Tillage

Intensive soil tillage is recognised as a significant factor causing soil organic matter declines in cultivated soils. Intensive tillage, particularly with soil inversion (e.g., moldboard ploughing), enhances decomposition by releasing organic matter protected within soil aggregates and by increasing soil temperature. Reduced tillage, and particularly no-till practices, have been shown to promote higher levels of organic matter in many systems, where productivity and organic matter inputs are not adversely affected. An analysis of 28 paired comparisons from no-till versus full tillage treatments in 19 long-term experiments in Canada, Europe and the United States showed mean increases under no-till of 0-30 % C, with an average of about 10 per cent (Paustian et al., 1997). The duration of the experiments ranged from 5 to 20 years. These data were normalised to compare equivalent soil mass (to below the depth of ploughing ca. 20-30 cm), in order to eliminate effects of changes in bulk density and differences in organic matter distribution with depth.

Experiments in the tropics have also demonstrated the potential for no-till systems to maintain higher soil carbon levels compared to conventional cultivation (Lal, 1986a). Reduced soil erosion and lower soil temperatures with surface mulches under no-till are particularly important attributes of no-till systems in the tropics (Lal, 1986a; Fernandes et al., submitted). Higher levels of carbon in no-till compared to cultivated treatments have been reported in a number of studies (Agboola, 1981; Jou and Lal, 1979; Aina, 1979). Jou and Lal (1979) reported nearly two times higher carbon contents in no-till vs. ploughed treatments in the top 10 cm (and no significant differences below 10 cm) under maize.

Residue inputs, mulching, cover crops

Maintenance of soil carbon depends on an adequate return of organic substrates which serve as the raw material for organic matter formation. In most agricultural systems, the primary sources of new carbon are crop residues, including roots, root exudates, and unharvested above-ground plant parts (e.g., straw or stover). The amount of carbon returned in the form of residues depends on the total biomass yield (including roots and related materials) and the proportion of that biomass which is exported from the field. Of the carbon applied to soil in the form of crop residues, about one third typically remains after one year and about one fifth remains after five years under temperate conditions (Jenkinson, 1971b). The remainder is returned to the atmosphere as CO_2 via biological decomposition. The rate of decomposition, and the proportion of carbon retained by soil, is influenced by climate, soil conditions, placement (surface versus buried), and the composition of the residue (Andrén et al., 1989).

Some agricultural soils also receive significant inputs in the form of vegetation grown, at least in part, to provide additional carbon and other nutrients to the soil. For example, legumes are sometimes included in cropping systems as a 'green manure'. Similar benefits are derived from vegetative additions in 'alley-cropping' systems.

A third source of carbon is various by-products which are applied as soil amendments. The most noteworthy of these are animal manure, but some soils also derive appreciable carbon inputs from sewage sludge and various industrial by-products. Although such additions can significantly increase soil carbon, gains in the soil must, from an atmospheric balance perspective, be compared with alternative uses of the resources. For example, if sewage sludge decomposes more rapidly in soil than in storage, the net effect will be an additional flux of carbon to the atmosphere.

Management practices which promote greater rates of return of crop residues or other organic amendments will result in increased soil carbon stocks. According to current theories of soil organic matter dynamics, there should be a linear relationship between changes in carbon inputs and soil carbon levels (Greenland, 1995; Paustian et al., 1995);

this relationship is supported by a number of long-term field studies (Paustian et al., 1997). In temperate zone cropping systems, carbon inputs can be increased through residue retention, cover crops, reduced summer (bare) fallow, rotations with perennial forage crops, and all practices that increase crop production and residue yields. In the tropics, these practices and others, including improved fallows, mulching and agroforestry, can increase carbon additions to soil (Lal, 1986b).

5.3.6 Management Categories

The estimate of CO_2 fluxes is based on inventorying the areas and C stocks for land-use systems predominating within a particular climatic region. As described above, the most significant practices that differentiate land-use and management systems are:

- clearing of native vegetation with conversion to cultivated crops or pasture;
- land abandonment;
- shifting cultivation;
- differing residue addition levels;
- differing tillage systems; and
- agricultural use of organic soils.

Criteria for defining management systems are that the distribution of land areas between the selected systems have changed over the past 20 years and that the systems differ significantly in their soil carbon stocks.

The recommended procedure is that country experts define and document an appropriate classification of systems for use in their inventory. A classification of land-use systems is included which can serve as an example for development of country-specific classifications. (See Module 5 for detailed description of land-use systems.) These classes are intended to be sufficiently general that they may be applicable in most countries and include systems that are likely to have significantly different C stocks, based on soil C responses to agricultural practices. Non-agricultural systems (e.g., forest, grassland) should be subdivided into categories on the basis of differences in soil carbon stocks (as well as soil and climate regimes). Organic soils that have been converted to agricultural use are considered separately (see Section 5.3.9).

TABLE 5-9
EXAMPLES OF MAJOR LAND-USE/LAND MANAGEMENT SYSTEMS WITHIN THE MAJOR CLIMATE DIVISIONS

Climate Division	Land-use System
Cold temperate, dry	Rangeland (unimproved) Small grain with summer-fallow Small grain with continuous cropping - conventional tillage Small grain with continuous cropping - no till Small grain/forage rotations Hay/improved pasture Successional grasslands Irrigated croplands
Cold temperate, moist	Forest Small grain monocultures Grain/root crop/perennial forage rotations Permanent pasture Forest/grassland set-aside
Warm temperate, dry	Rangeland (unimproved) Small grain with summer fallow Small grain/legume rotations with summer fallow Small grain with continuous cropping - conventional tillage Small grain with continuous cropping - no till Small grain/forage rotations Successional grassland Irrigated cropland
Warm temperate, moist	Forest Pasture/hay Intensive grain production systems, stratified according to: - residue return rate (production level, frequency of perennial forages in rotation, cover crops) - tillage intensity (full inversion, reduced, no tillage) Speciality crops with low residue return Forest/grassland set-aside and reverted lands
Tropical, dry	Savanna Subsistence farming with drought-resistant grain crops Irrigated cropland
Tropical, moist (includes systems for both short and long dry season categories)	Forest/woodland Unimproved/degraded pasture Improved pasture Shifting cultivation/fallow rotation Mixed continuous cropping Mechanised continuous cropping Plantations Irrigated cropland (including rice)
Tropical, wet	Forest/Woodland Agroforestry/perennial multi-strata systems Upland food crop production Perennial monoculture plantations Shifting cultivation/fallow rotation Improved pasture Degraded pasture Wetland (paddy) rice

5.3.7 Suggested Methodology for CO_2 Flux from Agricultural Soils

Three potential sources of CO_2 emissions from agricultural soils are included in the inventory. These are 1) net changes in organic carbon stocks of mineral soil associated with changes in land use and management, 2) emissions of CO_2 from cultivated organic soils (i.e., Histosols) and 3) emissions of CO_2 from liming of agricultural soils.

5.3.8 Changes in Mineral Soil Carbon Stocks

Inventory calculation period

Net carbon fluxes are calculated on the basis of changes in carbon stocks over a twenty-year period. For example, to calculate the inventory for 1990, land areas under each climate/soil/land-use class (Table 5-9) in 1970 and in 1990 are determined. Soil carbon values are then assigned to each class, and the summed differences in the total carbon stocks provide an estimate of the current net soil CO_2 flux. For mineral soils, only the top 30 cm are considered, which typically has the highest concentration of carbon and the greatest response to changes in management and landuse. In most soils, management effects on soil carbon at depth are minimal compared to changes that occur in the topsoil (Sombroek et al., 1993) and consequently most information on soil carbon responses to different management practices are limited to the upper soil horizons (0-30 cm depth).

The choice of a twenty-year period represents a compromise. The response time of a system to a change in management will differ according to a number of factors. Soil carbon approaches a new equilibrium more rapidly in the tropics compared to temperate soils. The rate of response to different practices also varies. For example, most of the loss of soil carbon following land clearing occurs within <10 yrs (Davidson and Ackerman, 1993). A build up of soil carbon, for example following land abandonment (Jenkinson, 1971a) or with increases in residue inputs, tends to occur more slowly, i.e., the approach to a new equilibrium value is more rapid for degrading systems than for aggrading systems. Thus, the longer the inventory period the closer systems will approach new equilibrium carbon levels. In general, however, the most rapid changes in soil carbon occur during the first 10-20 yrs following a significant change in management practices or land use. Furthermore, a long inventory period has two disadvantages. One is that past land-use information is likely to be less accurate and less available for further in the past. The second is that the balance approach carries an implicit assumption that the rate of land-use and management change over the period is constant. If rates of change are not linear with respect to time, there will be a bias in the estimates that increases with increasing the length of the assessment period. Twenty years was selected as an appropriate time period to include most of the change in carbon stocks resulting from land conversions to agriculture and most other management-induced changes in the tropics. To account for longer response times, such as for land abandonment in the temperate zone, it is recommended that one or more 'successional' system, having different soil carbon stocks, be defined (e.g., abandoned land for <20yrs and abandoned land >20yrs).

Soil carbon stock estimates

Carbon stock estimates should include the total organic carbon content to a depth of 30 cm as well as the carbon content of the surface litter mat, if present (e.g., in forests, grasslands, and pastures). Woody litter resulting from forest clearance should not be double counted as it is included in the inventory procedures in Forest and Grassland conversion (Section 5.2.2). Fresh crop residue in cultivated systems should not be counted. In no-till cropping systems, the minimum (over the year) surface residue loading should be included in the organic carbon stock.

The recommended option for assigning carbon stocks according to land management classes (within one or more of the six soil types) is that these be determined by experts in the participating countries. Where available, information from country soil surveys, field studies and long term agricultural experiments, as interpreted by knowledgeable soil scientists and agronomists, will provide the best estimates for these values. However, we have also provided a default methodology for estimating carbon stocks within predefined land-use/management categories (see Management Categories above), using estimates for carbon stocks under native vegetation derived from the FAO/USDA global soil carbon inventory (Eswaran et al., 1993).

Calculation procedures for mineral soils

The calculations for net CO_2-C emissions from mineral soils are straightforward and examples of their application are given in Table 5-10. Negative numbers represent a net decline in soil carbon stocks, hence a net emission or source of carbon to the atmosphere; positive numbers represent a net sequestration or sink of carbon in soil, over the 20-yr inventory period. To derive current net annual emissions the final total should be divided by 20. For the example shown, there is a net increase of carbon storage of 11.9 Tg over the 20-yr inventory period, thus annual net CO_2-C emissions for this example would be -0.595 Tg/yr, or a carbon sink.

Note: It is critical that the total area included in the inventory at time (t) and time (t-20) be identical. The area should represent at least all the land area of the country which has been subject to any significant changes in land-use and/or management practices over the past 20 years. An additional check should be made that the total area within each soil type is constant over the inventory period.

TABLE 5-10 EXAMPLE OF CALCULATIONS FOR NET CHANGE IN CARBON STORAGE IN MINERAL SOILS FOR A COLD TEMPERATE DRY REGION COUNTRY - FOR SIMPLICITY ONLY FOUR MANAGEMENT SYSTEMS ARE INCLUDED							
Landuse	Soil type	Soil Carbon (t C /ha)	Land Area (t-20) (Mha)	Land Area (t) (Mha)	C Stock (t-20) (Tg)	C Stock (t) (Tg)	Net change in Soil Carbon (Tg per 20 yr)
		[A]	[B]	[C]	[A x B]	[A x C]	[A x C] - [A x B]
Grassland	High activity	50	3.5	3.6	175	180	5
(unimproved)	Sandy	10	2.0	2.0	20	20	0
	Aquic	70	0.5	0.4	35	28	-7
Grain/summer-fallow	High activity	33	4.0	2.8	132	92.5	-39.6
with conventional	Sandy	7	0.5	0.5	3.5	3.5	0
tillage	Aquic	35	0	0	0	0	0
Grain/continuous	High activity	40	2.4	3.0	96	120	24
with conventional	Sandy	-	0	0	0	0	0
tillage	Aquic	45	0	0.1	0	4.5	4.5
Hay/improved pasture	High activity	50	1.5	2.0	75	100	25
	Sandy	-	0	0	0	0	0
	Aquic	-	0	0	0	0	0
Total			14.4	14.4	536.5	548.4	11.9

Default calculation procedures

If soil carbon stock estimates according to land-use and soil type are not available we have provided a procedure for estimating these. Estimates are based on global soils information (Table 5-11) compiled by the World Soils Resources division of the Natural Resources Conservation Service of the US Department of Agriculture (USDA), based on FAO and USDA soils information (Eswaran et al., 1993). These values serve as a first approximation and should not be considered as a preferable substitute for actual country-level data. Approximate organic carbon stocks are for the top 30 cm, in tonnes C/ha, under native vegetation. Histosols (peat soils) are considered in a separate calculation.

TABLE 5-11
APPROXIMATE QUANTITIES OF SOIL ORGANIC CARBON UNDER NATIVE VEGETATION
(TONNES C /HA TO 0-30 CM DEPTH)

Region	High activity soils	Low activity soils	Sandy soils	Volcanic soils (Andisols)	Wetland soils (Aquic)
Cold temperate, dry	50	40	10	20	70
Cold temperate, moist	80	80	20	70	180
Warm temperate, dry	70	60	15	70	120
Warm temperate, moist	110	70	25	130	230
Tropical, dry	60	40	4	50	60
Tropical moist (long, dry season)	100	50	5	70	100
Tropical moist (short, dry season)	140	60	7	100	140
Tropical, wet	180	70	8	130	180

To estimate soil carbon stocks by different agricultural land-use and management practices, we have compiled a set of coefficients to scale the carbon contents according to major management factors (Table 5-12). Estimates for the scaling factors were based on information from field studies, where available, and expert opinion. The database for these estimates is scanty, particularly from the tropics, and we emphasise that this default procedure is only intended as a first approximation and not as a substitute for country-level data where available. Carbon stock estimates are derived according to the formula:

$$\text{Soil Carbon}_{\text{managed}} = \text{Soil Carbon}_{\text{native}} \times \text{Base factor} \times \text{Tillage factor} \times \text{Input factors}$$

The base factor represents changes in soil organic matter associated with conversion of the native vegetation to agricultural use. Tillage and input factors account for effects of various management practices of lands in agricultural use. Thus these later two factors can be used to capture changes in management trends that have occurred over the inventory period. For example, a long-term cultivated high clay activity soil, under intensive (full) tillage and with low carbon inputs (e.g., straw removal) would be estimated to have 63 per cent (0.7 x 1 x 0.9) of the carbon content in a comparable uncultivated (native) soil. The same soil under no-till with high residue inputs (e.g., cover crops) would be estimated to have a carbon level equivalent to 85 per cent (0.7 x 1.1 x 1.1) of the native soil. Portions of the table where tillage and input factors are not given denote instances where these factors are not applicable to a particular management system or where information was deemed insufficient to go beyond estimating a base factor.

TABLE 5-12[a]
COEFFICIENTS USED IN DEFAULT CALCULATION PROCEDURES FOR ESTIMATING CARBON STOCKS IN MINERAL SOILS

System	SG[b]	BF[c]	Tillage Factor[d]			Input Factors[e]				
			No-tillage	Reduced tillage	Full tillage	Low input	Medium input	High input	Mature fallow	Shortened fallow
Temperate										
Long-term cultivated	A,B,C,D	0.7	1.1	1.05	1.0	0.9	1.0	1.1/1.2		
Long-term cultivated	E	0.6	1.1	1.05	1.0	0.9	1.0	1.1/1.2		
Improved pasture	All soils	1.1				ND	ND	ND		
Set aside (<20 years)	All soils	0.8				ND	ND	ND		
Set aside (>20 years)	All soils	0.9				ND	ND	ND		
Tropical										
Long-term cultivated	A,B,C,D	0.6	1.1	1.0	0.9	0.9	1.0	1.1/1.2		
Long-term cultivated	E	0.5	1.1	1.0	0.8	0.9	1.0	1.1/1.2		
Wetland (Paddy) rice	All soils	1.1	ND	ND	ND	ND	ND	ND		
Shifting cultivation (including fallow)	All soils	0.8	ND	ND	ND	ND	ND	ND	1.0	0.8
Abandoned/ Degraded land	All soils	0.5								
Unimproved pasture	All soils	0.7				ND	ND	ND		
Improved pasture	All soils	1.1				ND	ND	ND		

[a] Filled portions of the table, where tillage and input factors are not given, denote instances where these factors are not applicable to a management system. Where tillage or input factors were not determined (ND), information was deemed insufficient to go beyond estimating a base factor.

SG = Soil Group, BF = Base Factor

[b] Soil groups A = High activity, B = Low activity, C = Sandy, D = Volcanic, E = Aquic

[c] For temperate cultivated soils, the average loss of 30% (0.7) is based on paired profile comparisons by Mann (1985, 1986) and Davidson and Ackerman (1993). Greater losses for cultivation of wet (aquic) soils, relative to other mineral soils, are assumed due to artificial drainage and enhanced decomposition when cultivated (van Noordwijk et al., submitted). Conversion to paddy rice is assumed to slightly increase carbon contents (Greenland, 1985). Carbon levels in improved pastures can exceed native levels with fertilisation and species selection (Fisher et al., 1994, Cerri et al., 1994, Grace et al., 1994). Carbon under shifting cultivation (including the fallow phase) and abandoned degraded lands are based on estimates from Palm et al. (1986), Tiessen et al. (1992) and Woomer et al. (submitted).

[d] Use of no-till is assumed to increase soil carbon by 10% over full tillage (full soil inversion) in temperate systems, based on analysis of long-term experiments in Australia, Canada, Europe and the United States (Paustian et al., 1997); greater effects, over full tillage, are assumed for tropical systems (Aina, 1979, Juo and Lal, 1979, Agboola, 1981). Reduced tillage (i.e., significant soil disturbance but without inversion) is assumed to yield small increases over full tillage (Paustian et al., 1997).

[e] Input factors apply to residue levels and residue management, use of cover crops, mulching, agroforestry, bare fallow frequency in semi-arid temperate systems. Low input applies to where crop residues are removed or burned, or use of bare fallow; medium input to where crop residues are retained; high input applies to where residue additions are significantly enhanced with addition of mulches, green manure, or enhanced crop residue production (1.1) or regular addition of high rates of animal manure (1.2), relative to the nominal (medium) case. Based on temperate zone studies analysed by Grace et al. (1994) and Paustian et al. (1997), and tropical studies by Jones (1971), Wilson et al. (1982), Sidhu and Sur (1993), Lal et al. (1979, 1980), Mazzarino et al. (1993), Kang and Juo (1986), Inoue (1991), van Holm (1993) and reviews by van Noordwijk et al. (submitted) and Fernandes et al. (submitted).

5.3.9 Calculation of CO_2 Fluxes from Organic Soils

Conversion of organic soils to agriculture is normally accompanied by artificial drainage, cultivation and liming, resulting in rapid oxidation of organic matter and soil subsidence. The rate of carbon release will depend on climate, the composition (decomposability) of the organic matter, the degree of drainage and other practices such as fertilisation and liming. Unlike the situation with mineral soils, where carbon levels approach some new equilibrium following changes in land use/management, carbon losses from organic soils can be sustained over long periods of time, in principle, until the organic soil layer has been completely lost. As decomposition proceeds, the more recalcitrant organic matter fractions, having slower decomposition rates, will accumulate. This would tend to reduce CO_2 emissions over time. However, a compensating factor is that with tillage, less decomposed organic matter from below will be continually incorporated into the surface layer as it decomposes and the soil subsides. This process will tend to maintain high rates of CO_2 loss until much of the organic horizon is exhausted. Because of the variability in depth of organic soils, which in many cases is poorly known (Eswaran et al., 1993), a calculation procedure which incorporates the dynamic changes in the depth and the quality of organic matter in these soils was deemed unfeasible at present. Existing data on CO_2 emission rates from organic soils are typically given as rates per unit land area and this approach is used in the current methodology.

Use of organic soils for upland crops (e.g., grain, vegetables) gives greater carbon losses than for conversion to pasture or forests, due to deeper drainage and more intensive management practices (e.g., liming, cultivation) (Armentano and Verhoeven, 1990). Armentano and Menges (1986) estimated annual loss rates under crops to be 2.2 tonne/ha/yr in boreal regions (Finland, Russia), 7.9-11.3 tonne/ha/yr in temperate climates (USA and Western, Central and Eastern Europe, China, Japan) and 21.9 tonnes C/ha/yr in Florida and coastal California. Other data from Russian sources (references V.D. Skalaban, personal communication) suggest somewhat lower losses from cultivated organic soils in the boreal zone, on the order of 0.4-1.2 tonnes C/ha/yr. Estimates for annual losses under introduced pastures/forests ranged from 15-70 per cent, with most around 25 per cent, of the rate under crops. The rates recommended for inventory purposes are derived from these values. For tropical systems, there are fewer data although it is expected that rates should be generally higher compared to temperate zone soils due to sustained higher temperatures. The rate used for cropland (20 tonnes C/ha/yr) is twice that for the warm temperate zone, which is similar to the rates reported for subtropical Florida (21.9 tonnes C/ha/yr). We assume that loss rates from conversions to pasture are 25 per cent of those under cropland within each climate region. For the inventory, values are calculated on an annual basis.

5.3.10 CO_2 Emissions from Liming Agricultural Soils

Liming is commonly used to ameliorate soil acidification. Among the compounds used are carbonate containing minerals such as limestone $CaCO_3$ and dolomite $CaMg(CO_3)_2$. When added to acid soil these compounds release CO_2 in the bicarbonate equilibrium reaction. The rate of release will vary according to soil conditions and the compound applied. However, in most instances where liming is practised, repeated applications are made every few years. Therefore, for purposes of the inventory, we assume that the addition rate of lime is in near equilibrium to the consumption of lime applied in previous years. Emissions associated with use of carbonate limes can thus be calculated from the amount and composition of the lime applied annually within a country.

5.3.11 Total CO_2 Emissions from Agricultural Soils

Total annual emissions of CO_2, are calculated from i) net changes in carbon storage in mineral soil, ii) CO_2-C emissions from organic soils and iii) CO_2-C emissions from liming.

5.4 Refinements In Calculations

5.4.1 Introduction

There are a number of areas in which the basic calculations could be improved at least theoretically. Simplifying assumptions have been made in many places in order to produce methods consistent with data likely to be available in many countries. The basic calculations focus only on the most important categories for emissions of CO_2 within a much larger set of land-use and forest management activities having some impact on GHG emission fluxes. Some activities are known to result in GHG fluxes, but cannot be quantified based on the available scientific research results. Many of these issues are summarised below to assist users in considering which, if any, of these possible refinements could be included in national inventories, either currently, or in the future as scientific understanding improves.

The first section deals with the subcategories already discussed in the basic calculations, but highlights a number of ways in which these calculations could be augmented. The second section discusses additional categories of land-use change or forest management which could be added to the categories in the basic calculations.

5.4.2 Possible Refinements or Additions to Basic Categories

CHANGES IN FOREST AND OTHER WOODY BIOMASS STOCKS

Prescribed Burning of Forests: Non-CO_2 Trace Gases

The issue of prescribed forest burning is complex for two reasons. First, there is the question of the rate of change that humans have induced and second, there is the question of releases of trace gas several years after the burning. Prescribed burning is a method of forest management by which forests are intentionally set on fire in order to reduce the accumulation of combustible plant debris and thereby prevent forest fires, which could possibly be even more destructive. This activity is primarily limited to North America and Australia (Seiler and Crutzen, 1980). Because carbon is allowed to re-accumulate on the land after burning, no net CO_2 emissions occur over time, although emissions of CH_4, CO, N_2O, and NO_x result from the biomass combustion.

Some of the issues associated with prescribed forest burning, particularly in the temperate and boreal world, remain important research topics. Some have suggested that prescribed forest burning may be increasing carbon stocks in forests and hence serving as a CO_2 sink, but at the same time adding other radiatively important non-CO_2

trace gases to the atmosphere. An important issue is the change in burning rate because of human activity. Is prescribed burning, and its consequent emissions, just a man-made replacement for what would have occurred naturally? What is the rate change? If we assume that this question, the rate of change, can be answered, then the issue of trace gas release for prescribed burning is similar to trace gas emissions following forest clearing. This process is under evaluation in the development of the *Guidelines.*

The second complicating issue which should be considered is the release of non-CO_2 trace gases in years after burning. This is also discussed under *forest and grassland conversion* below. The same uncertainties apply here, although this may be a less important area for prescribed burning, because the forests will be regrowing quickly, and possibly overcoming the conditions which could cause longer term trace gas emissions.

Carbon Stock in Dead Organic Matter (excluding soil) of Forests

The quantity of carbon in litter, woody debris, belowground remains, and dry standing stems is a significant carbon reservoir in many of the world's forests. The present methodology does not account for any of these components, which could represent important carbon sink in regrowing forests after abandonment or logging or additional carbon sources when burned during forest clearing or fires. The role of dead organic matter in forest carbon budgets should be considered in future work on inventory methods.

Forest and Grassland Conversion

Forest clearing is a very complex and diverse set of activities which can have many interactions with biospheric fluxes of greenhouse gases over long periods of time. The components of this set of interactions which are included in the previous section are those on which there is general agreement among experts of their importance and simple estimation procedures. A number of other possible elements have been discussed in the scientific literature, but are controversial or difficult to calculate at present.

Emissions from Burning of Forests

A number of aspects of emissions due to burning could be treated in more detail.

> *a. Subsequent burns in years after clearing.* In some cases, where forests are cleared for agricultural purposes, the land may be partially burned in the year of clearing, but may also be burned again in later years. Fearnside (1990b) indicates that pastures in the Brazilian Amazon are typically burned two or three times over about a 10 year period. This would cause a larger fraction of carbon in cleared biomass to be released to the atmosphere sooner than the approach now included in the basic calculations, and would certainly increase emissions of non-CO_2 trace gases from biomass burning.
>
> *b. Non-CO_2 trace gases released after burning*. Basic calculations address the main issues in trace gas production by burning, however, they do not treat all issues. For instance, the effect of past burning, particularly of forests, on trace gas exchanges must eventually be considered. Specifically, the instantaneous release of non-CO_2 trace gases when forests are burned is included in Land Clearing calculations. However, the longer-term release or uptake of these gases following forest burning is an important research issue and should eventually be included in refinements of calculations. The issue of the contemporary release of non-CO_2 trace gases associated with past burning is complex. For example, clearing by burning may stimulate soil nutrient loss. Measurements in temperate ecosystems (e.g., Anderson et al., 1988; and Levine et al., 1988) indicate that surface biomass burning enhances emissions of N_2O and NO_x from the soils for up to 6 months

following the burn; however, in other studies measurements of N_2O emissions at a cleared and burned tropical forest site in Brazil, begun five months after the burn and continuing for a year, were not significantly different from those taken from a nearby intact forest site (Luizão et al., 1989). The "historical" issue is obviously complex and further research is needed before an adequate methodology for emissions calculations can be proposed.

Delayed Release of Non-CO_2 Trace Gases after Land Disturbance.

Even when no burning is involved there may still be a release of trace gases. An experiment in a temperate forest in the north eastern United States found that clearcutting resulted in enhanced N_2O flux to the atmosphere via dissolution of N_2O in the soil water, transport to surface waters, and degassing from solution (Bowden and Bormann, 1986). An experiment in Brazil found that N_2O emissions from newly clearcut tropical forests were about three times greater than those from adjacent undisturbed forests (Keller et al., 1986). Conversion of tropical forests to pasture also has been found to result in elevated N_2O emissions relative to the intact forest soils (Luizão et al., 1989; and Matson et al., 1990). Another example involves the loss of a sink for CH_4 which, in effect, adds to the atmospheric burden of CH_4. Specifically, the loss of forest area (tropical or temperate) may also result in increased net CH_4 emissions to the atmosphere. Soils are a natural sink of CH_4 (i.e., soils absorb atmospheric CH_4), and various experiments indicate that conversion of forests to agricultural lands diminishes this absorptive capacity of soils (Keller et al., 1990; and Scharffe et al., 1990).

Conversion of natural grasslands to managed grasslands and to cultivated lands may affect not only the net emission of CO_2 but CH_4, N_2O, and CO emissions as well. For instance, the conversion of natural grasslands to cultivated lands has been found in the semi-arid temperate zone to also decrease CH_4 uptake by the soils (Mosier et al., 1991). It is not clear what the effect on N_2O would be, unless of course nitrogen fertilisation occurs. The effect of conversion of natural grasslands to managed grasslands on trace gas emissions has not been evaluated in the field, except for the effect of associated nitrogen fertilisation on N_2O emissions. Nitrogen fertilisation on managed fields may increase carbon accumulation on land, relative to the unfertilised system, and grazing by domestic animals may also affect trace gas fluxes. CO fluxes may be affected due to changes in soil temperature and moisture. These effects on trace gas fluxes, however, are highly speculative and remain a research issue.

Methane from Termites Attributable to Biomass Left to Decay

When forests are cleared, a portion of the cleared biomass may be left to decay on the ground. Frequently some of the biomass decay is accomplished by termites which emit both CH_4 and CO_2 during this process. Fearnside (1990b) estimates that 75 per cent of the unburned carbon is decomposed by termites, and of this 75 per cent, 99.8 per cent is released as CO_2 and 0.2 per cent is released as CH_4. Fearnside suggests that forest clearing results in increased termite populations and thereby enhances natural termite CH_4 emissions. However, as discussed by Collins and Wood (1984), data from Malaysia, Nigeria, and Japan indicate that clearing and cultivation in some forests reduces termite populations. The only incidence of termite abundance increase following clearing cited by Collins and Wood was entirely due to a fungus-growing termite, a type of termite which is unlikely to produce CH_4. Because of the uncertainty of the effect of clearing on termite populations and associated CH_4 release, no guidance on calculation of this component is included in the methodology.

Fate of Roots in Cleared Forests

The basic calculation ignores the fate of living belowground woody biomass (roots) after forest clearing. The amount of belowground biomass affected, and its fate, need to be considered as work continues beyond the basic calculations. This belowground biomass could be treated as slash but with perhaps a longer (for coarse roots) or shorter (for fine roots) decay times. Alternatively, it might be more reasonable to deal with the belowground biomass in conjunction with soil carbon calculations. This is an area for further development by the relevant expert groups, and also by national experts in individual countries who are encouraged to carry out experimental calculations. See Box 8 for further information on the estimation of the amounts of belowground biomass.

Aboveground biomass after conversion

In the basic calculation, a single default value (10 tonnes dm/ha) is recommended for aboveground biomass which regrows after forests are cleared for conversion to crops or pastures. This may be somewhat variable depending on the type of crop or other vegetation which regrows. National experts carrying out more detailed assessments may wish to account more precisely for this variability, especially when perennial tree crop are planted.

Abandoned Lands

The basic calculations account only for the portion of abandoned lands which regrow toward a natural state. There may be additional releases of carbon from abandoned lands which continue to degrade, e.g., because of erosion. Where data are available, analysts doing detailed assessments may wish to account for this phenomenon.

5.4.3 Other Possible Categories of Activity

Several other land-use activities affect the flux of CO_2 and other trace gases between the terrestrial biosphere and the atmosphere. Shifting cultivation may now be reducing the storage of carbon in forests, because of shorter fallow periods, and thereby becoming a net source of CO_2 to the atmosphere. Furthermore, lands under shifting cultivation may be converted to permanent agriculture which, of course, affects the biomass assigned to the land being converted. The changing areas and distribution of wetlands may be adding to or reducing the CH_4 burden of the atmosphere. These issues are complex; often the sign of the flux is not even known, and simple models may not give reasonable results. In this section, some of the issues and possible methodological approaches are recorded; however, an agreed-upon methodology is not yet at hand.

BOX 8 **BELOWGROUND BIOMASS**	
For forest clearing, carbon in belowground (root) biomass is ignored in the basic calculations, but should be considered. There are large uncertainties concerning the time horizon over which this biomass would oxidise. As noted in the text, it could be considered with decay of slash left aboveground from forest conversion. There is no recommended step-by-step methodology for calculating the carbon released from this source in the current guidelines. However, interested national experts are encouraged to carry out such calculations and report them to the IPCC using their own methods.	
The following information about multipliers (root-to-shoot ratios - R/S, average and range of R/S) can be applied to total aboveground biomass to estimate the belowground biomass.	
Tropical forests	
moist forest growing on spodosols	1.5 (0.7 - 2.3)
lowland very moist forests	0.13 (0.06 - 0.33
montane moist forest	0.22 (0.11 - 0.33)
deciduous forests	0.47 (0.23 - 0.85)
(e.g., tropical dry and seasonal moist forests)	
Temperate forests	
coniferous	0.20
broadleaf	0.25
Boreal forests	
coniferous	0.25 (0.20 - 0.30)
broadleaf	0.20 (0.15 - 0.25)
forest-tundra	0.35 (0.30 - 0.50)
Sources: Brown, (1996) for tropical forests; Cooper, (1983) for temperate forests; and Bazilevich, (1993) and Isaev et al., (1993) for boreal forests:	
Estimation of CO_2 emissions from belowground biomass after clearing has been identified as an area of future work.	

Shifting Cultivation

Shifting cultivation, or slash-and-burn agriculture, is a common agricultural practice in the tropics in which short periods of cultivation (usually about 1 - 3 years) alternate with longer periods of fallow (about 10 to 30 years). Clearing occurs by initial cutting and felling, followed by a series of burns. When practised in the traditional manner, shifting cultivation produces some net CO_2 emissions because the forest is allowed to return part-way to its original biomass density during the fallow period.[29] However, increasing

[29] Following the first clearing (i.e., clearing of primary forests), the forest biomass may not recover fully to its original density during the fallow period, but instead reaches a reduced level, referred to as a secondary forest.

population pressure has reduced the lengths of fallow periods so that currently much of the fallow land recovers very little and higher net CO_2 emissions are believed to result (Myers, 1989; and Houghton, 1991). Loss of soil carbon also may occur during shifting cultivation, although the loss is certainly far less than for permanent cultivation.

Calculation of net emissions due to shifting cultivation requires calculation of average annual emissions due to clearing of forests for cultivation, and calculation of average annual uptake due to abandonment of cultivated lands in the fallow period of the shifting cultivation cycle. This involves monitoring a large number of small parcels of land over time and probably requires a model to do the book keeping.

The basic concepts are not difficult. The carbon calculations would proceed almost exactly like the conversion and abandonment terms in the basic methodology; however, the difficulty is that the abandonment period may be shorter, and this may only be apparent by using a cohort-based model and a finite stock of forest. In other words the increasing rate of shifting cultivation (the likely data) will force a shorter fallow period and hence less regrowth, and this dynamic may only become apparent when one models the shifting cultivation cycle within a specific area of available forest.

One intermediate simple approach is to split the calculation into the two logical components. The initial conversion component would be treated similarly to the basic calculations; namely, convert the above ground dry biomass[30] to carbon (multiply by 0.50) and assume 90 per cent of this material is released as CO_2 less the amount taken upon by the replacing crops (default value of 10 tonnes dm per hectare). To calculate the uptake of carbon by the regrowing forest during the fallow cycle, simply estimate the amount of land in abandonment (but not yet in steady-state) and the average rate of carbon accumulation per unit area in these fallow lands. The difference would be the net flux of CO_2 associated with shifting cultivation. For the biomass burned in shifting cultivation, non-CO_2 gases (N_2O, CH_4, NO_x, CO) should be calculated as described in the Forest and Grassland Conversion section above.

Flooding and Wetland Drainage

Land Flooding

Flooding of lands due to construction of hydroelectric dams, or other activities, results in emissions of CH_4 due to anaerobic decomposition of the vegetation and soil carbon that was present when the land was flooded, as well as of organic material that grows in the floodwater, dies, and accumulates on the bottom. The CH_4 emissions from this source are highly variable and are dependent on the ecosystem "type", and the status of the ecosystem, that is flooded (i.e., above- and below-ground carbon, plant types, whether any pre-flooding clearing occurred, etc.) and on the depth and length of flooding (some regions may only be flooded for part of a year)[31]. Rates of CH_4 emissions from freshwater wetlands are also strongly dependent on temperature, and therefore vary

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[30] Generally, shifting cultivation is practised in secondary forests, since the least dense and most accessible forest areas are most susceptible to this form of clearing. Aboveground biomass density estimates for secondary forests are highly uncertain, and vary significantly both within and among countries because of varying ecosystem types as well as varying intervals between clearings.

[31] A detailed analysis of CO_2 and CH_4 emissions from hydroelectric reservoirs in the Amazon has been made and is a significant issue in this and other regions because of the vast areas of forest submerged for the construction of the reservoirs (Rosa and Schaeffer, 1994, 1995).

seasonally, as well as daily. Net emissions of N_2O and CO also may be affected by this activity, although these fluxes are not well determined.

A straightforward CH_4 flux calculation can be based on the area of land flooded, due to hydroelectric production or other human-made causes, an average daily CH_4 emission coefficient, and the number of days in the year that the area is flooded. Since measurements of CH_4 emissions from freshwater wetlands are so variable, both spatially and temporally, the area should be divided into groups based on characteristics such as length of flooding, vegetation type, and latitude. Then appropriate emission coefficients can be chosen for each group, rather than choosing one emission coefficient for the entire area of flooding. Table 5-13 presents average daily CH_4 emission rates for natural wetlands, derived from measured emission rates in field experiments, and average CH_4 production periods based on data on monthly mean temperatures and inundation lengths. These rates and production periods can be used if countries do not have more appropriate estimates.

TABLE 5-13
AVERAGE METHANE EMISSIONS AND PRODUCTION PERIODS OF NATURAL WETLANDS

Wetland Categories ($mg\ CH_4/m^2.day$)	Emission Rate ($mg\ CH_4\text{-}C/m^2.day$)	Production Period or Length of Time Flooded (days)
Bogs	11 (1-38)	178
Fens	60 (21-162)	169
Swamps	63 (43-84)	274
Marshes	189 (103-299)	249
Floodplains	75 (37-150)	122
Lakes	32 (13-67)	365

Source: A.selmann and Crutzen, 1989.

Note: Average daily emission rates are derived from measured emission rates in field experiments (the range in measured emission rates is in parentheses after the average), and average production periods are based on monthly mean temperature data and lengths of inundation.

Wetland Drainage

Freshwater wetlands are a natural source of CH_4, estimated to release 100-200 Tg CH_4/yr due to anaerobic decomposition of organic material in the wetland soils (Cicerone and Oremland, 1988). Destruction of freshwater wetlands, through drainage or filling, would result in a reduction of CH_4 emissions, and an increase in CO_2 emissions due to increased oxidation of soil organic material (Moore and Knowles, 1989). The magnitude of these effects is largely a function of soil temperature and the extent of drainage (i.e., the water content of the soil). Also, since dryland soils are a sink of CH_4, drainage and drying of a wetland could eventually result in the wetland area changing from a source to a sink of CH_4 (e.g., Harriss et al., 1982).

Loss of wetland area could also affect net N_2O and CO fluxes, although both the direction and magnitude of the effect is highly uncertain. Natural dryland soils are a source of N_2O, believed to emit 9-28 Tg N_2O/yr (3-9 Tg N_2O-N) as a result of nitrification and denitrification processes (Seiler and Conrad, 1987). This emission estimate is highly uncertain, however, as emission measurements vary both temporally and spatially by up to an order of magnitude. Moreover, the measurements are not consistently correlated with what are believed to be controlling variables such as soil temperature, moisture, and composition, and vegetation type. Dryland soils both produce and consume CO. Carbon monoxide production, estimated at 2-32 Tg CO/yr (1-14 Tg CO-C), is an abiotic process due to chemical oxidation of humus material (Seiler and Conrad, 1987). It is strongly dependent on soil temperature, moisture, and pH. Destruction of CO is a biological process believed to be due to micro-organisms present in the soil. Carbon monoxide destruction (250-530 Tg CO/yr, or 107-227 Tg CO-C/yr) increases with increasing temperature, although it is independent of soil surface temperature and requires a minimum soil moisture (Seiler and Conrad, 1987). Desert soils have always been found to be a net source of CO, as have savanna soils, at least during the hottest parts of the day. CO destruction outweighs production in humid temperate soils; humid tropical soils are believed to also be a net sink of CO because of their higher soil moisture and lower soil temperature than deserts and savannas.

To calculate the reduction of CH_4 emissions due to wetland drainage, the area drained is multiplied by the difference in the average daily CH_4 emission rate before and after draining, and is multiplied by the number of days in a year that the wetland was emitting CH_4 prior to drainage. The number of days of CH_4 emissions prior to drainage can be approximated by using the number of days in the year that the wetland was flooded.

In summary, the difference in CH_4 emissions before and after drainage will vary depending on factors such as soil temperature, extent of drainage, and wetland type.

The direction and magnitude of the effects on these gases are highly uncertain and significant advances in our understanding of the biological processes as well as determination of the area extent of the activities will be required before these calculations can be adequately accomplished. It may be possible to include CH_4 calculations associated with land flooding in early refinements of the calculations, but the N_2O and CO calculations are more difficult and as yet of uncertain importance.

Surface Waters

Some national experts have pointed out that changes in surface waters due to human activities can result in sequestration of carbon, and presumably other emissions or removals. An example is pollution of lakes due to run off, which can cause eutrophication, increasing the carbon content of waters. Pollution of coastal waters could also have similar effects. No data have been obtained thus far to indicate whether the carbon sequestration effects of such changes are large enough to be significant. However, it is possible that some countries may want to carry out preliminary calculations and report these as part of the ongoing methods development effort.

These changes in surface waters are generally a result of combined effects including land-use changes, agricultural practices, wastewater treatment, etc. in the surrounding area. Thus, they do not fit neatly into any of the broad economic sectors which form the fundamental structure of these *Guidelines*. If national experts consider the changes in surface waters to be primarily a function of land-use changes, the results of preliminary calculations could be reported in the "Other" subcategory within the Land-Use Change and Forestry category. Alternatively, they could be reported under Waste, Agriculture, or the newly created general "Other" category.

T5 Technical Appendix: Deforestation Data

Data on rates of deforestation[32] are essential for calculating the fluxes of CO_2 and other trace gases between terrestrial systems and the atmosphere. When arranged on a country-by-country basis, these data provide the forcing function for computation of country-specific emissions from forest clearing. Recognising that such data sets are not yet available for many countries with the accuracy needed for these computations, this technical appendix provides suggestions for utilising the available global and national sources of data, while bringing new or better sources of information into the calculations when and where they are available.

T5.1 Food and Agriculture Organization (FAO) Published Data

Currently, the most comprehensive international source of data on rates of deforestation broken down to the country level is maintained by the FAO in the following forms:

1. Source data, preferably in the form of a time series, collected in co-operation with member countries, including data on: forest cover, ecofloristic zone and sub-national boundaries, biomass, plantations and conservation, collected and compiled in the form of a geographic information system.

2. Standardised estimates of forest cover, rate of deforestation, afforestation, and biomass/ha at the country level. Standardisation is done by FAO because of variations from country to country in:

   - the definitions of "forest", "deforestation" and "afforestation"
   - the reference years for forest cover and deforestation measurements

   The standardisation is intended to bring country data to common definitions of forest cover and reference data, and to make the country information useful for regional and global studies. The basis for standardisation is adjustment functions by ecological zones based on time-series data on forest cover of countries.

3. Data from a global sample survey of forest cover state and change during 1980 and 1990 based on a limited sample of high resolution satellite images using common definitions and measurement techniques. The main aim of this survey is to calibrate regional and global estimates and provide comprehensive information on various types of on-going forest cover changes, in the form of change matrices (1980 and 1990). It should be noted that the sample survey is not intended to check or replace country estimates, but only to provide reliable estimates (i.e., with standard error) of forest cover and rate of change at regional/global levels. This is being done taking into account the inherent limitations of aggregating heterogeneous country data at regional/global levels.

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[32] This appendix is limited to discussion of current and future international sources of data on rates of deforestation at the national level. It is understood, however, that other types of input data are also key sources of uncertainty in calculations and are also the subject of a great deal of ongoing activity. These include other types of land-use change and land cover data as well as more detailed information on growth rates and biomass densities for different types of forests and other ecosystems.

The survey is based on a sampling design covering all tropical countries. The World Reference System 2 (WRS2) for the LANDSAT satellites is used as the sampling frame. LANDSAT scenes covering approximately 3.4 million ha serve as sampling units.

In view of cost-benefit considerations, the sampling units were selected from all LANDSAT scenes with a minimum land area of 1 million ha and a forest cover of 10% or more, estimated on the basis of existing vegetation maps. This has restricted the area surveyed to some 62% of the total tropical land area but containing some 87% of the total tropical forest.

This first survey round is based on a 10% sample consisting of 117 sampling units randomly selected. The distribution of the selected sampling units by region is 47 in Africa, 30 in Asia and 40 in America. This sample size was chosen to estimate forest cover at global level with standard error less than ±5%. At each simple location, satellite images of the best quality and appropriate season, separated by an approximate ten-years interval, were selected for observation. The image close to 1990 provides assessment of the current state; whereas the area in common between "1990" and "1980" images provides the assessment to be made of the changes over time.

The interpretation was implemented at selected regional and national forestry and/or remote sensing institutions, which have a good knowledge of the sample locations and are traditionally involved in forest resources assessment activities. With the two-fold objective of improving national capacities for forest monitoring and the quality of image interpretation, the FAO Project organised three regional workshops and eight training sessions with national institutions, benefiting 27 countries and 81 participants.

The result and quality of the interpretation undertaken by local institutions were centrally reviewed and evaluated. The first result of the survey is its set of transition matrices, one for each Sampling Unit, that describe in detail the class-to-class changes for the *land cover classes* (see Box below).

LAND COVER CLASSES
Closed Forest
Open Forest
Long Fallow (forest affecting by shifting cultivation)
Fragmented Forest (mosaic of forest/ non-forest)
Shrubs
Short-Fallow (agricultural areas with short fallow period)
Other Land Cover
Water
Plantations (agricultural and forestry plantations)

The matrices associated with the sampling units can be aggregated at various levels following the standard statistical procedure. Mean transition matrices can be produced and subsequent change analysis has been carried out for the three regional and by three ecological zones (Wet and Very Moist, Moist, Dry).