C expected price for carbon, this would represent a loss of US$ 12–84 billion in potential revenue from the carbon benefits of reducing deforestation. Obviously, even if only a small fraction of this potential were realized it could have major economic benefits for tropical forest countries and major benefits for the global environment, not only through global warming mitigation but also by maintaining biodiversity and the roles of forest in the hydrological cycle, watershed protection, etc.

[Table 1 here]

2. PROBABILITY OF SUCCESS

Uncertainty enters decision-making both before the fact (ex ante) and after the fact (ex post). Ex ante decisions regarding deforestation are clearly faced with substantially higher levels of uncertainty than are ex post ones, as ex ante decisions involve great doubt as to how deforestation will proceed in addition to doubt concerning how any changes might be attributed to different causes. While decisions on which forms of mitigation to finance will undoubtedly be made ex ante, it is likely that any granting of credits will be done ex post.

Certainty could be a key factor determining whether carbon mitigation funds are used in LUCF options or in other sectors, such as many energy-sector options. Within the LUCF sector, these same concerns could be critical in determining whether plantation silviculture or deforestation-avoidance options are funded.

Plantation silviculture is much safer and better-understood than deforestation avoidance as a global warming mitigation option--i.e., uncertainty is much lower in the case of plantations. On the other hand, if successful, the potential carbon gains from investments in deforestation avoidance may be orders of magnitude greater than the best possible gains from plantations. The great disparity in the probability of success requires a Bayesian approach to interpreting such numbers. As in gambling, a prize of fabulous value is misleading if the probability of winning it is minuscule. The expected monetary value (EMV) of each choice is the value of the payoff for each outcome multiplied by its respective probability of occurrence, summed over all possible outcomes associated with each decision (e.g. [13]). A hypothetical numerical example representing plantation and deforestation-avoidance alternatives is given in Table 2, illustrating how deforestation avoidance can still be a rational choice even if investments in this area had a high (85%) probability of achieving nothing.

[Table 2 here]

3. EFFECT OF UNCERTAINTY REDUCTION

The credit that is awarded to mitigation measures is likely to depend on the benefits to global climate being demonstrable with a specified level of certainty. The logic is similar to that in analyses of the consequences of global warming impacts in terms of a "safe minimum standard" (SMS) of conservation [14]. Canada [15] has proposed that sinks only be credited for carbon that can be shown to have been held out of the atmosphere with 95% certainty. Marland and Schlamadinger [16] provide an example of simulated plantation benefits with varying levels of certainty, demonstrating that reducing uncertainty results in increasing credit if a given level of certainty is required, such as the 95% minimum proposed by Canada.

The potential benefit that reducing uncertainty would yield to those selling carbon credit is illustrated in Figure 1. If 95% certainty is required, the credit that can be awarded is C_1 under the low certainty case, but increases to C_2 if the level of certainty is improved (reducing the coefficient of variation, or the standard deviation as a percentage of the mean). The difference between C_2 and C_1 represents a gain that could be achieved by increasing the quantity and quality of data and their interpretation. In many cases this may be more cost effective than investments in expanding the scale of a given project.

[Fig. 1 here]

The multiplicative nature of uncertainties associated with chain calculations means that the uncertainty of the final result can quickly explode to very high levels [17]. The variance of the product of each multiplication (Z = X Y) can be calculated as:

$$s_z^2 = Y^2 s_x^2 + X^2 s_y^2$$

where X and Y are the means being multiplied, Z is the product, and s_x^2, s_y^2 and s_z^2 are their respective variances. This applies only if the terms are mutually independent; if any autocorrelations exist, the interaction terms that must be included in the equation usually result in much greater uncertainty of the final result [18].

Increasing uncertainty from chain multiplication is particularly important for estimating the benefits of deforestation avoidance. For example, if estimates of the number of hectares cleared, tons of biomass per hectare and carbon emission per ton of biomass each has a coefficient of variation (cv) of 20%, the cv of the result would increase to 34.6% as a result of the two multiplications. If an additional link in the chain were added with the same 20% cv, say for methane emission per ton of carbon emitted, the cv of the final result would increase to 40%, or double the cv of each component; an additional multiplication would raise it to 44.7%. The same proportionalities are maintained for other levels of uncertainty. The uncertainty of the final result tends to explode if multiplication chains include factors with cv values above 30% [17]. The final result increases greatly if any factor in the chain has a high cv, regardless of the size of the mean value of the factor involved.

Increasing levels of uncertainty have a sharp effect on carbon credit (Fig. 2). For a cv of 20%, about 70% of the full credit level is retained under a 95% certainty requirement, but if the cv is 40% the percentage of credit retained falls to 35%.

[Fig. 2 here]

4. EFFECT OF A REQUIRED LEVEL OF CERTAINTY

The uncertainty associated with the benefits of either plantation silviculture or deforestation avoidance is composed of two component uncertainties: uncertainty regarding the carbon benefit per hectare and uncertainty regarding the number of hectares of either plantation establishment or avoided deforestation resulting from a given mitigation investment. Uncertainty in per-hectare benefits can arise, for example, due to variation in estimates of biomass of the original vegetation, biomass of the replacement landscape, soil carbon changes, uncertainty in the baseline deforestation rate, etc.

In the case of plantations for charcoal, an example is given in Figure 3 based on average yield and biomass parameters from Brazilian plantations [6, pp. 314 and 317]. The uncertainty associated with both carbon benefit per hectare and the number of hectares is assumed to correspond to a coefficient of variation (cv) of 5%. It is assumed that the plantation lasts for 30 years, during which the carbon stocks in biomass and soils apply, ending at the conclusion of this period. The fossil carbon substitution benefits that accumulate over the 30 years are permanent. For simplicity, the timing of benefits over the 30-year project life is smoothed to a constant yearly rate averaging 67.7 t C ha^{-1}, of which 23.9 t C ha^{-1} are from biomass and soils.

[Figure 3 here]

The probability distributions of expected carbon benefits (e.g. Fig. 3C) were generated in this and other examples discussed in this paper by Monte Carlo simulations in which the area and benefit per hectare values were drawn from their respective probability distributions (e.g. Figs. 3A and 3B) and multiplied together in 2000 simulated cases. The mean carbon benefit (e.g. point $\overline{x}_p$ in Fig. 3C) and the benefit credited at different levels of required certainty (e.g. point C_p for 95% certainty in Fig. 3C) were calculated from the resulting simulated cases.

In order to compare silvicultural plantations with avoiding deforestation, assumptions must be made about the relative costs of these two options. The examples developed in the following paragraphs assume that slowing deforestation costs an average of US$ 60/ha—a value one order of magnitude cheaper than the US$ 625/ha installation cost of plantations [6, p. 317]. Avoiding deforestation prevents an average of 200 t C ha^{-1} from being emitted, rounded from the 194 t C ha^{-1} average net committed emission from 1990 deforestation in Brazilian Amazonia [7, updated from 8]. The example in Figure 4 avoids an average of 0.18×10^3 km^2 of deforestation, and so would cost US$ 10.8 million. This amount of money would pay for only 0.017×10^6 ha of plantations; at the 67.7 t C ha^{-1} benefit level for charcoal this would offset 1.17×10^6 t C, on average.

[Figure 4 here]

A carbon ton-year approach is necessary in order to compare the carbon benefits of deforestation avoidance with those of most silvicultural plantations (plantations other than those that produce fuelwood that substitutes for fossil fuel). This is because the benefits of deforestation avoidance are effectively permanent, at least in the case of countries like Brazil with large areas of remaining forest, whereas carbon sequestered in plantation biomass and in wood products can be expected to be released to the atmosphere at the conclusion of a given project's life [see 2, 6]. As an illustration, if one assumes a 100-yr time horizon for analysis, a 30-yr project life for plantations and a 5% annual discount rate, one ton of fossil fuel carbon that would have been emitted immediately (or one ton of avoided deforestation carbon for countries like Brazil with large areas of remaining forest) is equal to 19.9 ton-years, while one ton of plantation carbon in biomass or soil equals 15.4 ton-years. At this rate of discount, the carbon sequestered in plantation biomass (as distinct from substitution for fossil carbon) must be adjusted by a factor of 15.4/19.9 = 0.775 to obtain the equivalent in fossil fuel carbon at the same rate of discount. This equivalence has been used to express all values in metric tons of carbon (t C) equivalent to instantaneous avoidance of fossil fuel emission. The equivalence used does not take into account the natural removal of CO_2 from the atmosphere; however, this factor would be unlikely to substantially alter the relative benefits of plantation silviculture versus deforestation avoidance.

If pulpwood rather than charcoal were produced by the plantations, then carbon benefits would be about 30-fold lower, with an average benefit of 2.1 t C ha^{-1}. Under the same assumptions regarding uncertainty as those applied to the charcoal example, this per-hectare carbon benefit would produce a total carbon benefit of only 0.036×10^6 t C, and a credit at 95% certainty of 0.032×10^6 t C.

For deforestation-avoidance initiatives, uncertainty is especially high regarding the number of hectares that has been or would be saved by a given project. The shapes of the probability density curves associated with benefit per hectare (Fig. 4A) and area of avoided deforestation (Fig. 4B) are expected to be quite different: the curve representing benefit per hectare would be a bell-shaped normal probability distribution (e.g. [19]), while the corresponding curve for the number of hectares of deforestation avoided would have a peak at zero to represent a large chance that nothing would be achieved and a tail on the upper side extending to very high values. The distribution of the product of the two values (i.e., expected C benefits) would have a large peak at zero and a long upper tail representing the "jackpot" of potentially very valuable carbon benefits that might be achieved (Fig. 4C).

The high peak of probability of zero or near-zero outcomes in the case of deforestation avoidance indicates reducing this as the greatest priority for research in this area. Effort in understanding the causes of deforestation and developing functional models capable of generating scenarios under different policy assumptions may well produce greater dividends in making deforestation avoidance into a viable mitigation option than would effort in reducing the uncertainty surrounding carbon benefits per hectare of deforestation.

Expected carbon benefits from silvicultural plantations and avoided deforestation will have probability density functions with different shapes (Figs. 3C and 4C). Plantations (Fig. 3C) will have normally distributed benefits with low variance. Although not indicated in this example, there may be a small probability of zero benefit, and also a small probability of negative benefits should the project produce impacts, as by stimulating the clearing of high-biomass vegetation to make way for plantations, or by expelling people who clear forests elsewhere. Avoided deforestation will have the high peak at zero and the long tail representing the potential "jackpot" at the right hand side of the graph (Fig. 4C). A small probability of negative benefits will also exist. The mean carbon benefit, representing the expected monetary value (as in Table 2), is expected to be substantially higher in the case of avoided deforestation ($\overline{x}_d > \overline{x}_p$).

The differing shapes of the probability density curves for plantations versus deforestation avoidance (Figs. 3C and 4C) will affect the result of requiring a minimum level of certainty for carbon benefits. The effect of the large probability of obtaining results with zero or near-zero values in the case of deforestation avoidance is to drastically reduce the amount of carbon credit that could be awarded for avoided deforestation (C_d in Fig. 4C) to the point where it could be lower than that awarded for plantations (C_p in Fig. 3C; i.e., $C_d < C_p$).

In the case of a normal distribution, such as that for plantations (Fig. 3C), the mean value coincides with what can be achieved with 50% certainty, since half of the expected outcomes will have carbon benefits greater than this value. As one increases the level of required certainty (moving to the left in Fig. 3C), successively less of the expected (mean) value can be claimed. In the case of the avoided deforestation example, the expected (mean) value corresponds to a required certainty of 27%. The progressive loss of claimable value will not occur at the same pace as one moves towards a requirement of 100% certainty. In the case of the charcoal plantation example (Fig. 3C), a 95% certainty requirement reduces the credit (C_p) to 88% of the mean value ($\overline{x}_p$), whereas in the avoided deforestation case (Fig. 4C), the credit (C_d) is reduced to zero, thereby losing all of the substantially higher expected (mean) value ($\overline{x}_d$). The requirement of a specified level of certainty would significantly favor plantations over avoided deforestation, with the relative advantage of plantations increasing as the required level of certainty rises.

It is obvious that, if 95% certainty is required, any option with a substantial probability resulting in a zero value will be excluded (i.e., the credited level will be equal to zero). Deforestation avoidance options would be excluded regardless of the magnitude of the reward that could accrue should a "jackpot" be won by a successful reduction in clearing rates. The mean or expected carbon benefit, which is strongly influenced by a "jackpot" in the right-hand tail of the probability distribution, will likewise be irrelevant to choices based on a 95% certainty criterion. The most salient advantages of deforestation avoidance would therefore count for nothing under such a system.

The cost per ton of carbon sequestered would be equal to the mean if no certainty requirements apply; with the example parameters given above, this is US$ 9.24/t C for plantations producing charcoal and US$ 0.30/t C for deforestation avoidance. In the case of deforestation avoidance, because this example assumes a probability greater than 50% that zero benefit would result (55% in this example), any certainty requirement would immediately result in zero credit (and consequently an infinite cost per ton of carbon), whereas the cost per ton of carbon for plantations would only rise gradually, exploding to infinity only as the required certainty approaches the impossible-to-meet level of 100% (Fig. 5).

[Fig. 5 here]

The assumption that investment in deforestation avoidance has a high probability of resulting in zero benefit (the 0.55 probability that the area avoided will be zero in Fig. 4B) is prohibitive. This assumption may be overly severe; if some gain is assured, then the avoided deforestation curve in Figure 5 would not explode to infinity until a higher level of required certainty is reached.

Deforestation avoidance is generally seen as having more collateral benefits than expansion of plantations because forests provide environmental services other than carbon storage. Maintaining biodiversity and the hydrological cycle are particularly important in the case of Amazonia, and the willingness to pay for these values already represents a substantial amount [20, 21]. Giving additional weight to the benefits of deforestation avoidance, as compared to expansion of silvicultural plantations, can be justified on these grounds.

Decisions on the allocation between plantations and avoided deforestation will be critically affected by the choice of a required level of certainty; negotiators should be aware that demanding high levels of certainty has both positive and negative consequences for climate, biodiversity and sustainable development. The potential of such a requirement making deforestation avoidance worthless as a global warming mitigation measure should be regarded as a serious disadvantage. A system of weighting is needed that explicitly adjusts the index of benefits used in decision-making to reflect the additional environmental and social benefits of avoided deforestation. Such an adjustment would result in an upward shift in benefit curves such as those in Figures 4A and 4C and a downward shift in the cost curve for avoided deforestation in Figure 5. An additional adjustment to recognize the value of a possible large "jackpot" (the right-hand tail in Fig. 4C) could be applied through expected utility (EU) approaches. While all of these adjustments would contribute something to increasing the value attached to slowing tropical deforestation, they would do little to overcome the crippling effect of imposing a required high level of certainty. Uncertainty restrictions would be especially unfavorable to deforestation-reduction projects under the CDM, which requires demonstrating that project effects have "additionality" with respect to a no-project baseline.

5. CONCLUSIONS

Uncertainty regarding the magnitude and attribution of carbon benefits from efforts to mitigate global warming is expected to reduce the credit that can be assigned to relatively uncertain options. Reducing deforestation could yield much greater benefits for global climate than expanding plantation silviculture, but deforestation reduction is much more uncertain. The uncertainty associated with deforestation-reduction initiatives is particularly high if attribution of causes is required, as under the "clean development mechanism" (CDM) that applies to projects in countries outside Annex B of the Kyoto Protocol.

Requirement of a minimum level of certainty can influence the choices of land-use change and forestry options for mitigating global warming. Requirements for high levels of certainty would reduce the credit awarded for slowing deforestation, relative to that for expanding plantation silviculture.

Tropical forest countries could substantially increase their potential for gaining credit for reducing tropical deforestation by joining Annex B of the Kyoto Protocol, thereby eliminating the necessity of establishing the attribution of causes for changes in tropical deforestation rates (gaining credit through emissions trading under Article 17 rather than through the CDM under Article 12).

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FIGURE LEGENDS

Fig. 1 -- Effect of uncertainty reduction: under high uncertainty (A) the amount that can be credited (C_1) under a 95% certainty requirement is less than in the low-certainty case (B). The amount that can be credited is determined by 95% of the area under the curve being located to the right of the point (C_1 in the high-uncertainty case and C_2 in the low-uncertainty case). The difference between the amounts credited (C_2-C_1) represents the potential gain from improving certainty.

Fig. 2 -- Carbon credit at different levels of uncertainty (coefficient of variation = cv) for an example with a mean benefit of 200 t C ha^{-1} of avoided deforestation emissions and a requirement of 95% certainty. The right axis gives the percentage of full credit awarded.

Fig. 3 -- Silvicultural plantations for charcoal: expected carbon benefit (C_p) is derived from benefit/ha (A) and number of hectares (B). Both parameters are relatively well understood, here assumed for illustration to have cv values of 5%. This is reflected in the expected carbon benefit from plantations (C_p).

Fig. 4 -- Avoided deforestation: expected carbon benefit from deforestation avoidance (C_d) is derived from benefit/ha (A) and number of hectares (B). The number of hectares (B) has a high probability associated with zero or near-zero hectares, but also has a long tail representing small probabilities of avoiding large areas of deforestation. This pattern is reflected in the expected carbon benefit from deforestation avoidance (C_d). Differing shapes of curves for plantations and deforestation avoidance can reverse the outcome: although plantations (Fig. 3C) have a substantially lower expected benefit than avoided deforestation ($\overline{x}_p << \overline{x}_d$), a 95% certainty requirement can reduce the benefits assigned to avoided deforestation (Fig. 4C) to a level lower than the corresponding credit assigned to plantations ($C_d < C_p$).

Fig. 5 -- Effect of different levels of required certainty on the cost of carbon sequestration, using the example parameters. Deforestation avoidance, although much cheaper than plantations for charcoal as a mitigation option if no certainty requirement is imposed, becomes worthless if even modest levels of certainty are required.

Table 1. Deforestation versus carbon value in Brazilian Amazonia

Land price (NPV of deforestation)	US$ 150/ha	Fundação Getúlio Vargas [10]
Net committed emission	194 t C ha^{-1}	Fearnside [7] updated from [8]
Value of carbon	US$ 5-35/t C	Walsh [11]
Value of avoided emission	US$ 970-6790/ha	Calculated from above
Advantage of deforestation avoidance	6-45 times	Calculated from above
Value of C released by 1998 deforestation (1.74×10^6 ha)	US$ 1.7-11.8 billion	Calculated from above and Brazil, INPE [12]

Table 2. Hypothetical example of a Bayesian comparison of mitigation options

Carbon benefit (10^6 ton-years)	Probability of outcome		Expected ton-year value	
	Deforestation avoidance	Plantations	Deforestation avoidance	Plantations
0	0.850	0	0.0	0
10	0.050	1	0.5	10
100	0.050	0	5.0	0
1,000	0.025	0	25.0	0
10,000	0.020	0	200.0	0
100,000	0.005	0	500.0	0
Total	1	1	730.5	10

Fig. 1

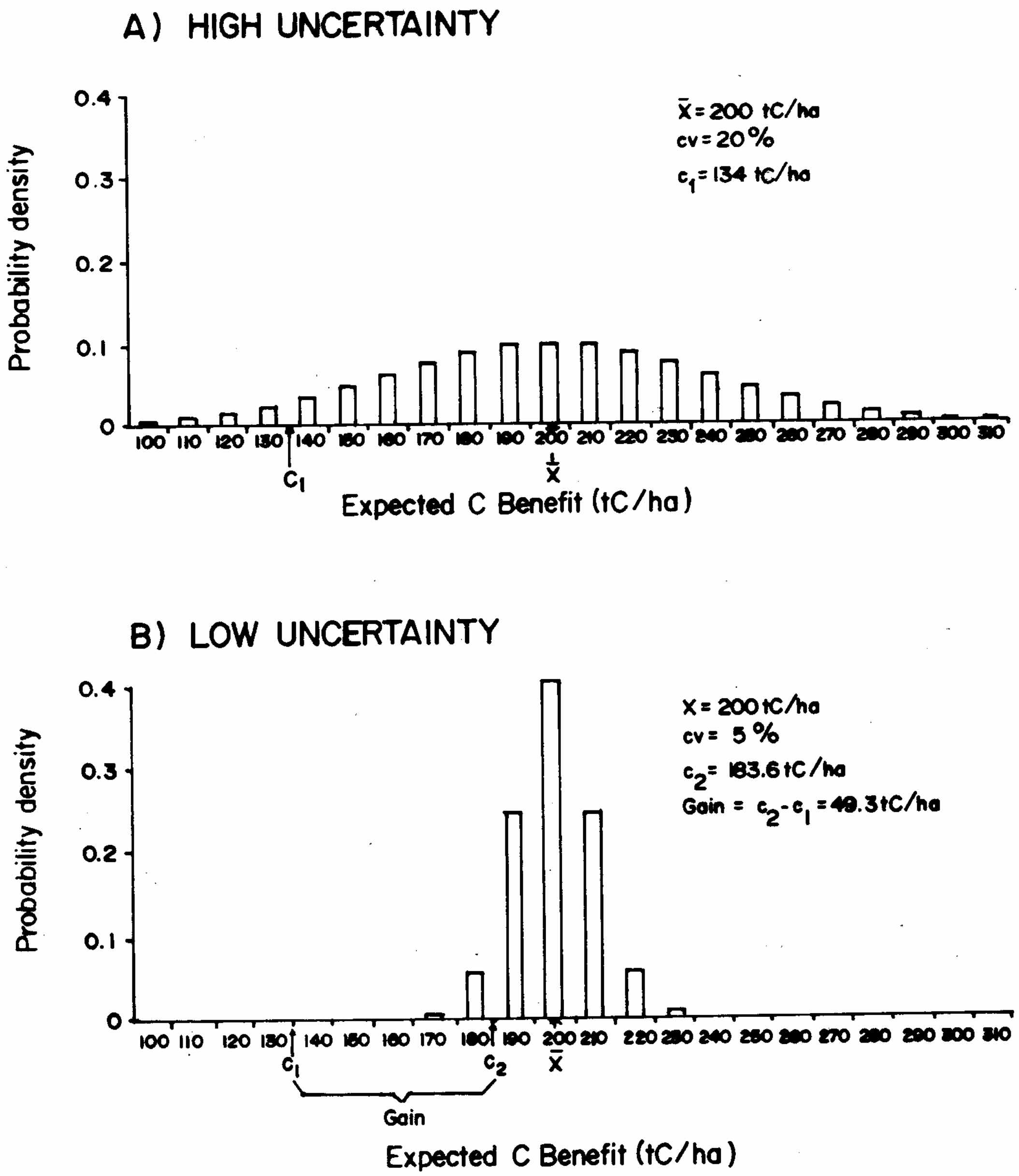

A) HIGH UNCERTAINTY
Probability density
0.4
0.3
0.2
0.1
0
x̄ = 200 tC/ha
cv = 20 %
c1 = 134 tC/ha
100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310
C1
X̄
Expected C Benefit (tC/ha)
B) LOW UNCERTAINTY
Probability density
0.4
0.3
0.2
0.1
0
X = 200 tC/ha
cv = 5 %
c2 = 183.6 tC/ha
Gain = c2 - c1 = 49.3 tC/ha
100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310
C1
C2
X̄
Gain
Expected C Benefit (tC/ha)

Fig. 2

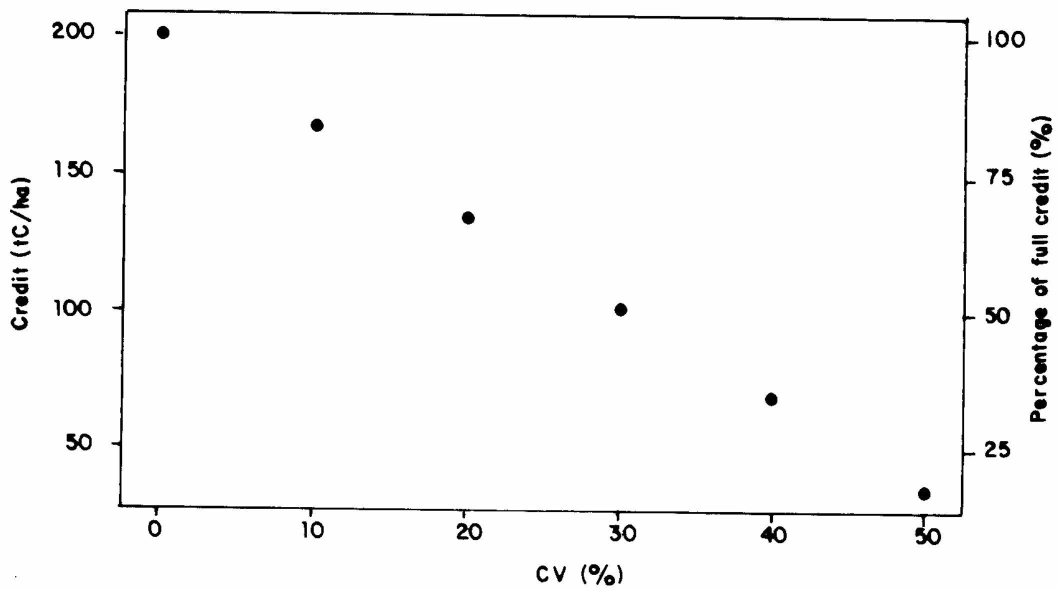

200
150
100
50
Credit (tC/ha)
0
10
20
30
40
50
CV (%)
100
75
50
25
Percentage of full credit (%)

Fig. 3

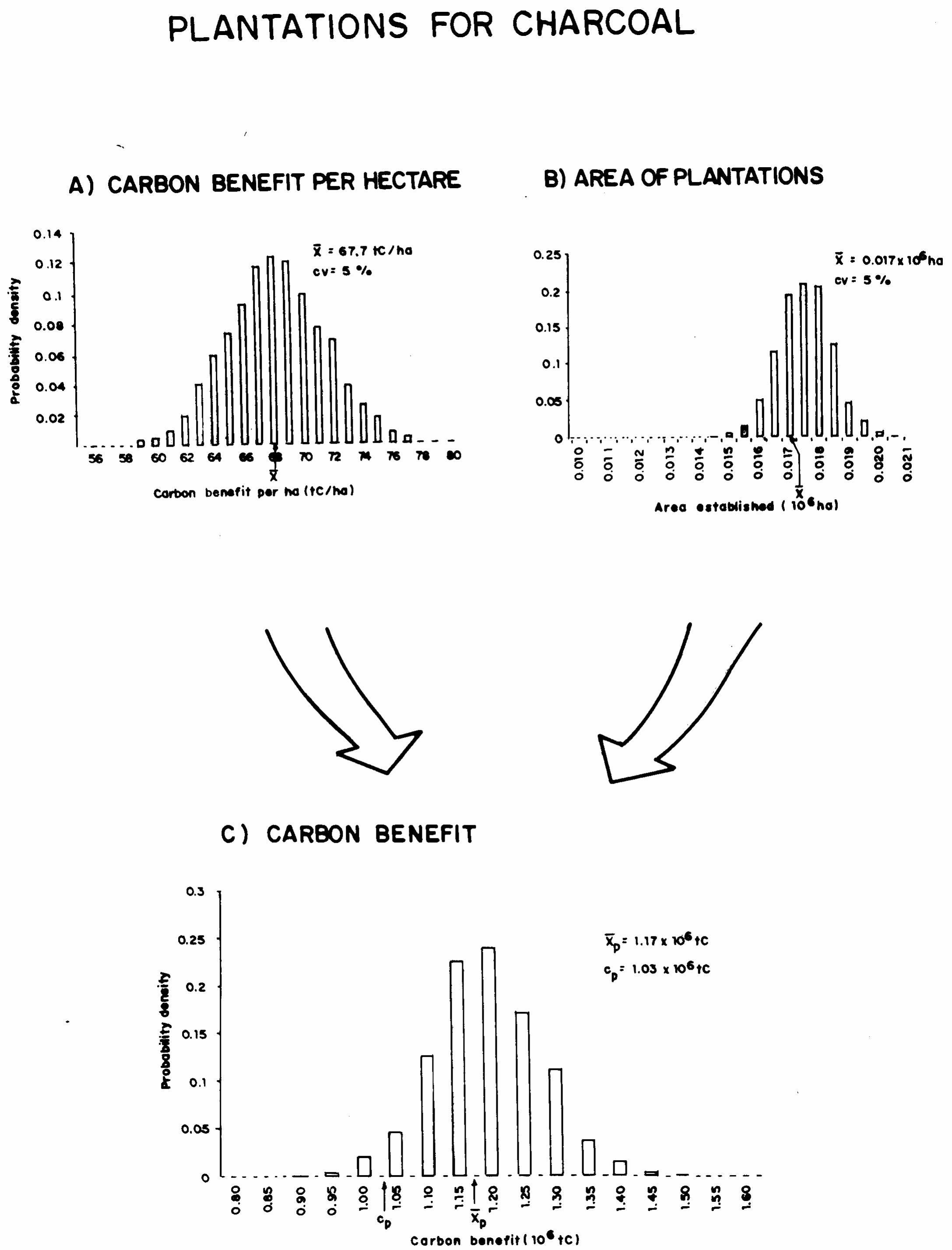

PLANTATIONS FOR CHARCOAL
A) CARBON BENEFIT PER HECTARE
Probability density
X̄ = 67.7 tC/ha
cv = 5 %
Carbon benefit per ha (tC/ha)
B) AREA OF PLANTATIONS
X̄ = 0.017 x 10⁶ ha
cv = 5 %
Area established (10⁶ ha)
C) CARBON BENEFIT
Probability density
X̄p = 1.17 x 10⁶ tC
cp = 1.03 x 10⁶ tC
Carbon benefit (10⁶ tC)

Fig. 4

AVOIDED DEFORESTATION

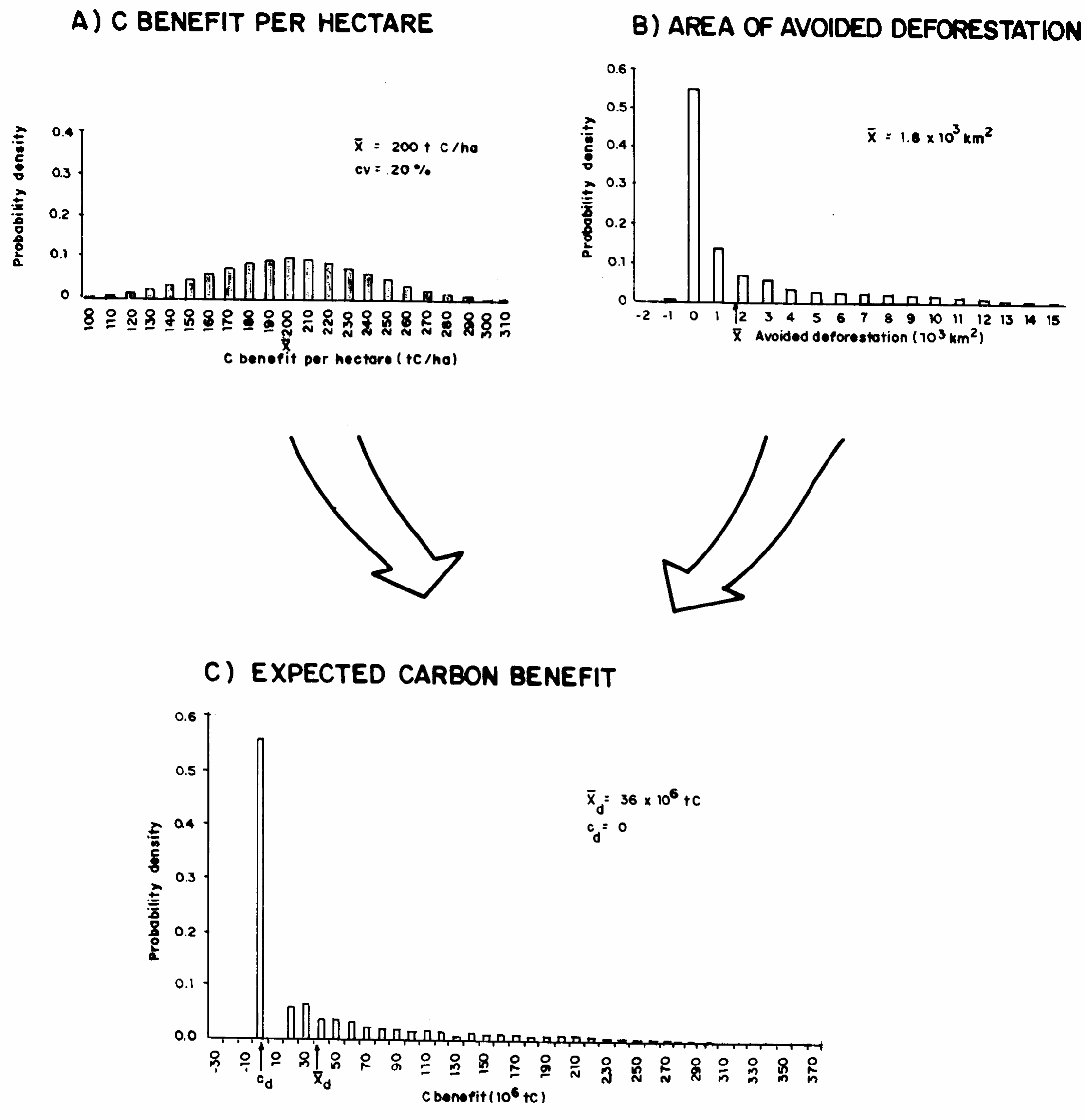
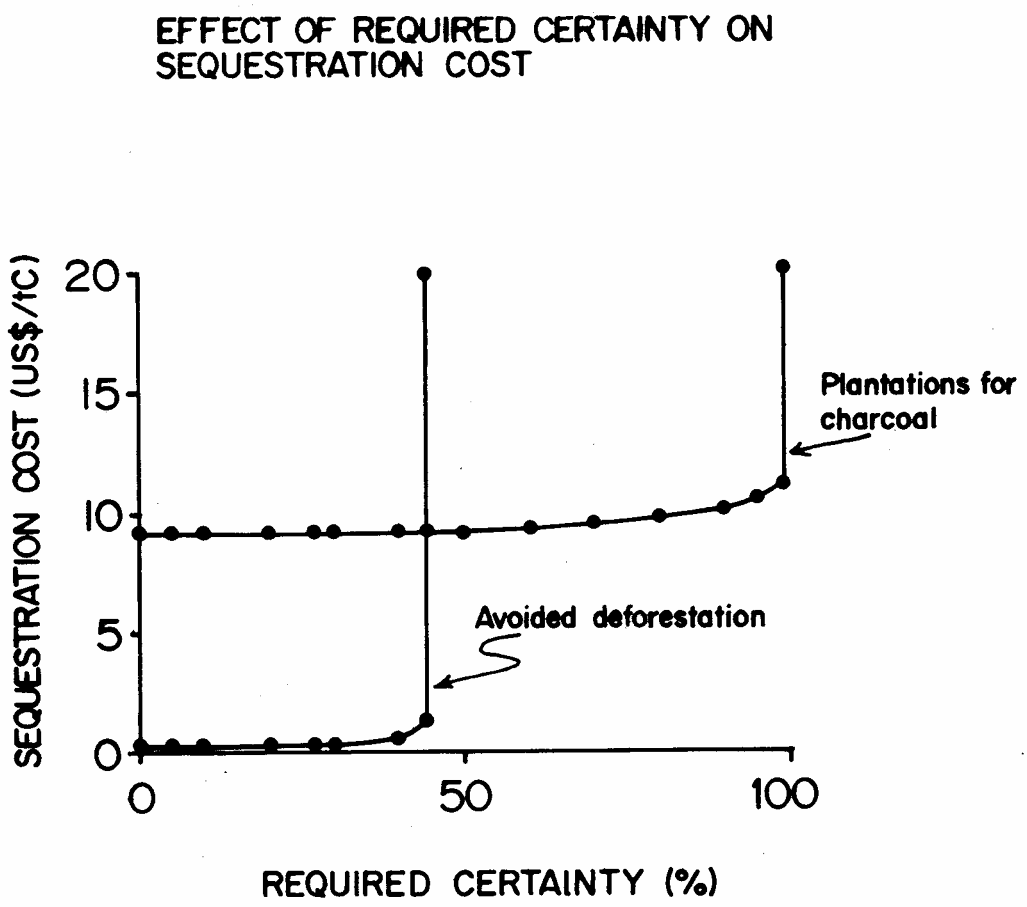


Fig. 5


EFFECT OF REQUIRED CERTAINTY ON SEQUESTRATION COST
SEQUESTRATION COST (US$/tC)
20
15
10
5
0
Plantations for charcoal
Avoided deforestation
0
50
100
REQUIRED CERTAINTY (%)