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Accounting for Biological and Anthropogenic Factors in National Land-base Carbon Budgets

Efforts to quantify net greenhouse gas emissions at the national scale, as required by the United Nations Framework Convention on Climate Change, must include both industrial emissions and the net flux associated with the land base. In this study, data on current land use, rates of land-cover change, forest harvest levels, and wildfire extent were analyzed under a common framework for three countries in order to compare net CO_2-carbon flux, and to identify key research areas. In the Former Soviet Union (FSU) and the conterminous United States (US), the stand age-class distribution on the forested land and the rate of logging tended to be the most important factors in the land-base flux, whereas in Brazil the rate of land-cover change and the vegetation regrowth in secondary forests on abandoned agricultural or grazing land were critical. The areas of greatest uncertainty for the FSU and US analyses related to the rates of woody debris and soil organic matter accumulation and to limitations in the age-class based inventory data available. In Brazil, the initial biomass in forests subject to deforestation, and the area of recovering secondary forest, were identified as important research issues. Continued database development, and close attention to methodologies for quantifying carbon flux, will be necessary if carbon budget assessments are to be of use to the policy community.

INTRODUCTION

With the ratification of the United Nations Framework Convention on Climate Change, signers are called upon to produce national-level inventories of net greenhouse gas emissions, including CO_2 sources and sinks associated with the land base (1). Countries differ in their land-base carbon (C) budgets because of variations in factors such as rates of land-cover change, the intensity of forest management for wood products, and the extent of agricultural practices which deplete soil organic matter. The diversity of land-use practices, the frequent interaction of biological and anthropogenic factors, and shifts in the relative importance of particular processes in different regions, make quantifying the land-base C flux a complex task. In an effort to view national C budgets from a common perspective, we have examined the major land-base C sources and sinks in three countries (the former Soviet Union, the conterminous United States, and Brazil) differing in phytogeography and level of economic development.

Interest in developing greenhouse gas inventories at the national level has resulted in several studies outlining methodologies or models. The Intergovernmental Panel on Climate Change (IPCC) has worked with the Organization for Economic Cooperation and Development (OECD) to produce an initial set of protocols for estimating the land-base flux (2). Makundi et al. (3) have reported a land-base C flux for seven significantly forested developing nations using the COPATH model (4), and Subak et al. (5) have produced initial flux estimates for 142 countries using existing national and global databases. Several national-level emissions inventories have been completed (6) and others are under development, with support from organizations such as the United Nations Environment Programme and the US Country Studies Program (7). Because these results may become relevant to the development of agreements to limit greenhouse gas emissions, a framework for reporting flux estimates is also being designed (2).

Although generalized methodologies have been worked out for constructing national-level C budgets, in practice the quantity and quality of available data will dictate to a great extent how the budget variables are estimated. The effort described here, to quantify the major C flux terms for three quite different countries, has indicated some of the differences which might be expected between countries, and identified some of the major research issues relevant to these comparisons. This study draws on earlier analyses which have examined the C budgets of the former Soviet Union (8–10), the conterminous United States (11, 12), and Brazil (13, 14), but the emphasis here is on viewing the C budgets from a common perspective.

APPROACH

The C flux associated with the industrial sector, i.e., energy production, transportation, and cement manufacture, are straightforward in the sense of being unidirectional—from the surface to the atmosphere. In contrast, the net flux associated with the land base is the product of C uptake via photosynthesis, and C release via autotrophic respiration, heterotrophic respiration, and fire. At the global scale, the net land-base flux is only a small proportion of the associated gross flux because heterotrophic respiration tends to offset C uptake by photosynthesis (15). At the regional scale, however, factors such as deforestation, which promotes C release by combustion and decomposition, or afforestation, which promotes C uptake, may create significant net C sources or sinks lasting for decades. The objective here, then, was to quantify the net CO_2 flux on an annual basis for the land surfaces associated with three particular countries.

The land-base C flux was partitioned into three categories: (i) net ecosystem production (NEP), which incorporates all the biologically-driven C transfers between the biosphere and atmosphere; (ii) the harvest flux, which accounts for removals associated with commercial tree harvest; and (iii) land-cover change combustion emissions generated by burning of phytomass and woody debris during deforestation. The complete land base, both managed and undisturbed components, was considered. Because tree growth rates are often modeled in 5–10 year time steps, and variables such as deforestation rates and fire extent are often reported over multiyear intervals, averages over a period on the order of a decade were used for some variables.

The initial step in developing the carbon budgets was to create a land-base classification for each country. The level of aggregation for the land-cover classes was similar across countries, but the number of classes in each country depended on its geographic diversity. In Brazil, 12 classes were identified based on the land-cover map of Stone et al. (16). In the former Soviet Union (FSU), the land-cover estimates were derived from published vegetation and soil maps as well as tabular data. Eleven classes were used. A land-cover map for the FSU based on coarse resolution satellite imagery (17) showed good agreement with the other sources. In the conterminous United States (US_c), five broad land-cover classes were established based on tabular data (18) from the US Department of Agriculture (USDA). As with the FSU, an effort was made to compare area estimates from satellite-based maps with the tabular data (19). For the purposes of describing how the three categories of C flux were quantified, the land-cover classes have been aggregated to three types—forestland, pastureland/agricultural, and other land.

Forestland

Forestland cover classes are the most likely to be associated with significant C flux because of the potential for large C accumulation in tree boles and dead wood, or large losses from deforestation. Globally, forests are estimated to contain 80% of aboveground organic C (15). Estimation of the C flux for forested land comes from understanding spatial and temporal patterns in net ecosystem productivity and knowledge of C losses or removals via disturbances such as logging, catastrophic fire, and deforestation.

Net Ecosystem Production (NEP) Flux

Where catastrophic disturbances are followed by regeneration, C is emitted early in stand development by decomposing woody residues generated during the stand-initiating disturbance. The uptake of C into trees begins to offset the source associated with decomposition near the time of canopy closure, then peaks and begins to decline as physiological or nutrient constraints begin to limit growth rates (20). Coarse woody debris (CWD) may accumulate in the mature forest if mortality exceeds decomposition. Thus, NEP is typically negative early in stand development, highly positive in middle-age stands, and slightly positive in older age stands (Fig. 1). Although this sequence is widely agreed upon in the literature (21), the time taken to reach specific stages may not be well known, particularly in tropical forests. In some temperate deciduous forests and moist tropical forests, the disturbance regime is characterized by single tree falls rather than catastrophic disturbances. Over a large enough area, these forests are theoretically in C steady state because of the mix of patch ages.

Data requirements for estimating the NEP on forestland are: (i) an inventory of the area by forest type and, in many cases, the age-class or size-class distribution within each forest type; and (ii) a stand-level C budget for each forest type indicating C pools and NEP over the course of stand development (Figs 1 and 2). The national-level NEP flux is then the product of the area within each inventory type and the associated NEP. In temperate and boreal zone forests, tree rings and diameter distributions may be used to age stands and estimate wood accumulation. The C flux in secondary tropical forest is more difficult to quantify because tropical species typically lack annual growth rings. Estimated rates of C accumulation must therefore be based on studies tracking changes in stand biomass over time.

Among the three countries studied, the most detailed forest inventory was available for the US_c. The USDA Forest Service Forest Inventory and Analysis units (22) perform repeated surveys, and a complete inventory is periodically assembled for the purposes of the Resources Planning Act Assessments (23, 24). There are 22 forest types used in the US_c inventory, and within each type there are numerous subclasses based on region, productivity, management intensity, and age class, with 5 to 10 year intervals in the age-class distributions. A forest inventory was also available for the FSU (25) but data were used in a more aggregated form. The methods employed and the availability of FSU inventory data are discussed in Shvidenko and Nilsson (26) and Kolchugina and Vinson (10). In Brazil, six major forest cover types were included within the forestland class but age-class distributions within each type were not available. Thus, a single NEP was estimated for each forest cover type (13).

The stand-level C budgets for the US_c were based on growth and yield tables (23) which summarize expected trends in growing-stock accumulation over time for each inventory type (11). Allometric relationships between growing stock and total-tree C were then used to estimate tree C pools at successive ages. Coarse woody debris pools at successive ages in the stand-level C budgets for the US_c were based on a CWD model which considered the input of woody debris after harvest, and forest-type-specific rates of mortality and decomposition (27).

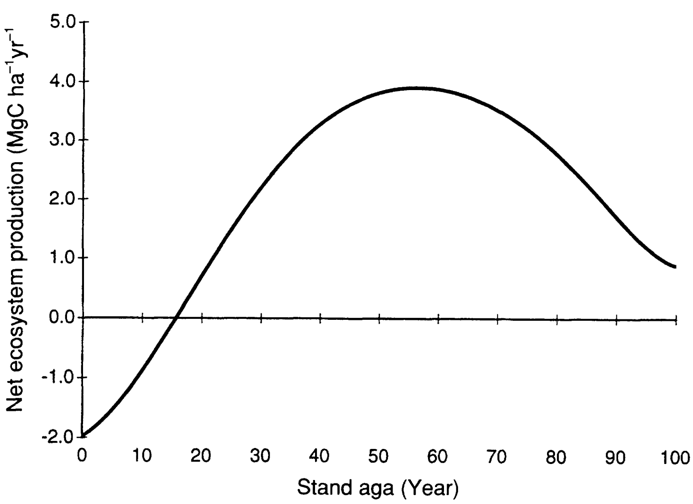

Figure 1. Generalized trend for course of net ecosystem production (NEP) over the course of stand development.

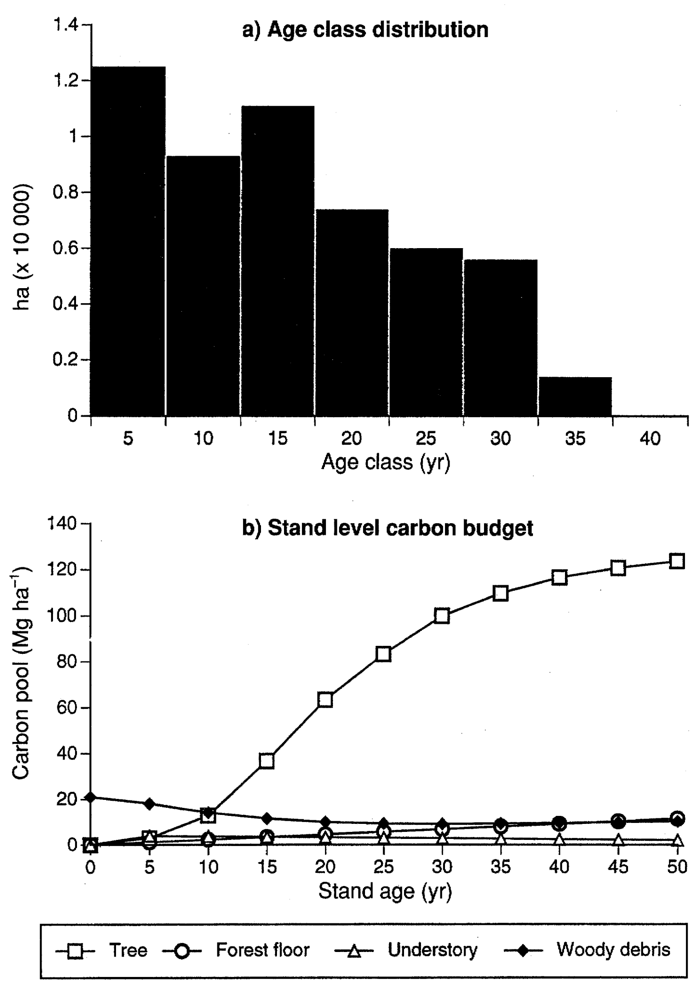

Figure 2. The age class distribution (a); and stand level carbon budget (b) for planted pine on private lands in the southeastern United States.

A managed forest landscape in the Cascade Mountains of the western United States. Stand age-class distribution strongly determines the sign and the magnitude of carbon flux. Photo: Courtesy of the Oregon State University College of Forestry.

Accumulation of carbon in long-lived products such as building materials represents a significant carbon sink.

In the FSU, ratios of growing stock to tree C were used in a similar manner but, again, with a much greater degree of aggregation. CWD accumulation rates were based on observations in even-aged stands. Inherited emissions, from decomposition of woody debris produced by fires and forest harvesting, were accounted for based on long-term averages for areas burned (25) and harvest rates.

In Brazil, the forest types themselves were indicators of the time since last disturbance; i.e., the classes included tropical moist forest, secondary forest, and pasturelands. The tropical moist forest class was assumed to be in C steady state; i.e., C uptake via tree growth was considered to be balanced by C release associated with decomposition of litter, fallen trees, and soil organic matter. However, the history of disturbance in what are apparently primary tropical moist forests is often not known, and estimating potential rates of C gain or loss is a significant research issue (28–30). Rates of C uptake in the secondary forests and net C emission in recently converted pasturelands were based on field studies in the relevant areas.

Emissions from forest wildfire were accounted for directly in the carbon budget of the FSU, indirectly in that of the US_c, and not at all in Brazil. In the FSU, wildfire emissions were estimated based on the long-term average area of closed forest which was reported burned (10). In the US_c, where fire suppression has been particularly successful, noncatastrophic fire was considered to be part of the background mortality and catastrophic fire was assumed to be salvage logged. Wildfire was not considered a C source in the forestland of Brazil because much of it is tropical moist forest with a low incidence of catastrophic fire. Selective logging in these forest increases the likelihood of fire (31), but these emissions were not quantified.

The Harvest Flux

Somewhat more complicated approaches than are discussed in the IPCC/OECD protocols for quantifying effects of harvest removals were adopted in this study. The principle budget terms associated with logging were (i) the mortality or reduction of tree C from the phytomass pool; and (ii) the partitioning of that tree C between logs removed from the forest, residue which is burned as slash, and residue which is left to decompose.

Total tree C mortality was a function of reported growing stock (merchantable volume) removals and the ratio of total tree C to growing stock C. In the US_c analysis, the ATLAS model (32) was used to simulate the distribution of the total prescribed harvest across regions, forest types and age classes. Reference was then made to the stand level C budgets to determine total tree C mortality. Region-specific estimates of the proportion of logging residue which was burned were developed from the literature for the US_c and were incorporated into the modeling of the CWD pool in the stand-level C budgets. Forest-floor accumulation during stand development and loss at the time of harvest are discussed in Turner et al. (11), but are not treated here in order to facilitate comparison with the FSU data in which the forest-floor dynamics were not quantified. In the FSU, the volume of growing stock harvested was derived from government statistics (25) and a single conversion factor was used to convert a national-level estimate of the volume harvested to tree C mortality. Estimates for slash emissions were taken from Melillo et al. (33).

Timber harvests from plantations in Brazil were taken from statistics compiled by the World Resources Institute (34), and a fixed tree C to growing stock C ratio of 2.0 was employed. Removals from primary forest were presumed to be accounted for in the emission estimates associated with deforestation. Fuelwood removals, some of which do not show up in summaries of roundwood or growing stock harvest, may be greater than commercial logging removals in tropical countries but no attempt was made to isolate this flux. Small-scale fuelwood gathering tends to be a dispersed activity and may be balanced to some degree by unquantified tree growth. Large-scale fuelwood consumption is captured in part by the treatment of deforestation.

The C in logs removed from the land base is assumed to be returned to the atmosphere in the IPCC/OECD protocol. However, some forest products have lifetimes on the order of hundreds of years and may thus represent a significant C sink. The pool of wood products still in use and in landfills is a function of inputs and outputs, and an accounting system which tracks current and historical inputs, turnover times of the different product types, and the return of product C to the atmosphere is desirable (35, 36). It was not possible in this study to assemble

Photo: Courtesy of the Oregon State University College of Forestry.

Residual coarse woody debris and slash after a clearcut in coniferous forests of the western United States. Decomposition of woody residues provides a long-term source of carbon to the atmosphere. Photo: J. Winjum.

the relevant data for this type of model and estimates for wood product accumulation based on highly simplified assumptions were taken from Birdsey et al. (37) for the US_c and from Melillo et al. (33) for the FSU. For Brazil, half of the lumber production was assumed to be accumulating.

Land-cover Change Combustion Emissions

Deforestation is the most significant land-cover change in terms of C flux. Direct emissions associated with deforestation are a function of several factors including the area converted during the base period, the initial C pools or standing crop, the burning efficiency, and the amount of charcoal formation (13).

Estimates for rates of land-cover change can be based on ground surveys. However, considering the pace of recent deforestation, remote sensing may also be needed (38). Of the three countries in this study, Brazil had by far the highest rates of deforestation; the average rate in the 1980s was estimated to be 1–2 Mha yr^{-1} (39). Thus, close attention was given to quantifying the relevant factors in Brazil. The land-cover distributions in the FSU and US_c are relatively stable, although the trend in the US_c is towards a slow decline in the area of timberland (40).

Approaches to estimating the standing crop in mature tropical forests of Brazil have included both destructive sampling (41) and forest inventory data (29). Results from both approaches were used to create a range of estimates for tree biomass (13). Burning efficiencies can be quite low in humid forests and for Brazil were assumed to be 27% of aboveground C in tropical moist forests, 60% in secondary forests, and 100% in cerrado woodland (13, 41). Charcoal formation is an important aspect of the C flux associated with deforestation because its resistance to decomposition means it can be a significant C sink. The estimate for the rate of charcoal formation on converted lands in Brazil was 3.6% of aboveground biomass (41). None of the biomass on converted lands was assumed to be transformed into long-lived forest products.

Pastureland and Agricultural Areas

Data requirements for estimating NEP on nonforestland relate to determining the land use and, in cases of recent conversion, estimating the time since conversion. Bare land which originates from deforestation is initially a C source because of the decomposition of woody residues and accelerated soil organic matter decomposition. These so called inherited emissions are a significant term in the overall C budget where recent deforestation rates are high. The magnitude of inherited emissions may be quite large, in part because burning efficiencies are typically low.

In the IPCC/OECD protocol, inherited emissions associated with woody residues are estimated by determining an average rate of deforestation over the previous 10 years, then summing the unburned phytomass C which would have been left, and assuming 1/10th of it is emitted in the reference year. Where a good current land-cover map is available, an alternative approach relies on knowing the area of recently converted land and estimating the average post disturbance emissions rate that might be expected. For Brazil we used the land-cover map of Stone et al. (16) for an estimate of the area of recently converted land. These lands fell into several categories, with emissions highest (3.2–5.1 Mg ha^{-1} yr^{-1}) from pastureland (41). Because these emissions were biologically driven, they were included as part of the NEP estimate.

On agricultural lands, the phytomass pool is assumed to be stable since most crops and residues are returned to the atmosphere via heterotrophic respiration relatively rapidly. The soil C pool, however, tends to decline over a long period after conversion of other land-cover types to agriculture (42); soil organic matter decomposition is accelerated because of tillage while inputs may decline because of crop utilization.

In Brazil, over 100 Mha of land now used for agriculture originated in totally or partially forested areas. These lands were assumed to now be losing soil C at a rate of 1% per year. Changes in agricultural management, as have been extensive in the FSU, were also accounted for by reference to the areas involved and the rates of C loss (43). Although these C losses in part are biologically driven, they are kept separate from NEP in the results presented here because they are a function of repeated human intervention, i.e., tillage. Uncertainties in the estimates of soil C loss are large because of the relatively few measurements on which they are based and the difficulty of distinguishing between losses via erosion and loss via an imbalance between inputs and decomposition.

Table 1. Net ecosystem production. All units are Tg yr^{-1}. Positive values are net carbon uptake and negative values are net carbon release to the atmosphere.

	Phytomass	Coarse woody debris	Soil	Total
FSU	558[a]	7[b]	96[c]	661
US[d]	359	–66	0	293
Brazil[e]	54	–75	5	–16

Notes:
a. Kolchugina and Vinson (10).
b. 122 (10) – 73 (slash decay; 33) – 42 (post fire emissions; 10) = 7.
c. 53 (peat) + 40 (SOM forest) + 5 (SOM nonforest) – 2 (postfire emissions) = 96. All values from (10).
d. Data from (12).
e. Data from (13).

Table 2. Timber harvest transfers. All units are Tg yr^{-1}. Negative values are carbon transfers to the atmosphere or off the land base.

	(1) Tree C mortality	(2) Growing stock removals	(3) Harvest emissions	(4) Carbon loss from land base (2) + (3)
FSU	148[a]	–101[a]	–39[b]	–140
US[c]	275	–125	–77	–202
Brazil[d]	22	–11	–7	–18

Notes:
a. (10).
b. (33).
c. (12).
d. (13).

Other Land

Other land-cover classes were generally assumed to be in C steady state. In woodlands, defined in the US as wooded land producing < 1.4 m^3 ha^{-1} yr^{-1} of merchantable wood, the low level of productivity tends to be balanced by wildfire and decomposition. A similar situation prevails in the cerrado woodland of Brazil. In rangelands, grasslands, wetlands, and tundra, there may be small C sources or sinks, but these were not quantified except in the case of peatlands, which represent a significant C sink in the FSU. The background geochemical cycling of C via volcanic emissions, mineral weathering, and riverine transport of soluble organic matter were not treated either.

Uncertainty

There was no systematic treatment of uncertainty associated with the flux estimates in this paper. When ranges were developed in the original analyses, as for biomass C burned per unit area deforested in Brazil (13) and for the forest phytomass increment in the FSU (10), unique values within the range were used here. This approach tends to mask the differences in uncertainty associated with different estimates, however, it is desirable for clarity of presentation. Kurz and Apps (44) have presented a formal sensitivity analysis of some components of the forest sector C budget for Canada and such efforts should be an integral part of national-level analyses.

RESULTS AND DISCUSSION

The NEP flux is positive, i.e. carbon uptake by the land base, in the FSU and US_c but negative in Brazil where decomposition associated with woody residues left behind after deforestation is greater than C uptake from regrowth (Table 1). The phytomass increment is greatest in the FSU which has the largest forest area (814 Mha, compared to 201 Mha for the US_c and 438 Mha for Brazil). Large areas of young forests in all three countries promote C accumulation, however, the origin of these stands differs greatly. In the US_c, the secondary forests are the product of extensive logging over the last century (45); in the FSU, their origin is extensive wildfire and anthropogenic disturbances (10, 46); and in Brazil, extensive deforestation followed by reversion after pasture abandonment is the main factor (38, 47).

The CWD component of NEP, i.e., the net effect of natural tree mortality and decomposition, is negative in US_c and Brazil. In the FSU, it appears that CWD may be accumulating. In the US_c, decomposition of woody residues in the relatively large area of young secondary forests determines the sign of the flux. Woody debris is also a relatively large source of C in Brazil because of decomposition of woody residue on pasturelands created within the last 10 years.

The soil organic matter component of NEP is a net C sink in Brazil. Soil emissions from pastureland areas associated with recent deforestation are less than the accumulation of soil C assumed to be occurring in the young secondary forests (30, 48). The FSU budget also indicates a significant gain (40 Tg yr^{-1}) in soil C associated with secondary forests, and peat accumulation (53 Tg yr^{-1}) more than doubles the C sink. Soil organic matter in the temperate zone forests of the US_c does not appear to respond to logging in any consistent way (49) so the forestland soil C pool is considered to be in steady state. If the large area of forestland in the eastern US_c, which originated from agricultural abandonment, is assumed to be still accumulating soil C, a larger soil C sink would be specified (50).

The harvest flux is relatively large in the US_c and FSU (Table 2). In both cases over 100 Tg yr^{-1} of growing stock is removed from the forest land base. Smaller harvest removals in Brazil reflect less industrial development, lack of infrastructure, few species identified to be commercially valuable, and less use of timber in construction. The direct emissions associated with commercial harvest are likewise largest in the US_c and FSU because of the level of logging.

The land-cover change combustion flux is greatest in Brazil (–132 Tg yr^{-1}) because of its high deforestation rate (Table 3). Estimates for 1990 rates of deforestation were 1.48 Mha of closed tropical moist forest, 0.35 Mha of secondary forests, and 1.0 M ha of cerrado. In contrast, the land-cover distributions in the US_c and FSU are relatively stable, thus, the flux estimates for land conversion emissions are quite low (< 4 Tg yr^{-1}). The net effect of the biological and anthropogenic factors on the land base is a C sink in the FSU (344 Tg yr^{-1}) and the US_c (85 Tg yr^{-1}), and a C source in Brazil (–251 Tg yr^{-1}).

With regard to the agricultural sector emissions, the extensive and relatively young agricultural lands in Brazil represent an 85 Tg yr^{-1} source of soil C. There is also a large C source (76 Tg yr^{-1}) estimated for the FSU. Much of C in the agricultural land in the US_c is probably approaching a steady state or even increasing due to improved soil conservation practices (51). The soil flux estimates do not include losses of soil organic matter via erosion, suggested to be about 200 Tg yr^{-1} in the US_c (52) and 36 Tg yr^{-1} in the FSU (43). Impacts of erosion were not included in the C flux estimates because it is not clear to what degree erosional losses end up in the atmosphere.

In a complete national-level CO_2-C budget, two additional flux components are included—forest product accumulation and fossil fuel emissions (Table 3). The accumulation of C in forest products still in use and in landfills is greatest in the US_c and FSU, which follows from the more extensive commercial logging in those countries. Emissions from energy use and production are the dominant terms in the US_c and FSU budgets but in Brazil they are small relative to land-base emissions. Combus-

Table 3. National CO_2-C flux estimates. All units are Tg yr^{-1}. Positive values are net carbon uptake and negative values are transfers to the atmosphere or off the land base.

	Net ecosystem production	Timber harvest	Land cover change emission	Agricultural emissions	Land base total	Forest products and landfills	Fossil[a]	National total
FSU	568[b]	–148	0	–76	344	33	–1139[c]	–762
US[d]	293	–202	–4	–2	85	36	–1306[e]	–1185
Brazil[f]	–16	–18	–132	–85	–251	3	–53[g]	–301

Notes:
a. (5).
b. 661 (Table 1) – 93 (direct fire emissions; 10) = 568.
c. (–1020, fossil fuel)+(–19, cement manufacture)+(–100, peat combustion) = –1139.
d. (12).
e. (–1296, fossil fuel) + (–10, cement manufacture) = –1306.
f. (14).
g. (–50, fossil fuel) + (–3, cement manufacture) = 53.

tion of peat for fuel is a large term (100 Tg yr^{-1}) in the FSU fossil C emissions.

For all three countries considered here, C sources exceed C sinks; i.e., each country is a net emitter of C. The US_c is the largest emitter because of its large population and high per capita fossil fuel emissions. FSU has a similar distribution of sources and sinks, and like the US_c, is a large net emitter. The land base sink in the FSU balances 20% of the fossil C emissions; the comparable value in the US_c is 7%. Brazil is notable in that the net land-base source is larger than the fossil source. However, of the three countries, net C emissions from Brazil (population ~150 x 10^6) are the lowest. In particular, the fossil fuel emissions are less than 5% of those for the FSU (population ~271 x 10^6) or the US (population ~263 x 10^6).

As is evident from considering even three countries, the quantity, quality, and availability of data relevant to implementing the approach to quantifying national-level C flux described in this paper varies widely. Thus, the specific types of research needed to construct consensual C budgets depends on the country and the flux category. Several papers have discussed important research needs (4, 5, 44) and selected topics are treated here.

For NEP, the importance of an age-class based inventory in the temperate zone has been discussed. Because of the economic importance of the forest sector, many temperate zone countries appear to have reasonably complete inventories (53), along with associated growth and yield tables for commercial forestland. Historically, forests in the boreal region have not been of commercial interest, due to slow growth rates or inaccessibility, so comprehensive information relevant to forest C budgets may not have been generated or be available (26). Forested area on lands reserved for habitat conservation and recreation may also not be as well inventoried because of its relatively low economic importance. Reserved forestland in the US constitutes 19% of public forestland and 6% of total forestland (24) yet an age-class based inventory of these lands is not available. High spatial resolution remote sensing appears to offer good prospects for developing simplified inventories in temperate zone forests (54, 55), however, the discrimination of age- or size- class in deciduous forests remains problematical.

For the tropical zone countries, an adequate land-cover map is more critical for an NEP estimate than an age-class based forest inventory. Efforts to develop a global 1 km resolution land cover-map using imagery from the Advanced Very High Resolution Radiometer (AVHRR) will significantly improve the situation for many countries (56). Quantifying the area of secondary forest in tropical nations is a particularly critical task (30) and progress has been made in distinguishing stages of secondary succession using Thematic Mapper (TM) spectral data with a spatial resolution of about 30 m.

Given an adequate land-base inventory, perhaps the area of greatest uncertainty with regard to estimating the NEP in many cases is the treatment of decomposition. Foresters have traditionally emphasized growth, thus it is well quantified. However, an understanding of woody debris decomposition is essential in the stand-level carbon budgets (35) and post-deforestation emission estimates. Dynamics of soil C following harvest or afforestation are also not well understood and have introduced large uncertainty into national-level flux estimates (57).

With regard to the quantifying the harvest flux, there is a general need for a complete forest products model and collation of the required input data. Recent modeling efforts have begun to treat the historical trends in factors such as the harvest level, harvest utilization patterns, and the rate of disposal of forest products into sanitary landfills (58). Application of these models at the national level (e.g. 36) will yield more comprehensive treatment of the forest sector C flux.

Estimates for combustion emissions associated with deforestation will depend on monitoring of deforestation and reforestation rates. The frequency, areal extent and intensity of forest fires is also critical because of the propensity for catastrophic wildfire in some regions (59). The task of monitoring forest cover is technically feasible using satellite remote sensing but may require some combination of TM and AVHRR imagery (47). Quantifying C flux in areas of rapid deforestation also requires dependable estimates of initial biomass C density. Forest inventory data have been suggested to yield better estimates of mean biomass C densities in tropical forests than earlier estimates based on the ecological literature (60). However, updated survey-based inventories are still needed in many areas. Measurements of C density in stages of secondary forest succession are also needed for more reliable flux estimates.

CONCLUSIONS

This effort to develop and compare national land-base C budgets for three quite different countries have revealed a complex interaction of biological and anthropogenic factors. Quantifying aggregate net ecosystem productivity depends on understanding current patterns of growth and decomposition, particularly as influenced by local disturbance regimes. Overlain on this predominantly biological flux are the effects of human resource use, particularly in the forest and agricultural sectors of the national economies. The results from this cross-country comparison have indicated some of the limitations in available data and relevant models. Continued database development and comparisons of this nature will strengthen the scientific basis for complete national land-base C budgets and contribute to the information base needed to address emerging global change issues.

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