CHAPTER 11
FORESTRY SECTOR

11.1 INTRODUCTION

Forestry mitigation options refer to those measures and policies that can lead to a reduction in the emission of greenhouse gases from forestry and/or increase carbon sequestration in forests, long-term wood products, and other tree vegetation. In most land use changes involving decomposition and oxidation, GHGs will be emitted into the atmosphere. These gases include CO_2, CO, methane, N_2O, NO_x and other NMHC. Although CO_2 accounts for the bulk of these gases emitted from the forest sector, it can also be re-absorbed by vegetation, soils and water bodies. The other GHGs, while emitted in trace amounts, accumulate in the atmosphere for their entire residence period without a possibility for re-absorption. The emissions of these trace gases can be estimated using standard ratios to the amounts of CO_2 released.

11.2 MITIGATION OPTIONS

Mitigation options for the forestry sector may be classified into two basic types. One type involves expanding the pool of carbon in soils, vegetation, and wood products. Expansion withdraws carbon from the atmosphere and sequesters it. The second type involves maintaining the existing pools of carbon in soils, vegetation, and the proportion of forest products currently in use. Maintaining existing stands, whether achieved through reduced deforestation, forest protection, or more efficient conversion and use of forest products, keeps the avoided GHG emissions from entering into the atmosphere for the duration of the pool maintenance. Although expansion and maintenance of carbon pools in standing trees, forest soils, and forest products may be very effective mitigation options, they may be difficult to implement since the alternative use of the land upon which the carbon is stored is often more valuable to local inhabitants than the trees are.

Another way to reduce carbon emissions is to use wood obtained from renewable sources like forest plantations as a substitute for non-renewable emission sources, particularly fossil fuels (Hall *et al*., 1991). This substitution will delay the release of carbon from the fossil fuel for as long as one continues to use wood from a renewable source in lieu of the fossil fuel. Similarly, wood derived from renewable sources, if used as a substitute for woodfuel derived from depletable natural forests, will also delay or stop carbon release from the non-renewable source. Forest sector mitigation options are summarized below.

11.2.1 Maintaining Existing Stocks

- **Forest Protection and Conservation**. This protects the carbon and other GHGs in both the vegetation and soil. Such measures are often included in projects which are put in place for non-carbon resource management purposes, such as wildlife protection, soil conservation, water catchment, and recreational reserves. Measures to improve wildfire protection and reduce forest losses from insects and diseases should also be considered under this category.

- **Increased Efficiency in Forest Management, Harvesting, and Product Utilization**. Measures to increase efficiency include natural forest management with selective harvesting; harvesting for multiple end-uses; residue utilization for fuel and tertiary products; increased conversion efficiency, possibly involving technological intervention; and salvage operations during conversion of forests to other land uses like hydropower development, etc.

- **Bio-energy Initiatives**. Mitigation options related to bio-energy will mainly reduce the use of biomass and thus maintain stocks of carbon while restraining emissions of trace GHGs. According to the *IPCC 1994 Draft Guidelines for National Greenhouse Gas Inventories*, all net emissions from biomass burning should be considered loss of forest stocks. Bio-energy options include: more efficient kilns for charcoal production, charcoal packaging (e.g., briquettes), improved woodfuel stoves; improved use of charcoal for industry (e.g., steel); and more efficient use of wood in agriculture (e.g., tobacco and tea curing).

  Use of sustainably-grown biomass for fossil fuel substitution is another option. Such biomass may also be used as a substitute for fuelwood from natural forests that are being depleted.

  Urban tree planting to reduce energy use for building cooling and heating should be handled in the energy sector analysis to the extent that one can compute the energy savings.

11.2.2 Expanding Carbon Sinks

Each of the options in this category must be separately identified and described depending on the intended use of the new biomass or the fate of the new land use. Uses include provisions of forest products such as woodfuel, timber, pulp and papers, and forest services like recreation, soil protection, and emission reduction through fossil fuel substitution. The fate of the biomass is critical in determining the carbon flows, cost and benefit streams, and the implementation possibilities of the specific mitigation options listed below.

- **Afforestation**: Planting forests on bare land, with biomass density commensurate to the objective of the project

- **Reforestation**: Replanting and/or natural regeneration of deforested areas

- **Enhanced Regeneration**: Increasing the biomass density of existing degraded and under-stocked forests

- **Agroforestry:** Some or all of the agroforestry forms listed below may be applicable to different sites in a country. The most commonly practiced forms are:

  - inter-cropping for the purpose of producing both agricultural and forest products

  - boundary and contour planting for wind and soil protection, as well as for providing agricultural and wood products.

- **Urban and Community Forestry:** This includes the additional biomass in non-contiguous tree cover which has not been described elsewhere. This may include residential shade trees, and road-side and demarcation trees in the rural areas. Expanded urban forestry, which sequesters carbon and may also reduce emissions through cooling and heating of urban residential and commercial buildings, should also be considered.

11.3 COMPREHENSIVE MITIGATION ANALYSIS PROCESS (COMAP): OVERVIEW

COMAP is intended to guide an analyst in undertaking a comprehensive assessment of the role of the forest sector in a country's climate change mitigation effort. This approach includes the following specific steps (See Figure 11-1):

- Screening to identify mitigation options significant to the country
- Assessing of the current and future land area available for restraining emissions and/or carbon sequestration given the demand for land by all sectors
- Identifying the mitigation options which could be implemented on the various available lands
- Estimating of the emission reduction and/or carbon sequestration per unit area for each mitigation option
- Estimating of the total and unit costs and benefits for each option
- Developing of future GHG net emissions and cost scenarios
- Evaluating the cost-effectiveness of mitigation options
- Exploring the policies, institutional arrangements, and incentives necessary for the implementation of mitigation options.

The first step involves categorizing and screening the mitigation options that are suitable for implementation. This is followed by a determination of the forest and agricultural land area that might be available to meet future demand for both domestic consumption and export. Demand for wood products includes demand for fuelwood, industrial wood products, and construction timber. The land which is left over after satisfying the future demands for products and the demand for conversion to other land uses can be considered to be available for carbon sequestration and/or other environmental purposes. In many countries there may not be enough land available. In this case, some of the wood demand may have to be met through wood imports or by using substitutes for forest products. Alternative combinations of land use and wood product demand patterns will lead to different scenarios of the future. The most-likely-trends scenario is chosen as the base line scenario against which the mitigation scenarios are compared.

The mitigation options are then matched with the types of future wood products that will be demanded and with the type of land that will be available. Matching options and demand requires iterating between satisfying the demand for wood products and land availability considerations. Based on this information, the potential for emission reduction and/or carbon sequestration, as well as the flow of costs and benefits per hectare of each mitigation option, are determined. The carbon and cost-benefit information is used to establish the cost-effectiveness of each option, which yields its ranking among other options. In addition, this information, in combination with land-use scenarios, is used to estimate the average and total cost of each and all mitigation options. Finally, the barriers, and the policies and incentives needed for the implementation of each scenario, are explored.

Such a comprehensive approach should result in a mix of mitigation options which use the fewest resources as well as provide the most benefits while mitigating climate change. This will allow for a cost-effective implementation of a subset of the options depending on the available resources at any point in time. This approach also reduces the possibility of double-counting of GHG flows, costs, and benefits.

Figure 11-1 here (full page, paste)

In Appendix 11-1, two examples are presented to illustrate the comprehensive assessment approach. The first example, forest protection, is drawn from the category of mitigation options intended to maintain existing stocks of biomass and carbon. The second example, reforestation, aims to expand carbon stock. In both examples, there is also a possibility of avoiding emissions of trace GHGs.

11.4 SCREENING OF MITIGATION OPTIONS

There is a need to screen out non-promising options prior to undertaking a comprehensive evaluation. While the general criteria for screening are similar to those described in Chapter 2, there are some criteria which are specific to the forestry sector. These criteria may include: conformity with existing forest management plans, equity and co-benefits issues, feasibility and/or ease of implementation, ecological soundness of the option, etc. The following are two examples of screening criteria:

- **Biophysical considerations**. Some options may be screened out due to biological or physiographic reasons. These may include site characteristics, e.g., climate, soil, drainage, and altitude. For example, large increases in productivity in a dry area through short rotation forestry in an area without possibility of irrigation can be screened out at this stage.

- **Political considerations**. Those options which are expected to significantly infringe on the sovereignty of a country or might tend to cause political instability should be screened out. For example, a measure which requires physical removal of large numbers of forest dwellers for re-settlement may be politically infeasible and socially unwise for the country in question.

11.5. LAND AVAILABILITY AND PRODUCT DEMAND/SUPPLY

As discussed in Chapter 10, both baseline and mitigation scenarios depend on the demands exerted on the forest resource for both wood products and other land uses. However, in many countries the dynamics of the economy shape the scarcity of land. Whether available lands are ever used for biomass growth depends on economic, political, demographic, social, cultural, and other factors.

Estimation of available land area can be done as described in Chapter 10. The easiest method is to use the existing plans on land-use management, such as government plans to increase the current forest cover to a given proportion of the land area in the future. A more involved method requires matching each mitigation option with the land available for its implementation, adjusting for any possible overlap where more than one option takes place on the same piece of land. This must take into account the minimum land requirements by the other sectors over time, especially the agricultural sector which has traditionally been given priority over forestry in land-use allocation.

11.5.1 Land-use Scenarios

An important element of the approach is developing scenarios for demand on land use, wood and other relevant products. These scenarios depict the amount of products that would be demanded and the land that would be required to support such a demand, given the capacities of the various land categories. The amount of carbon that can be potentially stored, and the net cost of doing so, varies with the type of options that will be included in the scenarios. The development of scenarios, discussed below, would form the basis for applying the method described in Chapter 10.

11.5.1.1 Baseline or likely trends scenario

This type of scenario is based on the current trends of land use and consumption of forest products in the country. It involves describing existing land-use distribution among and within sectors, the rate at which land is being converted from one use to another, and identifying the factors which drive the land-use distribution and conversion process. Factors such as population and income growth rates are used to extrapolate the demand for land and forest products to the future under given assumptions on the behavior of the factors.

11.5.1.2 Mitigation scenarios

- **Technical Potential Scenario**

  This scenario helps to estimate the amount of carbon that might be stored if the technically available land area were to be fully utilized for carbon sequestration. This scenario ignores many factors economic, institutional, cultural, legal, etc. that may limit the usability of available land for the sole purpose of storing carbon. Thus, the scenario represents an upper limit to the amount of carbon that might be stored through forestry options in a country.

- **Programmatic Scenario**

  A programmatic scenario is one which is based on specific existing programs. Examples of such programs include the America the Beautiful reforestation program (Andrasko *et al.*, 1991), the goal declared by the Noordwijk Convention to increase net world forests by 12 million hectares a year by the beginning of the next century, and various national plans/programs and bilateral initiatives, like the Tropical Forestry Action Plan (TFAP), which are in place in many tropical countries. If one does not use the comprehensive approach, a programmatic scenario is the most appropriate type of mitigation scenario to use.

  One disadvantage of a programmatic scenario is that it may yield wood far in excess of its domestic and/or export demand. This could lower the price of wood and reduce an option's net monetary benefit, depending on the price elasticity of demand of the relevant products. Programmatic scenarios are particularly likely to create an inequitable distribution of benefits (Adams *et al*., 1993) since they are usually driven by a single major purpose, e.g., to store carbon, to conserve fauna, to rehabilitate degraded lands, etc. However, the excess wood derived from such scenarios might be absorbed by an expanded program of using biomass to replace fossil fuels.

- **End-use Scenario**

  This type of scenario would be driven by the need for wood products and various land uses in a country. The end-use approach has been used extensively to understand the magnitude of future demand for energy (Sathaye *et al*., 1989). However, with the possible exception of some applications in developed countries (Adams and Haynes, 1980), this approach has not been applied to the forest sector with the same analytical rigor and specificity. The Food and Agricultural Organization (FAO) has done numerous studies on timber trends and outlook both at the global and regional level, but very few such studies for individual developing countries have been done (FAO 1963, 1967a, 1967b, 1986.).

End-use scenarios have the advantage that they take into consideration an end-user's needs for forest products and land. In tropical countries, where wood is scarce and forests are used as sources of many non-timber products, planting trees for carbon storage alone may not be sustainable. The trees will most likely be cut down and used for various products. Thus, only trees that provide multiple and adequate benefits, including carbon storage, to a diverse set of beneficiaries are likely to be managed sustainably. In order to satisfy the assumption that tree stock should be maintained in perpetuity, it is important that all participants be adequately compensated. An end-use-based approach that explicitly recognizes the needs of the participants will yield more plausible and sustainable future scenarios than a programmatic approach.

Construction of end-use scenarios is done with varying degrees of complexity. The simpler forms are used to project current consumption per capita into the future, adjusting for driving factors such as population growth and income. To improve on this, one can make further adjustments using known or estimated income elasticities of demand for the product in question. Many of the wood products outlook studies mentioned above are based on this approach. For example, the approach was recently applied to evaluate forest sector mitigation options for India (Kadekodi and Ravindranath, 1994).

The second way to construct end-use scenarios involves statistical estimation of a product consumption function with a few explanatory variables used to generate the coefficients needed for projection. Time series or cross-sectional information is used depending on the product in question and availability of data (FAO, 1991). A more rigorous variation of the statistical approach involves an econometric analysis of the product market (both demand and supply), including the use of some form of a land-use allocation model for tracking the required forest areas needed to meet such demands (Adams and Haynes, 1980). This approach usually includes a policy simulation phase which is used to forecast the impact of various policies, including those which may constitute mitigation options. This method will most likely lead to more precise projections of future demand and supply of forest products and forest land. However, its application requires a sound knowledge of econometric techniques and a good amount of data on production, consumption and price structure of forest products, and applicable factors (of production) and technology. Of the three methods, each country should use the one commensurate to its capability and availability of data and be aware of the different levels of precision associated with the resulting projections.

- **Achievable Scenario**

The end-use scenario described above shows the projected demand for both forest products and land use under the various mitigation options. This scenario may not be achievable depending on the likelihood of implementing the underlying mitigation options, which depends on factors such as land tenure and law, and available technical and human resources. In most cases, the achievable scenario is less than the economically defined scenario. Past experience with implementing similar projects can serve as a guide for estimating the magnitude of GHG mitigation that may be achievable.

In summary, one should construct a baseline scenario for the purpose of computing the change caused by mitigation options. Of the four mitigation scenarios, the technical potential is of some interest in that it shows the maximum physical potential. The programmatic scenario will be useful for those countries which do not apply the comprehensive approach. Wherever possible, the analyst should construct end-use scenarios and also estimate the achievable potential.

11.6 ANALYSIS OF MITIGATION OPTIONS

The aforementioned mitigation options either maintain or expand the stock of carbon in biomass, soil, and/or wood products. Two approaches have been used in the past to evaluate stored carbon. One approach assumes that trees will be planted for the purpose of storing carbon and will not be harvested after they grow to maturity. It suggests that carbon stock be estimated according to the amount accumulated in tree biomass, soil, litter, and understory over a period of time (Moulton and Richards, 1990). The time period may be that of a single rotation or multiple finite rotations. The second approach assumes that carbon will need to be stored in perpetuity and estimates the amount of stored carbon based on an average amount of on-site carbon over an infinite number of rotations (Dixon *et al*., 1991).

A modified version of the second approach has been used by Swisher (1991). The method adjusts average stock for the biomass remaining at maturity. Swisher also includes the carbon in soil, litter, understory, and wood products in estimating the total carbon storage of a given site.

Of the two methods mentioned above for evaluating stored carbon, the second approach is preferable, since (1) it is consistent with the fact that the economic value of stored carbon is unknown and thus the safest course of action would be to store carbon in perpetuity, and (2) intermittent harvesting of forest products provides a periodic income stream that strongly influences the financial evaluation of a mitigation option (Winjum and Lewis, 1993). See Appendix 11-2.

11.6.1 Greenhouse Gas Flows

Numerous mitigation options can be identified for implementation in different parts of the country. Their implementation will take place over a long period of time. The estimation of GHG flows should cover the following items:

1. Greenhouse Gas Emissions

Estimate carbon flows associated with each option at all stages of the project, including emissions from salvage, silvicultural operations, harvesting, and short-term products like pulp and paper and woodfuel. Also to be included are the emissions from soil disturbance and from future decomposition from medium- and long-term forest products in use. The other trace GHGs, such as methane, N_2O, NO_x, and NMHC, should be estimated if the option in question will eliminate the emission of significant quantities of them into the atmosphere. Despite the existence of a substantial level of uncertainty associated with estimating emissions of these trace gases, one should, at the very least, use simple emission ratios of these gases per unit of emitted CO_2-C. Appendix 11-3 provides applicable ratios for trace gas emissions from biomass burning and flooding.

2. Carbon Sequestration

This includes estimates of uptake by vegetation and soils within the area. This should be based on Net Primary Productivity of the woody biomass, including the net storage in soil and detrital material. Alternatively, carbon sequestration can be estimated for the various mitigation options based on the mean annual increment of the growing vegetation and the refurbishment of the soil carbon from organic matter.

11.6.1.1 Incremental carbon storage

In order to evaluate the incremental carbon benefit of a mitigation option, it is necessary to estimate the carbon that might have been stored without the project. For forest protection, the baseline amount of carbon stored may be estimated as that which would have been released in the absence of a protection measure such as a physical barrier, or monitoring and policing, relocation of forest dwellers, provision of alternative means of earning a living to the current users of the forest, or a subset of these measures (Swisher, 1991).

In the case of plantations or management of forests under rotation, the situation is more complicated. One needs to compare the incremental carbon which would be sequestered on land and in products indefinitely. On land, carbon will be stored in vegetation, soil, and the decomposing biomass. The carbon stored per hectare in a plantation or forest managed sustainably in rotations can be estimated as described in Appendix 1, Example 2.

It is important to include carbon stored in wood products when estimating the total carbon storage since wood-product carbon can amount to 30-40% of the carbon stored on land (Dewar and Cannell, 1992). By not including product carbon, studies such as Dixon *et al*. (1991) may overestimate the unit costs by a corresponding proportion.

A more comprehensive framework for tracking the carbon flows from all forestry mitigation options in a country is a spreadsheet model named COPATH (Makundi *et al*., 1991). This model provides a coherent framework for tracking all the carbon flows from each scenario over as long a period as desired while providing the analyst the capability to assess the carbon balance in the sector at any point in time under each scenario. In brief, the model allows estimation of the existing carbon stock in the forest areas, which may be affected by the mitigation options, as well as estimation of the carbon release from decomposition and oxidation of the affected biomass. It also helps estimate the carbon sequestration in vegetation, soil, and wood products.

11.6.2 Estimating Costs and Benefits of Mitigation Options

To evaluate the mitigation options, a set of criteria should be assembled for each option. The evaluation should cover a variety of criteria, including physical, socio-economic, and other environmental factors so as to make comparison of options exhaustive. The physical criteria such as land availability, biomass productivity, and net GHG flows for each option have been described above. Below is a discussion on evaluating the suggested economic criteria.

- **Physical Inputs and Outputs**

  Although the physical criteria determine the capacity of the various options to mitigate climate change, the economic criteria are essential decision variables in choosing mitigation options. In this section, we discuss the approach and issues involved in compiling the economic criteria.

  The first step is to identify and quantify all necessary physical inputs required for implementing each option covering the initial operations, management, harvesting (if applicable), etc. These should include estimates of land, labor, equipment, and material needed to support the project or option throughout its lifetime. For the land-intensive options, different categories of land must be identified and their suitability for various options assessed. For all options, the analyst must also identify constraining factors such as expertise, technology, and capital investment because these may affect the cost as well as the likelihood of implementing the option.

Together with the physical inputs, one must estimate the physical output in terms of desirable products like timber, woodfuel, and agricultural produce (for agroforestry options) that are expected from each mitigation option.

- **Unit Costs and Benefits**

In order to create policies and measures to stabilize future GHG emissions, national policy-makers need information on the costs and benefits of options in addition to their carbon implications. Policy-makers must weigh the costs, benefits, and impacts of climate change mitigation and adaptation options in the face of competition for limited funding from the government and other sources. The policy goal for climate change mitigation options is to identify which mix of options will best achieve the desired forest resource utilization goals at the least cost. In other words, the policy should attempt to maximize economic and social benefits from forestry while minimizing local and global environmental and social impacts.

It is important to draw a system boundary within which the costs and benefits of a project will be evaluated. Costs and benefits should be evaluated up to the roadside and not to the millsite or market place. Roadside costs would include the cost of harvesting wood, which in turn includes the required forest-road construction costs. By choosing to report costs only up to the roadside, we exclude the costs and carbon emissions associated with transporting the produce to the market. This also eliminates the need to collect data and make projections on the location of mills which will likely change if a large magnitude of projects have to be implemented in order to significantly reduce nationwide emissions. The post-roadside costs should be handled in the respective end-use sectors such as industry (sawmilling) and residential (biomass fuels).

For each of the physical inputs (e.g., labor), one has to obtain the cost per unit at the time of use. For each desirable product (e.g., timber or woodfuel), an estimate of product price will be necessary. These will be used to calculate the cost and benefits of the monetary elements of each option.

Costs. The costs of carbon storage of a mitigation option include the (1) present value of the stream of expenses sufficient to cover the project's planning, development, and occasional and recurrent expenses, and (2) present value of the project's opportunity cost. Swisher and Masters (1992) refer to the present value of future project costs as an endowment.

The endowment includes the initial cost of establishing the project, cost of silvicultural operations, management, extension services, protection, and cost of monitoring the project's performance. For perpetual management of a given forest project, the benefits derived during the first rotation may be sufficient to cover the operation and management of future rotations.

The 1990 IPCC report on Response Strategies to Climate Change reviewed the then existing literature on costs and benefits and noted that halting deforestation was a low-cost option for reducing a unit of atmospheric carbon (IPCC, 1991). The report quoted regional average annual costs of about $8/tC for tropical forestation and reduction of deforestation, and about $28/tC for forestation in non-US OECD countries. The cost of establishing a forest plantation, excluding the opportunity cost of land, was estimated to range from $230 to $1000 per hectare with an average cost of $400 per ha (Sedjo and Solomon, 1988).

The unit cost estimates for carbon sequestration have been improved in several ways since the IPCC report. First, unit costs have been estimated for individual countries by different types of mitigation options rather than by regions or for the globe as a whole. For example, Dixon *et al.* (1991) estimated establishment costs for 94 countries by combining survey data with information gathered from the literature.

Secondly, other cost components such as land rental (opportunity costs), maintenance, and monitoring and evaluation, which were not included in the earlier IPCC report, are now being addressed (Swisher, 1991; Moulton and Richards, 1990). The opportunity cost evaluation is important since it captures the benefits derived from land use in the absence of a mitigation option, given the current broad land-use patterns. Opportunity cost may be evaluated using various methods depending on the land in question and the likelihood of producing various goods and/or services if it is not used for the given option. These approaches include land rent, land market price, and net benefits obtainable from an alternative land use. In all these cases, land values and benefits from alternative use should be adjusted to account for existing significant price distortions due to subsidies, zoning regulations, etc. For example, land rental costs for the US were estimated at $142 per ha by Moulton and Richards (1990), and the land purchase price was estimated between $400 and $1000 per ha by Sedjo and Solomon (1988).

Land prices are likely to be lower in developing countries. For Thailand, Wangwacharakul and Bowonwiwat (1994) reported an estimate of $44-89 per ha for present value of the opportunity cost of land. For degraded lands suitable for reforestation in India, the land price is very low ($20/ha) (Ravindranath and Somashekhar, 1994). For China, the forest lands are already allocated for forest development, while the dry croplands are reserved for agroforestry development. Thus, the opportunity cost of non-forestry land use or land classified for forestry may be close to zero (Xu, 1994).

Benefits. In addition to carbon storage, implementing a mitigation option will result in other monetary and non-monetary benefits. These benefits may be classified as direct or indirect benefits depending on their role in, and level of, economic activity and non-monetary forest values. Direct benefits may include goods such as fuelwood and timber and services such as recreation. Indirect benefits may include such items as employment for local inhabitants, air pollution and micro-climate control, watershed protection, and development of social infrastructure such as schools, roads, and hospitals. In addition to these benefits, the forest has a value derived from the stock as a resource. This value may be influenced by concern for future generations and social status.

There is no consensus at present on the monetary value of reducing a unit of atmospheric carbon. Preliminary estimates of the marginal cost (including taxes) of stabilizing emissions from fossil-fuel burning in the US range between $100 to $200 per tC (Cline, 1992; Nordhaus, 1993), based on top-down models which do not include significant improvements in low-cost energy intensity in the economy. The unit cost estimates for mitigation options in most of the F7 countries[1] fall well below this range, and in the case of India they are also below the unit costs of energy-efficiency options.

A unique feature of the methodology presented in this section is the explicit evaluation of the direct benefits which may be derived from the sale of timber and other wood and non-wood products. As has been demonstrated in the F7 studies (Sathaye *et al.*, 1993), the benefits are sufficiently large to offset the life-cycle cost of many sink expansion options. In effect, carbon may be sequestered at a net benefit to society.

11.7 COST-EFFECTIVENESS EVALUATION

11.7.1 Initial Cost per ha and per tC

Initial costs do not include future discounted investments needed during the rotation period. This indicator provides useful information on the amount of resources required to establish the project.

Most cost studies estimate this indicator (Dixon *et al*. 1991; Andrasko *et al*. 1991; Volz *et al*. 1991). The other cost components and the option's benefits are often ignored. The studies take into consideration the carbon stored in live biomass and most account for soil carbon. The Dixon (1991) study uses the mean stock of carbon as a measure of the amount of carbon that would be stored by a mitigation option. The other studies report several estimates of the cost per tC, but their method of carbon estimation is unclear.

11.7.2 Endowment Requirements per ha and per tC

This is the sum of establishment cost and the discounted value of all future investment and recurring costs during the lifetime of the project. For rotation projects, the costs of second and subsequent rotations would be paid for by the revenues derived from the first rotation and thus would not be included in estimating the endowment. For projects which do not have substantial monetary benefits, this indicator is quite useful because it provides the endowment necessary to maintain the project in perpetuity. Swisher (1991) uses this indicator to evaluate project cost-effectiveness.

11.7.3 Net Present Value (NPV) per ha and per tC

This indicator would provide the net direct benefit to be obtained from the project. For most plantations and managed forests, it should be positive at a reasonable discount rate. For options such as forest protection and reforestation (Appendix 11-1), the NPV indicator is also positive if indirect benefits and forest value are included, both of which are subject to controversial evaluation. Appendix 11-2 provides the mathematical formulation for deriving this indicator for plantations and managed forests.

11.7.4 Benefit of Reducing Atmospheric Carbon (BRAC)

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[1] The F7 network is a group of researchers from nine countries who have been doing research on Tropical Forestry and Global Climate Change, coordinated by Lawrence Berkeley Laboratory, for the past four years. The countries are Brazil, China, India, Indonesia, Malaysia, Mexico, Nigeria, Tanzania, and Thailand.

$$BRAC = NPV\ /\ (\frac{1}{a}\sum_{0}^{Te} C_t\ )$$

This indicator expresses the NPV of a project per unit of atmospheric carbon reduced as opposed to the reduction of net emissions. In so doing, it captures the atmospheric residence time of carbon. The formulation of the indicator varies with the rate at which economic damage might increase, and it allows time-dependent evaluation of atmospheric carbon as may be deemed necessary. The expression for deriving BRAC when the economic damage caused by atmospheric carbon increases at the real societal rate of discount is given below. For complete coverage of the BRAC indicator, see Sathaye *et al*. (1993).

where NPV = Net present value of benefits
a = Decay rate of carbon
T_e = Time duration of carbon flows
C_t = Net carbon flow in time t

11.7.5 Imputed and Non-monetary Costs and Benefits

After compiling the criteria given above, all the identifiable costs and benefits that one is currently unable to evaluate should be listed for each mitigation option. Imputed values should be listed separately from the direct costs and benefits. The intangible benefits and costs should also be listed in a separate column for each mitigation option. To the extent it is possible, identify the likely bearers of costs and benefits, including the non-monetary items. All these criteria may play an essential role in the choice and subsequent implementation of mitigation options.

11.8 DEFINING BASELINE AND MITIGATION SCENARIOS

Having compiled the physical, economic, and the intangible criteria for each mitigation option, one uses them to define mitigation scenarios containing a set of options. One useful method is to summarize the results as a supply curve for emission reduction or carbon sequestration. For example, the establishment cost per tonne of carbon or per hectare can be used to plot a cost of conserved carbon (CCC) curve for all mitigation options. The curve shows the amount of carbon that could be stored at increasingly higher establishment cost. The other indicators (endowment requirement, NPV, or BRAC) could also be used to plot similar curves.

The unit values are combined with the area availability for each option to obtain a step function of all options in a scenario. From these curves one can calculate the total area and financial resources required to achieve a given scenario, and the total amount of carbon and other GHGs saved. Although there may not be a coherent method for comparing the non-monetary and intangible costs and benefits associated with each option, their enumeration helps the policy-makers in the choice and implementation of the various mitigation options.

11.9 MITIGATION POLICIES

11.9.1 Identifying Implementation Policies

Having constructed the baseline and mitigation scenarios, one has to identify and describe the policies which may be necessary to implement the mitigation options. These policies can be divided into two groups: (1) forestry policies which govern the use of forest resources, and (2) non-forestry policies which happen to influence levels of activities in the forestry sector.

(1) Forestry Policies

Policies that can be used to maintain carbon stocks and/or expand carbon sinks include the following:

- Forest protection and conservation policies. One has to consider both national, regional, and local measures to preserve existing forests and vegetation cover. Examples include local laws prohibiting conversion of steep slopes to agricultural lands or national laws gazetting vulnerable ecosystems into nature reserves.

- Policies on shared responsibility for managing existing protected areas between local communities and the central agencies, which also include the sharing of benefits from the protected area, tend to reduce "encroachment" by the surrounding population. Such policies have been applied effectively in many developing countries. A recent example is the shared wildlife management in Zimbabwe.

- Policies governing terms of timber harvest concessions (allowable cut, concession duration, levels and structures of fees and royalties) will influence the implementation and effectiveness of mitigation options that improve the efficiency of forest and product utilization. These policies may even include logging bans in specified ecosystems. Policies which emphasize export of higher-value timber products or ban log exports may reduce the rate of forest degradation while maintaining the forest sector's contribution to the country's foreign exchange earnings.

- Tax rebates and dissemination policies governing the adoption of efficient charcoal kilns and wood stoves have been shown to substantially affect the success of such programs in the bioenergy field.

- Aggressive afforestation and reforestation policies both by villagers and forest departments will help expand the carbon sinks in a country. These policies may include village afforestation schemes and incentives for private ownership of degraded lands for reforestation, emphasizing expanding plantation forestry for industrial wood instead of relying on natural woodlands.

(2) Non-forestry Policies

These policies are intended to manage the other sectors of the economy, but have large influences on the depletion of the carbon stock, and at times may provide a disincentive to increasing forest cover. The mitigation policies which lie in this area are:

- Land tenure policies that encourage private ownership of some lands with an express mandate to sustainably develop them. Policies to the contrary have been shown to encourage wasteful conversion of forests to other land uses so as to meet the criteria for property rights assignment.

- Land tenure policies that increase the certainty of tenure tend to encourage the owners of the land to plant and retain trees on their land. Such policies will be necessary for mitigation options involving agroforestry or woodfuel plantations.

- Agricultural policies that do not encourage extensive and wasteful conversion of natural forests to agricultural lands. Policies which emphasize more intensive farming and conversion of fewer marginal woodlands tend to lead to production of the same agricultural output from less area using the same amount of resources.

- Infrastructural policies governing mining, dam construction, and road construction can reduce unnecessary emissions.

- Taxes, credits, and pricing policies also play an important role.

11.9.2 Barriers and Incentives for Implementation

The policies described in the last section may not easily be translated to mitigation programs due to the existence of barriers and lack of incentives to implement them. A diverse array of criteria will have to be satisfied before a project can be implemented. The analyst should identify and describe potential solutions to these barriers. The most common barriers to the implementation of forestry mitigation options can be divided into three categories:

(1) Technical and Personnel Barriers

- Availability of scientific data on silvicultural practices and soil conservation may be a limiting factor in evaluation of various options. Availability of seed material, research on species provenance, multi-cultural management, including harvesting techniques and silvi-pastoral systems, may be lacking for individual sites.

- In the short to medium term, there may be a lack of qualified local personnel to carry out the projects and provide extension services necessary for the successful involvement of local populations.

(2) Financial and Resource Barriers

- Funding for forestry projects has been very low in most cases. Participation of the commercial sector may depend on incentives for long-term investment in forestry. The borrowing rates from banks may be too high for private investors and/or local communities to get credit for forestry projects. Bilateral and foreign-source funds are restricted to those forestry sections that are more profitable, and as such there may not be enough funds for broad investment in the identified response options.

- Agricultural activity may compete for labor with the forestry sector, depending on the types of crops and the seasonal demands on labor.

- Procedures and mechanisms for identifying beneficiaries, cost-bearers, and ways to apportion credit from the options may be a barrier to implementation.

(3) Institutional and Policy Barriers

- Land tenure and land law may prove be the strongest hindrance in implementing the mitigation options, especially in developing countries.

- Institutions necessary to allow various parties to participate in the options may not exist in the country. For example, there may not be a mechanism for sharing benefits between the central authorities and the local participants in community-based mitigation options.

- Policy barriers to harvesting, marketing of forest products, pricing, tariffs, and quotas for exports and imports may also hinder implementation of some of the mitigation options.

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APPENDIX 11-1
EXAMPLES OF COMPREHENSIVE ASSESSMENT APPROACHES FOR THE FORESTRY SECTOR

EXAMPLE 1: MAINTAIN CURRENT CARBON STOCKS FOREST PROTECTION

The steps in this example are illustrated in Table 11-1 for the hypothetical Country X.

Steps 2 and 3: Determine current and future land area under two scenarios, baseline and mitigation options. In our example, the baseline scenario assumes that in 1990 there were 12,000 ha of protected forests which had declined from 15,000 ha in 1980. It is further assumed that the forest degradation and conversion of land to agriculture would continue in the future until only 1000 ha are left in the protected area by 2030. Conversion of land to annual agriculture implies that the stored carbon is reduced from a high equilibrium consistent with forest ecosystem to a much lower level consistent with annual crop production.

In the mitigation scenario, adequate steps are taken to ensure that the area is protected and the 12,000 ha of land remain protected until 2030. In addition, protection increases the biomass density and carbon density of the protected area.

Step 4.1: Determine the current and future biomass density under each scenario. In order to determine the carbon pool and sequestration, it is necessary to know the biomass density, the soil carbon density, and the carbon content of biomass. If this information is not available from destructive sampling data, it can be estimated using the following formula:

$$\textit{Dry Biomass Density}(t/ha) = SV * AS * TA * DW * WD$$

where	SV	=	Stemwood Volume (m^3/ha)
	AS	=	Above-ground biomass over Stemwood volume ratio
	TA	=	Total biomass (above plus below-ground) to Above-ground ratio
	DW	=	Dry to Wet biomass ratio
	WD	=	Wood Density (t/m^3)

In our baseline scenario, we assume that the biomass density continues to decline as the forest area is degraded, starting with 200 t/ha in 1980 to 160 t/ha by 1990. The density is assumed to continue declining at a rate of 1% each year to 107 t/ha by 2030.

Alternatively, the dry biomass density increases in the mitigation scenario at 1% annually to reach 238 t/ha by 2030.

Step 4.2: Determine the current and future carbon density under each scenario. The carbon ratio of biomass varies between 0.45 and 0.55 for most vegetation, with a few exceptions like rubber, which can have substantially higher carbon content. Multiplying the biomass density by the carbon ratio (C%) yields the carbon density (tC/ha) for each scenario. In our example, we assume that the carbon ratio (C%) is the same for both baseline and mitigation scenarios at 0.5. Biomass carbon declines from 80 tC/ha to 54 in the baseline scenario and increases to 119 tC/ha by 2030 in the mitigation scenario.

Step 4.3: Determine the soil carbon density for each scenario. We assume that the soil carbon density remains unchanged at 100 tC/ha in the baseline scenario but increases with the gradual rise in biomass density to 149 tC/ha by 2030 in the mitigation scenario.

Step 4.4: Determine the total carbon density under each scenario. Adding the biomass and soil carbon density yields the total carbon density for each year under each scenario. Total carbon density (tC/ha) decreases from 180 to 154 for the baseline scenario and increases to 268 in the mitigation scenario.

Step 5.1: Determine the cost of forest protection. In our baseline scenario, the area was poorly protected and the expenditure, which may be based on the annual government budget, was $2/ha/year. In the mitigation scenario, this increases to $9/ha/yr which is assumed to provide adequate protection to the area. This figure is the present value of a stream of costs from 1991 to 2030 (**Step 5.1.1)**. Initial costs are $5/ha in 1991 and recurrent costs are $0.5/ha/year until 2030.

Step 5.2: Determine the benefits from land conversion. In the baseline scenario, a portion of the protected land was lost each year to encroachment from which settlers derived monetary benefits, which we assume to be $50/ha/year. No land conversion occurs under the mitigation scenario.

Step 5.3: Determine the cost or benefit of alternative means of satisfying the settlers demand for products and services. In the mitigation scenario, the settlers would either occupy other lands, which would have carbon consequences, or their needs would have to be met through import of products. We assume, for simplicity, that their needs would be met by imports of products. The nation would bear the cost of these imports, which would normally be higher than the settlers benefits. We assume the imports to cost 5% more than domestic products. Had the settlers' demand been met by allocation of other land, it could have resulted in a net benefit to the economy.

Step 5.4: Determine the benefits of protection. In the baseline scenario, the protected area provided certain recreation and other benefits which were valued at $2/ha/year. These increase to $15/ha/year as mitigation reduces the degradation of the vegetation in the protected area.

Step 6.1: Determine the carbon pool and annual sequestration for each scenario. Multiplying the total carbon density (tC/ha) by the land area (ha) under each scenario yields the pool (tC) of carbon for each year. Since the carbon density and the land area decline in the baseline scenario, the carbon pool declines from 2,160,000 tC in 1990 to 153,518 in 2030. In the mitigation scenario, it increases to 3,215,946 tC by 2030.

It is important to compute the annual increase in the carbon pool in the mitigation scenario and compare it with the annual change in the baseline scenario. The annual incremental carbon is 80,480 tC in 1991, which declines to 74,748 tC by 2030.

Step 6.2: Determine the total costs and benefits. Here we aggregate the costs and benefits for the baseline and mitigation scenarios. For the baseline scenario, the cost of forest protection is computed by multiplying the **Step 5.1** cost by the protected area. For example, for 1991, the cost is calculated as $2/ha/year * 11725 ha = 23,450 $/year. Similarly, the benefits of land conversion are computed by multiplying the figures for 1991 in **Step 5.2** by converted land area, and benefits from protection are calculated by multiplying the figures in **Step 5.4** by land area. Adding these three estimates yields the net benefit for the baseline scenario for each year ($13,750 for 1991).

The costs and benefits for the mitigation scenario for 1991 amount to a net benefit of $52,343. The incremental net cost for 1991 = -$52,343 + $13,750 = -$38,593 or the incremental net benefit for 1991 = $126,300.

The present value of the stream of costs and benefits from 1991 through 2030 is computed next. In this illustration, we assume a discount rate of 10%. Experts should use discount rates appropriate to their economies. The present value of incremental net cost amounts to $1,936,317.

Step 7: The cost-effectiveness of conserving carbon may now be expressed using the aforementioned indicators. The net present value of benefits is -$0.63/tC and -$161/ha and the corresponding BRAC value is -$0.047/tC. The initial cost of forest protection is $0.02/tC and $5/ha. The endowment required to protect forests until 2030 is $0.23/tC and $59/ha.

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EXAMPLE 2: EXPAND CARBON STOCKS REFORESTATION

The steps in this example are illustrated in Table 11-2 for the hypothetical Country X.

Steps 2 and 3: Determine current and future land area for the baseline and mitigation options scenarios. In this example, it is assumed that for the baseline scenario 40,000 ha of wasteland exist in 1990 and persist at its current level until 2030.

In the mitigation scenario, adequate steps are taken to ensure that 1000 ha are reforested each year so that by 2030 the wasteland is converted to closed forest. The reforested land will be managed in rotations consistent with the planted species and the desired forest products.

Step 4: Determine the current and future carbon pool, emissions, and sequestration for each scenario.

Step 4.1: Baseline Scenario: In order to determine the carbon pool and sequestration of wastelands, it is necessary to estimate the 1) biomass density, 2) carbon content of biomass, and 3) soil carbon density. The dry biomass density (t/ha) may be expressed as

$$Dry\ Biomass\ Density(t/ha) = SV * WD * TA * DW * AS$$

where	SV	=	Stemwood Volume (m^3/ha)
	AS	=	Above-ground biomass over Stemwood volume ratio
	TA	=	Total biomass (above plus below-ground) to Above-ground ratio
	DW	=	Dry to Wet biomass ratio
	WD	=	Wood density (t/m^3)

In our baseline scenario, we assume that the biomass density remains fixed until 2030 at 20 t/ha. Multiplying the biomass density by the carbon ratio (C%) yields the carbon density (tC/ha) for each scenario. We assume a carbon ratio of 45%.

The soil carbon density is assumed to be 70 tC/ha. Experts will have to obtain data for their countries in order to ascertain the density for wastelands.

Step 4.2: Mitigation Scenario: Reforestation has the potential to increase carbon density through increased carbon in vegetation, soil, decomposing matter, and wood products. The carbon density may be computed using the following procedure:

Total carbon stored = Land carbon + Product carbon
Land Carbon = (Vegetation + soil + decomposing matter) carbon

The computation of each term in the above formula for stored carbon is summarized in the equation given below. A brief description of the elements and associated assumptions is given after the equation.

$$Carbon\ Stored\ per\ ha = c_v * T/2 + c_d * t/2 + c_s * T + \sum_i c_{p\,i} * n_i$$

- **Vegetation Carbon:** For the plantation response option, consider that the plantation is operated in rotation for an indefinite time period. This would ensure that at least half the carbon sequestered by an individual plot is stored away indefinitely. The formula for estimating the amount of carbon stored per ha is:

  Vegetation Carbon stored per ha = c_v*T/2
  where c_v = average annual net carbon sequestered per hectare
  T = rotation period

  In our example, we assume that the planted species has a rotation period of 10 years, a yield of 12 t/ha/year, and a carbon ratio of 0.5. Users may wish to change these values from one year to another if the species planted are different in each year or management regime is expected to vary.

- **Decomposition is equivalent to storing carbon:** The decomposing biomass on land also creates a stock of carbon. In perpetual rotation analysis, this carbon stored in the biomass may be estimated using the following formula:

  Decomposing Matter carbon stored per ha = c_d*t/2
  where c_d = average annual carbon left to decompose per hectare
  t = Decomposition period

  In our example, we assume that the decomposition period is 6 years, and the amount of decomposing carbon left behind is 6 tC/ha/year. Users should apply values applicable in their case.

- **Soil Carbon:** There is considerable uncertainty in the literature regarding the soil carbon content and the influence of factors that affect it. Hence, we should analyze economic costs and benefits with and without considering soil C. Where soil carbon data are not available, soil carbon data from other countries with similar conditions may be used. Note that the increase in soil carbon is more significant (i.e., higher percent of total carbon benefit) where the current above-ground biomass is low and vice versa. Further, we assume that the soil carbon loss and gain during harvesting and regrowth are very small compared to initial gain on degraded land.

  Soil Carbon stored per ha = c_s*T
  where c_s = Increase in soil carbon per hectare
  T = rotation period

  In our example, we assume that the soil carbon increases at 2 tC/ha/year over the rotation period of 10 years and then remains fixed in the soil in perpetuity. Users may wish to apply different values if the trend of soil replenishment is known for the area given the species.

- **Forest products:** If the forest products are renewed continually, they can store a stock of carbon over an infinite period. The amount of carbon stored in the form of products will depend on the product life. The longer the product life, the more carbon will be stored away. The amount stored over an infinite horizon, which assumes that products are replenished at the end of their lifecycle, will increase with product life according to the

$$\textit{Carbon stored per ha} = \sum_i c_{p\,i} * n_i /2$$

formula:

where c_{pi} = amount of carbon stored per ha in product i
n_i = life of product i

We assume that the product oxidizes or decomposes at the end of its lifetime. If the character of disposal of the product is different, then applicable assumptions should be used.

In our example, we assume that the average product life is 30 years and the amount of carbon in the product is 30 tC/ha.

The total carbon stored by the mitigation option is the sum of the four components discussed above, which amounts to 583 tC/ha. The pool of carbon stored is the sum of this amount and the baseline soil carbon of 70 tC/ha, for a total pool of 653 tC/ha.

Step 4.3: We summarize the carbon density estimated in **Steps 4.1 and 4.2** for both scenarios in this step.

Step 5.1: Determine the cost of reforestation. In our baseline scenario, the cost per ha is assumed to be $5/ha. In the mitigation scenario, reforestation incurs an initial cost in 1991, 1992 and 1993. Recurrent maintenance costs are incurred which increase from $10/ha to $100/ha as the reforested area expands from 100 ha to 1000 ha. Similarly, monitoring costs increase from $5/ha to $50/ha. The stream of total costs per ha are shown in **Step 5.1.1.** The present value of these costs is $2,927/ha.

The present value of the stream of costs and benefits from 1991 through 2030 is computed using a discount rate of 10%. Users should apply a discount rate appropriate to their economy.

Step 5.2: Determine the benefits from land conversion. In the baseline scenario, the annual benefits from working the wastelands amount to $20/ha. For the mitigation scenario, the benefits are derived from timber production in the tenth and subsequent years, and from the sale of fuelwood and fruit which may be collected annually. The total benefits amount to $7.5/ha in 1991 (**see Step 5.2.1)** which then increase to reach an annual equilibrium value of $175/ha/year. The present value of these benefits amounts to $5,663/ha.

Step 6.1: Determine the carbon pool and annual sequestration for each scenario. Multiplying the total carbon density (tC/ha) by the land area (ha) under each scenario yields the pool (tC) of carbon for each year. Since the carbon density and the land area remain unchanged in the baseline scenario, the carbon pool stays at 3,160,000 tC. In the mitigation scenario, it is higher at 3,734,000 tC in 1991, which continues to increase as the fraction of land area being reforested increases.

The annual incremental carbon is 574,000 tC and the total pool is 22,960,000 tC by 2030.

Step 6.2: Determine the total costs and benefits. Here we aggregate the costs and benefits for the baseline scenario and also for the mitigation scenario. For the baseline scenario, the annual wasteland costs are $200,000, and the corresponding benefits are $800,000 for the 40,000 ha of land.

The costs and benefits for the mitigation scenario for 1991 amount to a net benefit of $3,320,830. These continue to increase as an increasing fraction of the wasteland is reforested. Net benefits reach $2,735,883 by 2030.

The difference between the baseline and mitigation scenarios' net benefits yields the total incremental benefit whose present value is $22,975,791.

Step 7: The cost-effectiveness of conserving carbon may now be expressed using the aforementioned indicators. The net present value of benefits is $1.00/tC and $574/ha, and the corresponding BRAC value is $0.075/tC. The initial cost of reforestation is $3.4/tC and $1946/ha. The endowment required to reforest and maintain the tree stands until 2030 is $1.19/tC and $684/ha.

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APPENDIX 11-2
ESTIMATING NET PRESENT VALUE OF FORESTS MANAGED IN PERPETUAL ROTATION

This note explains the computation of the net present value (NPV) for a plantation or forest which is managed in perpetual rotations. We provide the formulas for computing the NPV for one rotation on a single plot, that for perpetual rotations on a single plot, and finally for a mosaic of perpetual rotations on multiple plots.

$$NPV = \sum_0^T (R_t - C_t) e^{-r t}$$

1. NPV per hectare for one rotation on one plot:

where R_t = Revenue per hectare in time t

C_t = Cost per hectare in time t

r = Rate of Discount

T = Rotation age in years

e = Natural log base

$$NPVP = NPV \; / \; (1 - e^{-r T})$$

2. NPV per hectare for perpetual rotations on one plot (NPVP):

Note that for coppice plantations, a rotation should be taken to mean the length of time until replanting. The coppice harvest and costs should be treated as intermediate output and costs.

3. NPV per hectare of perpetual rotations on multiple plots (NPVMP):

The NPV of perpetual rotations on multiple plots is

$$= NPVP \sum_0^T e^{-r T}$$

$$= NPVP \, (1 - e^{-r T}) \, / \, (1 - e^{-r})$$

The NPVMP is obtained by dividing the above equation by T, which is

$$NPVMP = NPVP \, (1 - e^{-r T}) \, / \, T \, (1 - e^{-r}).$$

APPENDIX 11-3
TRACE GAS EMISSIONS FROM FORESTRY

Some mitigation options in forestry reduce the emission of radiatively forcing trace gases such as CH_4, N_2O, NO_x, i.e., NO + NO_2, CO, and other NMHC. Such gases are emitted during (1) biomass-burning in forest clearing, (2) woodfuel combustion, (3) forest/savanna fires, (4) possibly when some termites digest biomass, (4) flooding of forest areas by dams, and (5) digestive processes of animals, mainly the ruminant group. However, the bulk of these emissions originate from biomass combustion.

Crutzen and Andreae (1990) estimated compound ratios of trace gas to total carbon released during biomass burning. For CH_4, CO, and NMHC, the ratio is to total carbon. For N_2O and NO_x, the ratio is for NO_x to C. The compound ratios for savanna burning are:

Ratios for trace gases:

Compound	Ratio
CH_4	0.007 - 0.013*
CO	0.075 - 0.125
N_2O	0.005 - 0.009
NO_x	0.094 - 0.148
NMHC	0.0131

* A more recent estimate by Delmas and Ahuja gives an estimate of 0.002 - 0.006, quoted in IPCC 1994.

Source: IPCC 1994.

C-CH_4 ratios for biomass fuels:

Fuel Type	C-CH_4/Total C Ratio	
Fuelwood	0.012	(0.009 - 0.015)
Agricultural Residues	0.005	(0.003 - 0.007)
Dung	0.017	
Charcoal combustion	0.005	(0.0014 - 0.0085)
Charcoal production	0.063	(0.040 - 0.090)

Source: Delmas and Ahuja, quoted in IPCC 1994.

To convert the ratios to full molecular weights, the emissions of CH_4 and CO are multiplied by 16/12 and 28/12 respectively, and the emissions of N_2O and NO_x are multiplied by 44/28 and 30/14 respectively.

Other trace gas parameters:

	Compound	Value	Units
Hydro dams	CH_4	0.157	MT/ha/yr**

** Based on the global average for lakes.
Source: Aselmann and Crutzen, 1990.