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Land-use change in the Soviet Union between 1850 and 1980: causes of a net release of CO_2 to the atmosphere

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ABSTRACT

A detailed analysis of the history of land-use change in the Soviet Union that included tree cutting and regrowth, oxidation of woody debris, decay of wood products, and clearing of lands for agricultural expansion showed that the net carbon flux between the USSR and the atmosphere resulting from these activities was approximately zero in 1980; that is, there was only a small net flux of 0.037×10^{15} g carbon from the land to the atmosphere in that year. These results are in contrast with previous analyses that found the USSR to be a net carbon sink. In our analysis, we found that regrowth of forest vegetation following harvest, when considered alone, was responsible for an annual net storage in the USSR of about 0.136×10^{15} g C for the period 1955–1975, a value intermediate between estimates derived from a previous analysis. This storage was balanced by a net release to the atmosphere of about the same amount of carbon from a variety of processes, including the oxidation of woody debris and decay of wood products. In 1980, the carbon flux between the land and the atmosphere due to land-use change throughout the entire northern hemisphere's temperate and boreal systems was also small, as these systems accumulated only 0.025×10^{15} g C that year.

1. Introduction

Estimates of the current net carbon balance for the temperate and boreal zones vary from a net storage of 1.9×10^{15} g C/yr (Johnson and Sharpe, 1983) to a net release of 0.5×10^{15} g C/yr (Houghton et al., 1983). The discrepancy is now larger for the temperate and boreal zones than it is for the tropical zones (Houghton et al., 1985). Most of the discrepancy is from uncertainty with regard to the USSR which, according to extant analyses, accounts for more than half of the estimated net flux outside of the tropics.

Armentano and Ralston (1980) considered the consequences of forest harvest and regrowth in the temperate zone for the global carbon budget. They concluded that forests of the temperate zone were acting as a net sink for atmospheric carbon, with the mean annual storage rate in temperate and boreal forests between 1.0 and 1.2×10^{15} g during the period 1953–1975. In their analysis, Armentano and Ralston (1980) estimated that the forests of the Soviet Union were acting as the largest carbon sink among temperate and boreal zone forests, with an annual storage of up to 0.5×10^{15} g. They did, however, question the reliability of the data they used in the Soviet analysis.

Using a different approach and different data, Shaver et al. (1982) concluded that the harvest and regrowth of forests in the Soviet Union resulted in a net release of 0.199×10^{15} g to the atmosphere in 1975. Part of the difference between this analysis and the Armentano and Ralston analysis for forests is that the former considered the fate of carbon in the forest floor and mineral soil following harvest and the latter did not.

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Because there is disagreement about how forest harvest and regrowth in the USSR have affected the global carbon budget, we have re-analyzed the problem. We have expanded the analysis by including consideration of the decay of wood products, clearing of forests for agriculture, and abandonment of agricultural plots.

2. USSR regional carbon flux model

The model used in this analysis was a modification of the Marine Biological Laboratory/Terrestrial Carbon Model (MBL/TCM) (Moore et al., 1981; Houghton et al., 1983). In this analysis, three ecosystems and two geographic regions of the USSR were considered. The three ecosystems were the boreal forest, temperate deciduous forest, and temperate grasslands. The USSR was subdivided into a western and eastern region. The west included all areas west of the Ural Mountains. The east included all republics of Central Asia, Western and Eastern Siberia, and the Far East. The time step was annual.

To calculate net carbon flux between the land and the atmosphere following land-use change, two general types of information were needed: the area undergoing a specific land-use change within each ecosystem type, each year; and the response of the carbon pools of each system to the change. A full accounting of the response of carbon pools to land-use change, in turn, required that four factors be considered: (1) the difference between the biomass (vegetation mass) and soil organic matter of natural and managed systems; (2) the amount of biomass removed from the disturbed area and the rate at which it burns or decays; (3) the amount of biomass left as "slash" (woody debris generated from vegetation during a harvest or clearing) on the disturbed area and the rate at which it burns or decays; (4) the rate and maximum level of carbon accumulation in the biomass and soil as a system recovers from disturbance.

The dynamics of the various carbon pools of an ecosystem following disturbance were incorporated in the model through a suite of vegetation, soil and slash response curves (Fig. 1). Each ecosystem type had its own characteristic response functions for agricultural clearing and forest harvest. Wood products removed from a system were assumed to decay with rates dependent on the use of the wood.

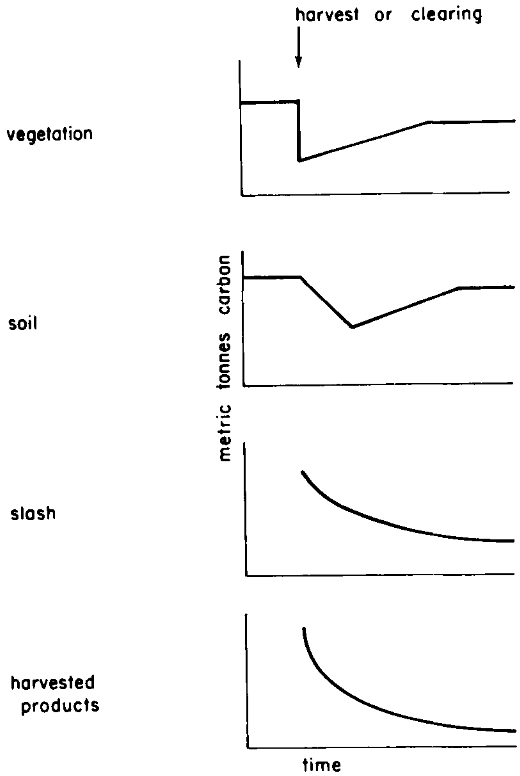

Fig. 1. Idealized response curves in the MBL/TCM model. A different set of curves was assigned for each type of land use within each ecosystem.

Data on rates of agricultural clearing and forest harvest were taken from primary sources where possible and secondary sources where necessary. We relied heavily on Soviet scientists for the data we used to construct the vegetation and soil response curves. Documentation of the data sources for our reference run is given in the following sections. Considerable uncertainties were associated with some of the input data so we tested the importance of these uncertainties by making additional model runs with alternative data and assumptions.

2.1. *Agricultural clearing*

2.1.1. Rate of agricultural clearing. Consideration of agricultural clearing began with a historic record of land under cultivation in each of the three ecosystem types in the USSR. Data on land in agriculture between 1860 and 1980 were taken from Yatsunskiy (1982a, b) and from the official statistical records of the USSR (National Economy of the USSR, 1959–1981). The amount of agricultural land converted from each of the three ecosystems was then estimated by comparing the geographic distribution of vegetation types with the location of land in agriculture (Ceriomuskin and Burminova, 1960; Lydolph, 1970; Yatsunskiy, 1982a, b) (Table 1).

Table 1. *Time series of land in agriculture taken from each of three ecosystems*

Ecosystem	1860	1912	1940	1950	1958	1970	1980
Boreal forest	1	1	1	1	1	1	1
Deciduous forest	46	51	55	52	62	66	68
Grasslands	33	63	93	92	132	139	146
Total land in agriculture	80	115	149	145	195	206	215

All data are in millions of hectares.
Series derived from data in Yatsunskiy (1982a, b), National Economy of the USSR, and Ceriomusckin and Burminova (1960).

Our estimate of annual clearing rates for agriculture was conservative because we considered only "sown" land; that is, we considered only land actually used to produce annual crops, and not land that had the potential to be so used but was not, or land used for other agricultural purposes, such as fruit tree cultivation.

2.1.2. Response of ecosystem carbon pools to agricultural clearing. Conversion of natural ecosystems to agricultural ones results in changes in the size of the pools of carbon in the vegetation and soil. Conversion lowers the carbon stocks in the vegetation (Fig. 1a). Carbon in the cut vegetation is released to the atmosphere from slash decaying on site, woody materials decaying off site, and wood and other plant materials that are burned. Conversion also lowers soil carbon stocks (Fig. 1b). The values used to define the inflection points, minima, and maxima of the response curves for conversion of grasslands and forest to agriculture are given in Table 2.

Initial carbon pools. We assumed that, prior to clearing, the carbon in the vegetation and the soils of each of the three ecosystems was uniform throughout its distribution across the USSR.

Table 2. *Data used in the terrestrial carbon model to define changes in the carbon in vegetation and soils of ecosystems following conversion to agriculture and subsequent abandonment in the Soviet Union*

	Temperate grassland	Temperate deciduous forest	Boreal forest
Carbon in vegetation of undisturbed ecosystems (10^6 g/ha)[a]	10	135	90
Carbon in vegetation of recovered ecosystems (10^6 g/ha)	10	108	72
Carbon in crops (10^6 g/ha)	5	5	5
Time required for an abandoned system to recover (years)	10	40	80
Carbon in soils of undisturbed ecosystems (10^6 g/ha)[b]	189	134	206
Carbon in soils of "recovered" systems (10^6 g/ha)	189	134	206
Fraction of carbon in vegetation that becomes slash following clearing	0.50	0.20	0.20
Fraction of carbon in vegetation assigned to decay pools after clearing:			
1 year	0.4	0.48	0.48
10 years	0.1	0.24	0.24
100 years	0	0.08	0.08
Carbon content of soil after initial, rapid change following clearing (10^6 g/ha)[c]	161	114	175
Minimum carbon content of soil in cultivated systems (10^6 g/ha)[c]	151	107	165
Time (years) required for[c]:			
initial rapid change in soil carbon following clearing	15	10	15
carbon in soil to reach minimum value during cultivation	30	30	65
carbon in soil to reach "recovered" level in an abandoned system	45	40	80

[a] Values derived from data of Rodin and Basilevitch (1967).
[b] Values derived from data for carbon in the upper 1 m of soil in Schlesinger (1977, 1984).
[c] Estimated from data of Kononova (1961), Drachev (1927), Lazarev (1936), Ivanov (1938).

We assigned initial (predisturbance) vegetation carbon stocks to each ecosystem from data given by Rodin and Bazilevich (1960), and initial soil carbon stocks to each system from data given by Schlesinger (1984) (Table 2).

Fate of cut vegetation. In the model, when forest and grassland ecosystems were transformed to agriculture, a fraction of the vegetation was transferred to the slash pool, and the carbon in slash was then released to the atmosphere according to an exponential decay function (Fig. 1c). The assignment of biomass to the slash pool was based upon distribution of carbon in plants and our assumptions about the fate of the biomass of these systems at the time of conversion to agriculture. For forests, we assumed that the biomass of branches, stumps, and roots accounts for 33% of the total biomass carbon of the tree (Rodin and Bazilevich, 1976), and that these components are left to decay as slash, following the conversion of forests to agriculture. The remaining 67%, representing the bole of the trees, was allocated to decay pools with residence times of 1, 10 or 100 years for fuelwood, paper products and building materials, respectively, with the largest fraction being placed in the one-year decay pool because most wood is burned (Symons, 1972) (Table 2).

In the case of grasslands, we assumed that 50% of the biomass is above ground and 50% is below ground. Of the above-ground vegetation, 80% was assigned to the one-year decay pool and 20% to the 10-year pool. The below-ground biomass was allocated to the slash pool and decayed according to an exponential function as previously described.

Soil disturbance. There is much data to support the idea that the cultivation of land results in net carbon losses from the soil (cf. Schlesinger, 1984). Kononova (1961) cited several studies of the long-range effects of tillage on soil carbon content in the USSR. A 13-year study by Drachev (1927) indicated that 43% of the organic matter in the top 20 cm of the soil was lost as a result of cultivation. In other studies, Lazarev (1936) found that 16–23% of the total humus reserve of the arable layer had been lost over a 23-year period, and Ivanov (1938) reported a 19–27% loss of humus in the top 20 cm over a 12-year period. For the reference run of the model, we assumed that the loss of carbon from agricultural land is 20% of the original soil carbon content of the top 1 m of the soil (Table 2). Most of this loss occurs within the first 15 years following clearing, with the time course of loss following a two-component linear decay pattern (Table 2).

Abandonment of agriculture. We assumed that after agricultural land is abandoned the vegetation and soil carbon of grassland ecosystems recover to 100% of their original carbon contents. For land recovering to forest, we assumed that the vegetation recovers to 80% of its original biomass carbon and soil carbon to 90% of its original mass. We assumed this incomplete recovery of forest biomass and soil carbon because disturbance created by prolonged cultivation is enough to slow forest recovery by many years, and in some cases, to result in replacement of forests by other ecosystems (Keller, 1927). It should be noted that abandonment of agricultural land rarely occurred in the USSR between 1850 and 1980 (Table 1), so assumptions about the size of carbon pools on abandoned agricultural lands are of minor concern.

2.2. *Forest harvest*

To calculate the carbon flux between the Soviet forests and the atmosphere it was necessary to determine the area of forest harvested each year between 1850 and 1980 and the response of carbon pools in forests during the cutting and regrowth cycle.

2.2.1. Rate of forest clearing. Area of forest harvested each year was determined by dividing

Table 3. *Time series of wood demand in the USSR*

Region	1850	1913	1932	1945	1960	1970	1980
West							
non-ind	32.5	57.9	52.8	32.0	8.9	8.1	7.1
ind	1.8	17.0	38.7	37.9	81.5	77.3	66.1
East							
non-ind	5.3	11.7	14.1	10.0	3.1	3.0	2.8
ind	0.0	1.6	10.7	12.6	29.4	38.2	41.0
USSR							
non-ind	37.8	69.6	66.9	42.0	12.0	11.1	9.9
ind	1.8	18.6	49.4	50.5	110.9	115.5	107.1

Non-industrial wood production from Blandon (1983); industrial wood production from Tseplyaev (1965) and FAO (1946–1981). All units are million mtC.

total wood demand for a specific year (Blandon, 1983; Tseplyaev, 1965; Food and Agriculture Organization (FAO), 1946–1981) (Table 3) by the amount of wood extracted from each hectare harvested (the harvest efficiency). Harvest efficiencies used in the analysis of the USSR were based on data from Tseplyaev (1965), Barr (in press), Shcherbakov (1977), Vasil'ev (1973), and Gorovoy and Shlykov (1978) (Table 4). Harvest efficiencies for industrial and non-industrial clearing were different (Table 5). The values used in the reference run of the model represented the average estimates of harvest efficiency derived from the above sources.

Table 4. *Estimates of harvest efficiency for forests in the USSR*

Estimate	Forest type	Source
20.5–25	Boreal	Shcherbakov (1977)
45–60	Pine	Shcherbakov (1977)
36–44	Boreal	Shcherbakov (1977)
33.6–43.2	Boreal	Gorovoy and Shlykov (1978)
60	undefined	Barr (In press)
34	Deciduous	Tseplyaev (1965)
40.5	Boreal	Tseplyaev (1965)
46.5	Pine and Spruce (Boreal)	Tseplyaev (1965)
50.1	Pine	Vasil'ev (1973)

All units are mtC per hectare.

Table 5. *Data used in the terrestrial carbon model to define changes in carbon of biota of primary forest during harvest and regrowth of Soviet forests*[a]

	Temperate deciduous forest	Boreal forest
Carbon in vegetation of undisturbed forests (10^6 g/ha)[b]	135	90
Carbon in harvested wood (10^6 g/ha)	30 (40)	35 (50)
Carbon in slash	8 (95)	9 (40)
Carbon in live vegetation left on site at time of harvest (10^6 g/ha)	97 (0)	46 (0)

[a] Numbers in brackets are those for industrial harvest. Appearance of a single value indicates that this value is used to define the response curves for both non-industrial and industrial harvest.

[b] Values derived from data of Rodin and Basilevitch (1967).

2.2.2. Response of ecosystem carbon pools to forest harvest. Vegetation. When forests are harvested, some of the cut vegetation is removed from the site (products) and some is left on the site at harvest (slash). The slash left on site, including stumps, roots, branches, leaves, and other debris, undergoes decay, assumed exponential in the model (Fig. 1c). The amount of live vegetation on site following harvest was assumed to be zero in forests harvested commercially because clear-cutting is the dominant industrial harvest practice in the USSR (Sutton, 1975; Zuchov, 1976; Eronen, 1982; Blandon, 1983). For non-industrial harvest, the amount of live vegetation left on site was assumed to be all but the amount taken as products (the bole and branches of the tree) and the amount of slash associated with the products (the stump and roots). These proportions were determined using information about the distribution of biomass in trees in Rodin and Bazilevich (1967) (cf. section 2.1.2).

Soil. For the reference run of the model we assumed that soil carbon pools were unaffected by harvest and regrowth cycles. This assumption represented a significant change from our earliest analyses where we assumed a 50% reduction in the organic carbon of soils (Houghton et al., 1983).

Decay of woody materials. Wood products were assigned to separate decay compartments as described for agriculture (section 2.1.2). All carbon in fuelwood was released to the atmosphere within 1 year of harvest, while carbon in wood used as building material was released within 100 years. The amount of wood assigned to each category changed through time, largely as a result of lower fuelwood demands in recent years (Fig. 2).

Forest regrowth. We assumed that all harvested forests regrew. Forests that recovered to ~80% of their original carbon density were defined as secondary forests (Blandon, 1983). In the model, primary forests, secondary forests, and regrowing forests could be harvested to meet the wood demand in a given year. The hierarchy was such that secondary forests were harvested preferentially. Primary forests were harvested if the demand could not be met by harvest of secondary

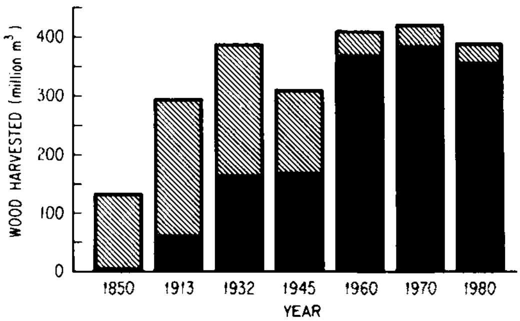

Fig. 2. Wood removal in the USSR for selected years from 1850 to 1980. Striped areas represent non-industrial harvest (primarily fuelwood). Solid areas represent industrial harvest.

forests. If a region had exhausted both secondary and primary forests, a regrowing forest was harvested. The ability to harvest growing forests represented a change in the structure of the MBL/TCM, and it was made to accommodate the intensive harvest pressure on the forests in the western region of the USSR (Blandon, 1983; Barr, in press).

2.3. Other land uses

The effects of grazing, wetland drainage, and irrigation in arid regions were not explicitly considered in this analysis. The response of vegetation and soils to grazing is uncertain, and data on pasture land are difficult to interpret because of variable definitions. Much of the wetlands area of the USSR is in the boreal region where agriculture has not been important. However, a small fraction of peatlands in the boreal region has been drained and the peat used for fuel over the past 200 years (Armentano and Menges, 1986), and we consider the net flux from this wetland drainage later in this analysis.

According to USSR statistical sources on land-use (National Economy of USSR, 1959–1981), irrigated area has never exceeded 6% of the total area sown in the USSR. Since this percent of total agricultural land is small and because the effects of irrigation on carbon balance of ecosystems can result in either a net accumulation or a net loss of soil carbon (Kononova, 1961), we chose not to include this in our analysis.

3. Results and discussion

The reference run of the model showed that the Soviet Union was a small net source of 0.037×10^{15} g C to the atmosphere in 1980. In that year, the harvested forests of the USSR were acting as a net carbon sink of 0.048×10^{15} g, and the agricultural lands and the products pools were acting as net carbon sources of 0.039×10^{15} g and 0.046×10^{15} g, respectively.

In order to compare our results for forests with those of Armentano and Ralston (1980), we calculated the mean value for the period between 1955 and 1975 for the vegetation component of forest ecosystems and used it for the comparison (Table 6). Our estimate of the average annual

Table 6. *Net annual carbon flux between various components of harvested forests in the Soviet Union and the atmosphere*

Source and time interval	Vegetation	Slash decay	Slash burning	Total
MBL/TCM (mean 1955–1975)	−0.136	+0.073	+0.039	−0.024
Armentano and Ralston (1980) (Table 4)	−0.012	—	—	
Armentano and Ralston (1980) (Table 6)	−0.215 to −0.304	—	—	
Armentano and Ralston[1] (1980) (Table 4, modified)	−0.021	—	—	
Armentano and Ralston[1] (1980) (Table 6, modified)	−0.376 to −0.532	—	—	

[1] The original estimate is multiplied by 1.40 to account for the above-ground forest components in addition to merchantable tree boles. This estimate is then multiplied by 1.25 to account for below-ground biomass in addition to above-ground biomass.

All units are in 10^{15} g C. Negative values indicate a net accumulation of carbon on land; positive values indicate a net release of carbon from the land to the atmosphere.

accumulation of carbon in trees over this period was 0.136×10^{15} g. Armentano and Ralston (1980) provided two estimates for accumulation of carbon by Soviet forests between the mid-1950s and the mid-1970s. From their Table 4, we calculated a carbon accumulation in merchantable timber of 0.012×10^{15} g for a period in the mid-1970s. From their Table 6, we calculated an annual accumulation of 0.215 to 0.304×10^{15} g over the period of the mid-1950s to the mid-1970s. Armentano and Ralston (1980) also provided expansion factors to account for additional above-ground non-merchantable biomass (1.40) and below-ground biomass (1.25). If we apply these factors, their estimates are increased to 0.021×10^{15} g C and 0.376 to 0.532×10^{15} g C, respectively (Table 6). Our estimate for the carbon flux to vegetation lies between the estimates provided by Armentano and Ralston (1980).

When we consider, in addition to regrowing vegetation, the burning and decay of slash, our estimate of carbon flux from Soviet forest ecosystems changes from an annual carbon sink of 0.136×10^{15} g to an annual carbon sink of 0.024×10^{15} g during the two decades (Table 6). This suggests that these forests have been neither accumulating nor losing much carbon in the interval between the mid-1950s and the mid-1970s as a result of forest harvest and regrowth. When agricultural expansion and the decay of wood products are also included in the analyses, the estimate of the flux of carbon for the Soviet Union becomes a small net release to the atmosphere, 0.037×10^{15} g in 1980.

3.1. *Results of changes in the input data of the regional model for the USSR*

Because the data used in some parts of the model were based on assumptions with only qualitative information (e.g., more-or-less rather than 10%-more-or-20%-less), we made a series of changes in the data to determine the degree to which our estimates of flux were affected by these assumptions. Of the many possible changes we could have made to the input data, changes were made where the data or assumptions were most questionable, and where we suspected that a change would most affect the 1980 estimate of carbon flux. We did not make changes that would have required substantial changes in the structure of the model itself. The consequences of these changes are discussed below.

Results of the additional runs of the model are shown in Table 7 with the results of the reference run. The estimates of carbon flux for 1980 range between 0.007×10^{15} g and 0.103×10^{15} g. The net flux was always a net release of carbon from the land to the atmosphere, albeit in some cases a very small one.

3.1.1. Carbon pools. We substituted for the values used in the reference run (Tables 2 and 5) the biomass estimates of Olson et al. (1983) and the soil carbon estimates of Olson, given in Richards et al. (1983). This resulted in a decrease in the release of carbon to the atmosphere in 1980 to 0.011×10^{15} g (Table 7). The biomass values given by Olson et al. are similar to the values we used (Table 2), but the soil carbon values for grasslands and boreal systems are substantially lower than the estimates used in the reference run. Since the biomass values were similar, there is no substantial difference in the forest harvest or the product decay components in this run as compared to the reference run. Most of the change is seen in the value of carbon flux due to agricultural clearing and abandonment. This is because a large proportion of the land in agriculture is cleared from grassland ecosystems, and it is for this ecosystem that the values for soil carbon given by Olson (Richards et al., 1983) differ most from the estimate used in our reference run.

For the reference run we assumed that the carbon mass in the vegetation and soils of abandoned agricultural land does not recover completely. Data to support this assumption are few, although it seems reasonable. When we changed this assumption to allow complete recovery, there was only a small reduction in the estimated flux of C to the atmosphere in 1980 (0.032×10^{15} g C).

In the reference run of the model, no carbon was lost from forest soils as a result of either commercial or non-commercial forest harvest. Many authors have noted the loss of carbon from forest soils following clear-cutting, although the degree to which the carbon stocks of forest soils are affected and the length of time required to restore the initial conditions as the forest regrows, may differ. For example, Tamm and Petterson (1969) reported the frequent obser-

Table 7. *Net carbon flux between the terrestrial carbon stocks in the Soviet Union and the atmosphere in 1980*

	Agricultural clearing and abandonment	Forest harvest	Products decay	Net flux
Reference	+39	−48	+46	+37
Olson biomass and soil carbon values[1]	+21	−52	+42	+11
Full recovery of forest biomass and soil carbon following harvest[2]	+35	−49	+46	+32
Soil carbon loss following commercial forest harvest[3]	+39	−15	+46	+70
Faster soil and vegetation recovery time[4]	+46	−85	+46	+7
High agriculture clearing rates[5]	+53	−48	+50	+55
Lower forest harvest efficiency[6]	+39	+20	+44	+103
Higher forest harvest efficiency[7]	+39	−58	+46	+27
Burning of slash following harvest[8]	+39	−38	+46	+47
Increased fuelwood harvest[9]	+39	−77	+54	+16
Allocation of a larger fraction of wood products to the 1000-yr decay pool[10]	+39	−48	+34	+25

[1] Values for biomass and soil carbon were taken from Olson et al. (1983) and Richards et al. (1983), respectively and were substituted for the reference run values for forests and forest and grassland soils. A value of 100 mtC per ha and 87 mtC per ha were used for deciduous and boreal forests, respectively. The value for grassland biomass given by Olsen et al. (1983) was equal to that in our reference run. Soil carbon values for deciduous forest, boreal forest, and grasslands were changed to 120 mtC per ha (both forest types) and 80 mtC per ha, respectively.

[2] Reference run forests recover to 80% of their original biomass. Recovery is 100% in this run.

[3] The soils under forests that are harvested commercially lose 15% of the original soil carbon stock following harvest.

[4] Time for recovery of vegetation and soils is one half of the time in the reference data set.

[5] The values for land in agriculture were increased by 25%.

[6] Forest harvest efficiency decreased to 20 mtC per ha and 25 mtC per ha for deciduous and boreal forests, respectively.

[7] Forest harvest efficiency increased to 50 mtC per ha and 60 mtC per ha for deciduous and boreal forests, respectively.

[8] Fraction of slash created by industrial harvest allocated to the 1-yr decay pool was increased from 0 to 60%.

[9] Fuelwood harvest increased by a factor of four throughout the time series.

[10] 50% of the carbon in industrial wood assigned to the 100-yr decay pool was allocated to the 1000-yr decay pool.

Units are 10^{12} g C. Negative values denote net accumulation of carbon on land. Positive values denote net release of carbon from the land.

vation of a net loss of soil humus following harvest in the northern boreal forests of Europe. Similar observations have been made for deciduous forests in North America and Japan (e.g., Covington, 1981; Kawaguchi and Yoda, 1986). Therefore, a run of the model was made to examine the carbon flux resulting from a 20% loss of initial soil carbon content with commercially harvested forests. The change resulted in an increase in the carbon flux to the atmosphere to 0.070×10^{15} g in 1980. The loss of soil carbon from newly harvested forests was partially offset by the accumulation of carbon in regrowing forests. The net result was a smaller carbon sink in the forest harvest component of the model in this run as compared to the reference run.

3.1.2. Rate of recovery from disturbance. The lowest estimate of the flux of carbon from terrestrial systems to the atmosphere in 1980 (0.007×10^{15} g) resulted from a change in the recovery time for vegetation and soils. In this run, we increased the rate of vegetation and soil recovery by a factor of two; grassland soil and vegetation recovered within 5 years, deciduous and boreal forests recovered within 20 and 40 years, respectively. This change had no effect on the products pool, but the flux of carbon from terrestrial systems to the atmosphere as a result of agricultural clearing and abandonment was increased in 1980. The faster recovery time in this run led to fewer recovering systems in 1980 due to previous abandonment and thus to a greater release from current agricultural activities. In the forest harvest component of the model the faster recovery time resulted in a larger amount of carbon per unit time being accumulated on land, and therefore the total flux of carbon to the forests was larger in this run than in the reference run. The area harvested was greater than the area abandoned, and so the overall effect was to reduce the net release of carbon in 1980.

3.1.3. Clearing and harvesting rates. There was a small increase in the estimate of carbon flux to the atmosphere in 1980, to 0.055×10^{15} g, when we doubled the clearing rate for agriculture. This change was made because for the reference run we were conservative about the definition of land in agriculture, and thus conservative in our estimate of the rate of clearing to produce agricultural plots.

The alteration that created the largest net carbon flux to the atmosphere, 0.103×10^{15} g in 1980, was the decrease in the harvest efficiency for commercial or industrial harvest (Table 7). In this run, the forest harvest efficiency was reduced from 40 mtC per hectare to 20 mtC per hectare and from 50 mtC per hectare to 25 mtC per hectare for deciduous forests and boreal forests, respectively. These values represented the low end of the range of estimates of harvest efficiency for Soviet forestry as reported in the literature (Table 4). The change in forest harvest efficiency reversed the role of harvested forests from a carbon sink of 0.048×10^{15} g to a source of 0.020×10^{15} g C. This is because the harvest efficiency and the yearly wood demand determined the amount of forest land to be clear cut. The harvest efficiency in this run was reduced by one half, and, therefore, the area of forest harvested in any given year was doubled to meet the demand for industrial wood. In addition, the lower harvest efficiency increased the amount of slash left to decay. The release of carbon from the large pool of slash and the large area of disturbed forest that resulted from the lower efficiency offset the carbon gained from regrowing forests (even though this area was also doubled), resulting in a net release of carbon from harvested forest in 1980.

Increasing the harvest efficiency had the reverse effect. It decreased the net carbon flux to the atmosphere to 0.027×10^{15} g in 1980, when the amount of wood removed per hectare was increased from 40 mtC per hectare to 50 mtC per hectare and from 50 mtC per hectare to 60 mtC per hectare for deciduous and boreal forests, respectively, in the commercial forest harvest portion of the model.

3.1.4. Fate of slash. A small increase of carbon flux to the atmosphere in 1980, to 0.047×10^{15} g, occurred when the model was altered so that 60% rather than none of the slash created during commercial forest harvest was burned on site immediately following the harvest. This change was made because in some areas of the USSR it is common to burn slash prior to replanting.

3.1.5. Fuelwood demand. There is considerable uncertainty about the amount of wood used as fuel, particularly in the rural areas of the USSR (Armentano and Loucks, 1985). The data used in the reference run must be considered conservative. A quadrupling of fuelwood demand caused a small decrease in the net flux of carbon in 1980, to 0.016×10^{15} g C, because of the historical pattern of fuelwood use. Fuelwood use has been decreasing over time, so quadrupling its use increases the absolute disparity between historical and current use. This in turn increases the area of regrowing forests in 1980 and, hence, increases the net annual storage of carbon in 1980.

3.1.6. Decay of harvested wood products. For the reference run, we allocated wood to various decay pools based on descriptions of how the Soviet peoples use wood products (Blandon, 1983; Barr, in press). The decay times for various product pools were "order-of-magnitude" estimates. Therefore, we felt a test of these assumptions was warranted. When half of the wood products originally allocated to the 100-year decay pool were transferred to the 1000-year decay pool, the result was a small decrease in the estimate of carbon flux to the atmosphere in 1980, to 0.025×10^{15} g.

3.1.7. Summary. The changes made in the data set for the USSR produced a relatively small range of estimates of carbon flux from the USSR in 1980. They did not change the conclusion presented earlier regarding the flux of carbon from the ecosystems in the Soviet Union: *the net flux of carbon between the land and the atmosphere in 1980 as a result of land-use change was very small relative to net carbon fluxes to the atmosphere from fossil fuel burning (Rotty and Masters, 1985)* *and from land-use change in the tropics (Houghton et al., 1985) in that year.*

3.2. *Other ecosystems and assumptions not considered*

There are several land uses we did not consider in this analysis. With regard to irrigated lands and pasture lands, we expect that their effects would decrease or show no net change relative to the reference estimate of carbon flux from the USSR presented in Table 7. Since the area of land in each of these categories is significantly smaller in size than the area we estimated to be farmed or harvested, we expect that the additional estimates produced by the inclusion of these two land uses would lie within the range of estimates shown in Table 7.

The drainage of wetlands for agriculture and the combustion of peat might be expected to increase the calculated flux. According to Armentano and Menges (1986) the drainage of peatlands in agricultural areas of the USSR has changed the "sink strength" of these peatlands from approximately 0.018×10^{15} g C in the mid-1800s to about 0.002×10^{15} g C in 1980. The use of peat as a fuel in the USSR resulted in a release of between 0.032 and 0.039×10^{15} g C in 1980. In 1980, then, the peatlands in and near the urban and agricultural areas of the USSR were a small source of carbon to the atmosphere. The net carbon balance of the more remote peatlands of the boreal zone in the USSR is unknown. It is possible that these lands may be functioning as net accumulators of carbon, and that the rate of accumulation is high enough in these remote peatlands to compensate for the net release of carbon from the peatlands undergoing change in the more populated areas of the USSR.

3.3. *Carbon flux for the temperate and boreal zones of the northern hemisphere*

We have combined our new results for carbon flux from the USSR with modified estimates for other regions of the temperate zone including North America, the Pacific Basin, Europe, North Africa, the Middle East, and China. The values presented for all regions except the USSR are based on data given in Houghton et al. (1983) with one exception. The original data set assumed a 50% loss of carbon from the upper meter of the soil following disturbance. In the analysis reported here we assumed a 20% loss of carbon from soils brought under cultivation and no loss from soils associated with harvested forests.

If we consider only the carbon flux between forest vegetation and the atmosphere, the new results show that the temperate zone forests were functioning as a 0.973×10^{15} g sink in 1980 (Table 8). This number is directly comparable to the estimates made by Armentano and Ralston (1980) and Johnson and Sharpe (1983) who con-

Table 8. *Net flux of carbon between the temperate and boreal ecosystems of the northern hemisphere and the atmosphere in 1980*

Land use	USSR	North America	Europe	Other*	Total
Forest harvest and afforestation					
Regrowing vegetation	−154	−407	−225	−187	−973
Slash decay	82	301	143	97	623
Burned material	24	6	16	46	92
Subtotal	−48	−100	−66	−44	−258
Expansion and abandonment of croplands	39	−4	−26	19	28
Decay of 10- to 1000-year wood products	46	96	51	12	205
Total**	37	−8	−41	−13	−25

* China, Japan, North Korea, South Korea, Oceania, Northern Africa, and the Middle East.

** These totals differ from those reported recently by Houghton et al. (1987) because in that analysis the soils of harvested forests were assumed to undergo a temporary, 20% reduction in organic matter. The difference changes the total flux reported here from a net storage of 25×10^{12} g C in 1980 to a net release of 105×10^{12} g.

Units are 10^{12} g C. Negative values denote a net accumulation of carbon on land. Positive values denote a net release of carbon from land.

cluded that the temperate zone forests were functioning as carbon sinks of 1.0 to 1.2×10^{15} g and 1.6 to 1.9×10^{15} g, respectively. As described above for the forests in the Soviet Union, our results concerning the role of forest vegetation in the carbon balance are not appreciably different from either of these studies. We do, however, draw a different conclusion regarding the net flux of carbon from the temperate and boreal zones of the northern hemisphere in 1980, when we include agricultural clearing and the decay of products in our analysis.

The estimates of net carbon flux between the major terrestrial carbon pools and the atmosphere for each region in 1980 appear in Table 8. The loss of carbon from terrestrial systems to the atmosphere as a result of agricultural clearing we estimate as 0.028×10^{15} g. Forest harvest (including tree regrowth, slash decay and burning) resulted in a net flux of carbon from the atmosphere to the vegetation of 0.258×10^{15} g in 1980. Product decay released 0.205×10^{15} g C to the atmosphere. We estimate that the total net flux of carbon from the atmosphere to the land of the temperate and boreal zones of the northern hemisphere was thus 0.025×10^{15} g in 1980.

4. Conclusions

We have provided a refined estimate of the carbon exchange between forest and grassland ecosystems of the USSR and the atmosphere, and a new estimate of carbon exchange for the northern temperate and boreal zones in 1980. Our estimates indicate that there was a small net release of carbon to the atmosphere from the USSR in 1980 due to land-use change, and a small net uptake of carbon by the temperate and boreal zones of the northern hemisphere as a whole.

Our estimate of the flux of carbon between the atmosphere and forest vegetation is within the range of estimates made by Armentano and Ralston (1980) and Johnson and Sharpe (1983). However, our conclusion about the role of temperate and boreal forests in the global carbon cycle differs due to our inclusion of other ecosystem components and other types of land-use change.

The results of our sensitivity analysis suggest that the estimate of carbon exchange between the land and the atmosphere for the USSR in 1980 due to land-use change will not vary much above or below zero with further refinements to the existing model. However, there are data limitations still to be resolved, especially with regard to the amount and rate of decay of slash left in forests following harvest and the rate of decay of harvested wood products. Further analysis of the role of the USSR in the net carbon balance between the land and the atmosphere will require careful consideration of ecological information and forestry statistics that apparently exist (Armentano, personal communication) but are not readily available to non-Soviet scientists. Finally, the possibility of change in the natural processes of carbon exchange in areas not subject to human use also needs to be considered.

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