Teuchert's. Each of his inventories of α-emitters created by neutron capture was therefore reduced by the ratio of the inventories (Teuchert's/Rütten's) of the nearest precursor listed by both authors on the dominant neutron buildup chain leading to the isotope in question. This procedure leads to a slight overestimate of the HTGR spent fuel α-activity and ^{239}Pu inventory.
8. We ignore the fissile isotope ^{241}Pu here since it has such a short half-life (13 years). The critical spherical mass of ^{239}Pu diluted with up to an equal amount of nonfissile ^{240}Pu + ^{242}Pu in a metallic α-phase surrounded by a thick uranium neutron reflector is 4 to 5 kg. The complete fissioning of 1 kg of heavy metal would yield energy approximately equal to the explosion of 20,000 tons of high explosive [T. B. Taylor, *Ann. Rev. Nucl. Sci.* **25**, 407 (1975)].
9. Some of the ^{238}U is transmuted by neutron capture and subsequent radioactive transformations into ^{239}Pu, some of which is fissioned in place. Thorium-232 is similarly converted into fissile ^{233}U. Pure ^{233}U is weapons-usable but differs from ^{239}Pu in that, like ^{235}U, it will be "isotopically denatured" for nuclear-weapons purposes as a result of its dilution by the ^{238}U in the fuel [see (*1*)].
10. See figure 7D1 in (*2*), p. S116.

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Carbon Budget of the Southeastern U.S. Biota: Analysis of Historical Change in Trend from Source to Sink

Abstract. *Documentation of settlement patterns and deforestation in the southeastern United States allows evaluation of regional carbon dynamics since A.D. 1750. From 1750 to 1950, the Southeast was a net source for carbon at an average rate of 0.13 gigaton per year. Only in the past 20 to 30 years has increased productivity of commercial forests resulted in a sink for atmospheric carbon dioxide of 0.07 gigaton per year.*

The observed increase in atmospheric CO_2 over preindustrial levels has been ascribed largely to burning of fossil fuels (*1*) and to forest clearing and burning (*2*). We examined the carbon dynamics of the southeastern United States over the past two centuries in order to estimate the presettlement carbon pool, document carbon losses from deforestation, and determine whether this region is a source or a sink of atmospheric CO_2. Such reconstructions provide insight into the source or sink strength of the terrestrial biosphere through time and suggest a future trajectory of carbon dynamics under given conditions of land use (*3*).

U.S. agricultural census statistics (*4*) and forest survey records (*5*) provide data for determining changes in land use during the settlement of Alabama, Arkansas, Delaware, Florida, Georgia, Kentucky, Louisiana, Maryland, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia, an area of 1,405,737 km^2 (*5*), or 12 to 16 percent of the world's temperate forest area (*2*). Before settlement (A.D. 1750) (Fig. 1), 91.6 percent of the land area of these states was forest, 3.8 percent was prairie, and 4.6 percent was marsh (*6*). Forests and native prairies were rapidly converted to agricultural land as settlers pushed the frontier westward during the late 1700's and early 1800's (*4, 7*). By 1880, less than 35 percent of the Southeast remained in virgin forest—principally in the southern Appalachian Mountains, Mississippi River bottomlands, Ozark and Ouachita mountains of Arkansas, and Gulf Coastal Plain pinelands (*8*). The coastal plain and southern Appalachian forests were logged between 1880 and 1920 (*9*). Southeastern bottomland forests are expected to be converted largely to cropland before 1990 (*10*).

However, since 1950, clearing of the bottomlands has been offset by upland old-field succession, particularly in the Piedmont (*11*). Intensively managed commercial (secondary) forest holdings have increased in size as farm woodlots have diminished (Fig. 1). Today, virgin forests occupy less than 1 percent of their former area (Fig. 1), persisting only in small isolated stands.

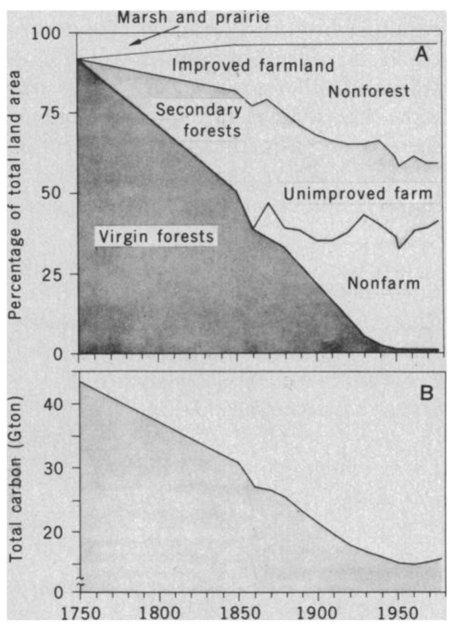

Fig. 1. (A) Land-use history and (B) changes in total carbon for the southeastern United States, A.D. 1750 to 1977. The areas in forest and rainforest for 1950 are based on the natural vegetation map of Shantz and Zon (*6*). The data for 1850 to 1950 are from (*4*), with improved farmland defined as cleared land in cultivation or pasture and unimproved farmland defined as including pastured and unpastured woodlots. The data for 1952 to 1977 are based on inventories by the U.S. Forest Service (*5*), with the nonfarm secondary forest category including commercial forests in national and state forests, paper and lumber company holdings, and other private ownerships (excluding farmland).

Estimates of timber volume for virgin forests of 1880 (*8*) and for secondary forests of 1952, 1962, 1970, and 1977 (*5*) were used to estimate total live (aboveground and belowground) biomass and total carbon (including detrital soil carbon) on forested land (*12*). The aboveground biomass of the virgin forests averaged 343 Mg/ha, total live biomass was estimated as 460 Mg/ha, and total carbon averaged 327 Mg/ha (*12*). The aboveground biomass figure, estimated from Sargent (*8*), is less than that estimated by Whittaker (*13*) for undisturbed cove hardwood forests (500 to 600 Mg/ha), but greater than that for old-growth commercial forests of the southern Appalachians (176 Mg/ha) (*14*). The cove forests examined by Whittaker represent an upper limit, a potential not attained uniformly across the presettlement landscape because of various disturbances (*15*). Biomass on agricultural land was calculated by using the production values of DeSelm (*16*). Land clearing and cultivation were estimated to diminish soil carbon by 40 percent (*16, 17*).

From 1750 to 1960, total carbon in soil and vegetation decreased nearly linearly from 43.3 to 15.1 Gton (Fig. 1 and Table 1). Replacement of nearly 55 percent of the original forest land with secondary forests did not restore carbon reserves depleted by extensive agricultural utilization over that 210-year period. With an average release of 0.13 Gton of carbon per year (Table 1), the southeastern United States has served as a major carbon source to the atmosphere during most of the time since the Industrial Revolution.

Between 1952 and 1977, the aboveground biomass on commercial forest land increased from 53.2 to 72.2 Mg/ha (*5*). This gain reflects the increase in holdings of intensively managed forest land (Fig. 1), on which net annual growth has increased due to reforestation of nonstocked areas and control of species composition and stand density (*10*). Increased storage of wood in planted or early successional commercial forest stands has resulted in a net increase of yield over harvest in the past 20 to 30 years (*18*). This, in the context of overall stabilization of forest and nonforest land areas, has reversed the trend in carbon

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Table 1. Carbon in gigatons for virgin forest, secondary forest, and nonforest land of the southeastern United States, A.D. 1750 to 1977, with projections to 2030.

Year	Virgin forest	Secondary forest	Nonforest land	Total carbon	Carbon flux (gigatons per year)
1750	42.6	0.0	0.7	43.3	−0.13
1850	23.4	5.8	1.6	30.8	−0.37
1860	17.8	7.3	2.0	27.1	−0.04
1870	16.7	8.2	1.8	26.7	−0.13
1880	15.3	7.9	2.2	25.4	−0.21
1890	12.5	8.3	2.5	23.3	−0.17
1900	10.0	8.8	2.8	21.6	−0.18
1910	7.4	9.5	2.9	19.8	−0.16
1920	4.9	10.3	3.0	18.2	−0.14
1930	2.6	11.2	3.0	16.8	−0.07
1940	1.2	12.0	2.9	16.1	−0.09
1950	0.7	11.0	3.5	15.2	−0.01
1960	0.5	11.2	3.4	15.1	+0.04
1970	0.5	11.5	3.5	15.5	+0.07
1977	0.5	12.0	3.5	16.0	
2030*	0.5	15.8	3.5	19.8	+0.07
2030†	0.5	10.8	4.0	15.3	−0.01
		Net change			
1750–1960	−42.1	+11.2	+2.7	−28.2	−0.13
1960–1977	0.0	+ 0.8	+0.1	+ 0.9	+0.05
1960–2030*	0.0	+ 4.6	+0.1	+ 4.7	+0.07
1977–2030†	0.0	− 2.8	+0.5	− 0.7	−0.01

*Assuming that the land area of virgin and secondary forests and nonforest land is the same as in 1977 and that productivity of commercial (secondary) forests increases at the same rate as in 1970 to 1977 (1.78 Mg of live biomass per hectare per year). †Assuming that the land area of virgin forest is the same as in 1977, that the area of secondary forest decreases by 10 percent as cultivated and urban land increases, and that productivity of commercial forests remains at 1977 levels.

flux. Explicit treatment of the proportion of wood carbon in such products as paper and lumber would slightly lower the estimated loss of biospheric carbon to the atmosphere before 1950 and would increase the net gain after 1950 (*19*).

Since at least 1960, the Southeast has functioned as a carbon sink (Fig. 1 and Table 1). These results support the contention of Armentano and Ralston (*18*) that forests in eastern North America today are sinks for carbon rather than sources. However, in the Southeast, only 0.07 Gton of carbon is being restored annually, or half the rate at which it was lost. This amounts to a recovery thus far of only 3.1 percent of the carbon lost from 1750 to 1950.

The balance between source and sink is sensitive to changes in land use. Under the assumptions given in Table 1 (footnotes), a 10 percent decrease in the area of commercial forests changes the Southeast from a carbon sink to a small source. Only with sustained high productivity, stabilization or increase in commercial forest area, and greater net growth can the terrestrial system of the Southeast continue to gain carbon.

Change in land use is the dominant factor controlling the carbon budget (*3*). Because of the difference in biomass between virgin and secondary forests, managed reforestation can never completely offset the losses incurred by initial deforestation. However, carbon loss resulting from deforestation of one area could be offset by reforestation elsewhere. Until these forest growth patterns are known for specific regions, there is no basis for a final judgment on whether the terrestrial biosphere is acting as a source or sink for atmospheric CO_2.

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References and Notes

1. C. F. Baes, Jr., H. E. Goeller, J. S. Olson, R. Rotty, *Am. Sci.* **65**, 310 (1977); B. Bolin, *Sci. Am.* **223**, 125 (September 1970).
2. B. Bolin, *Science* **196**, 613 (1977); G. M. Woodwell, R. H. Whittaker, W. A. Reiners, G. E. Likens, C. C. Delwiche, D. B. Botkin, *ibid.* **199**, 141 (1978); G. M. Woodwell, *Sci. Am.* **238**, 34 (January 1978); J. A. S. Adams, M. S. M. Mantovani, L. L. Lundell, *Science* **196**, 54 (1977); C. S. Wong, *ibid.* **200**, 197 (1978).
3. W. S. Broecker, T. Takahashi, H. J. Simpson, T. H. Peng, *Science* **206**, 409 (1979).
4. U.S. Bureau of the Census, *7th–17th Decennial Census of the United States* (Government Printing Office, Washington, D.C., 1854, 1862, 1872, 1885, 1897, 1902, 1913, 1922, 1933, 1943, 1952).
5. U.S. Forest Service, *Forest Statistics of the U.S.: 1977* (Government Printing Office, Washington, D.C., 1978).
6. H. L. Shantz and R. Zon, *Map of Natural Vegetation of Contiguous U.S.* (Advance Sheet No. 6, Government Printing Office, Washington, D.C., 1924).
7. F. J. Marschner, *U.S. Dep. Agric. Agric. Handb. No. 153* (1959).
8. C. S. Sargent, *Report on the Forests of North America* (Government Printing Office, Washington, D.C., 1884).
9. R. M. Harper, *Ala. Geol. Surv. Monogr. 8* (1913); H. B. Ayres and W. W. Ashe, *U.S. Geol. Surv. Prof. Pap. No. 37* (1905).
10. U.S. Department of Agriculture, *An Assessment of the Forest and Range Land Situation in the United States* (Government Printing Office, Washington, D.C., 1979).
11. E. V. Brender, *J. For.* **72**, 34 (1974).
12. Carbon in aboveground + belowground biomass + soil carbon in megagrams per hectare = Ei) total timber volume in cubic feet per acre × (ii) 1.34 × (iii) 1.16 × (iv) 517.16 × (v) 0.028/0.4047 × 10^{-3} × (vi) 1.04 × (vii) 1.34 × (viii) 0.496 + (ix) 07.7. (i) Virgin forests: Highest mapped density of southeastern forests in 1880 was class 7 (50 to 100 cord/acre) (*5*). An average of 75 cord/acre was used to estimate forest density (cords per acre × 79 = cubic feet per acre) [J. S. Spencer, Jr., and H. W. Thorne, *U.S. Dep. Agric. For. Serv. Res. Bull. NC-15* (1972)]. Secondary forests: Total timber volume includes growing stock volume, rough and rotten timber, and salvageable dead timber ≥ 12.5 cm in diameter at breast height on commercial forest land in 1952, 1962, 1970, and 1977 (*5*). Estimates from 1952 were then applied to areas of secondary forest from 1750 to 1950. (ii) Whole merchantable tree volume = timber volume × 1.34 averaged for softwoods and hardwoods [N. D. Cost, *U.S. Dep. Agric. For. Serv. Res. Note SE-266* (1978); J. P. McClure, N. D. Cost, H. A. Knight, *U.S. Dep. Agric. For. Serv. Res. Pap. SE-191* (1979)]. (iii) Saplings (2.5 to 12.5 cm in diameter at breast height) constitute 14 percent of forest volume in South Carolina. Total aboveground woody volume = whole merchantable tree volume × 1.16 (McClure *et al.*, *ibid.*). (iv) Average wood density (dry weight) of all eastern North American tree species is 517.16 kg/m^3 [U.S. Forest Products Laboratory, *Wood Handbook: Wood as an Engineering Material* (Government Printing Office, Washington, D.C., 1974)]. (v) Metric conversion factor: cubic feet per acre × kilograms per cubic meter × (0.028 m^3/ft^3)/(0.4047 ha/acre) × 10^{-3} = megagrams per hectare [*Standard for Metric Practice* (American Society for Testing and Materials, Philadelphia, Pa., 1975)]. Aboveground wood volume × wood density = aboveground woody biomass. (vi) Foliage averages 3.6 percent of the total aboveground biomass in the Walker Branch watershed, Tennessee [W. F. Harris, R. A. Goldstein, G. S. Henderson, in *IUFRO Biomass Studies*, H. E. Young, Ed. (International Union of Forest Research Organizations, Orono, Maine, 1973), pp. 41–64]. Aboveground woody biomass + foliage = aboveground woody biomass × 1.04. (vii) For the diameter classes encountered in temperate forests of the southeastern United Staes, belowground woody biomass (roots) is 25 percent of total biomass [D. Santantonio, R. K. Hermann, W. S. Overton, *Pedobiologia* **17**, 1 (1977)]. Total biomass = total aboveground biomass × 1.34. (viii) Carbon is 49.6 percent of forest biomass [D. E. Reichle, B. E. Dinger, N. T. Edwards, W. F. Harris, P. Sollins, in *Carbon and the Biosphere*, G. M. Woodwell and W. V. Pecan, Eds. (National Technical Information Service, Springfield, Va., 1973), p. 345]. (ix) Soil detrital carbon (including litter), averaged from six temperate U.S. forest ecosystems, is 97.7 Mg/ha [W. H. Schlesinger, *Annu. Rev. Ecol. Syst.* **8**, 51 (1977)]. This value was applied to both primary and secondary forests, since carbon recovery in litter and soil is rapid in experimentally deforested watersheds reverting to secondary forest [F. H. Bormann and G. E. Likens, *Pattern and Process in a Forested Ecosystem* (Springer-Verlag, New York, 1979), p. 22].
13. R. H. Whittaker, *Ecology* **47**, 103 (1966).
14. D. M. Sharpe and W. C. Johnson, personal communication.
15. F. H. Bormann and G. E. Likens, *Am. Sci.* **67**, 660 (1979); H. R. Delcourt and P. A. Delcourt, *Ecology* **58**, 1085 (1977); S. Z. Guffey, *Tenn. Anthropol.* **2**, 121 (1977); see also (*11*).
16. Average production data for row and cereal crops, hay, and pasture in Tennessee during 1959 and 1964 was 4.51 Mg/ha [H. R. DeSelm, *Tennessee Productivity Profiles, Eastern Deciduous Forest Biome Memo Report 71-13* (1971)]. Carbon content of herbaceous plants is 45 percent of the biomass [G. M. Woodwell and R. H. Whittaker, *Am. Zool.* **8**, 19 (1968)].
17. Loss of soil carbon after cultivation of forested land was estimated as 40 percent of the original carbon pool [H. Jenny, *Factors of Soil Forma-*

tion (McGraw-Hill, New York, 1941), p. 253]. Total carbon on nonforest land = 60.65 Mg/ha.
18. T. V. Armentano and C. W. Ralston, *Can. J. For. Res.* **10**, 53 (1980); C. W. Ralston, *Science* **204**, 1345 (1979).
19. For the Southeast in 1976, total wood storage products = 3.42×10^9 ft^3 = 0.025 Gton of stored carbon (5). At this rate, the total carbon gain would be increased 20 percent by A.D. 2030 but total carbon would amount to only 6.38 Gton for the combined biomass and wood products.
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Episodic Ice-Free Arctic Ocean in Pliocene and Pleistocene Time: Calcareous Nannofossil Evidence

Abstract. *Today's ice cover (2 to 4 meters thick) over the Arctic Ocean provides a shadow that prevents coccolithophorids (photosynthetic, planktonic algae) from living there. Sparse, low-diversity, but indigenous coccolith assemblages in late Pliocene to mid-Pleistocene (but not Holocene) sediments imply deep penetrating warm currents or an ice-free Arctic Ocean, or both, as those layers were being deposited.*

The climatic history of the Arctic has been a matter of debate ever since the study of its sediments commenced. The early Soviet investigators (*1*), using "radium distribution," estimated that the rates of sedimentation were ~ 1.2 to 2 cm per 10^3 years and interpreted the uppermost foraminiferal-silty layer (10 to 15 cm thick), which covers vast areas of the sea floor, as representing postglacial deposits and the underlying foraminifera-poor beds as representing colder, glacial sediments (*1*). However, uranium series isotope dates (*2*) and the magnetic stratigraphy of Lomonosov Ridge and Alpha Cordillera cores (*3, 4*) indicate that the sedimentation rates are only 1 to 3 mm per 10^3 years. Herman (*5, 6*) has argued that the "foram-poor" layers deposited intermittently during the Brunhes magnetic epoch and throughout most of the Matuyama epoch represent milder periods than those of today, possibly seasonally ice-free intervals. Clark (*7*), on the other hand, has held that the Arctic has been covered continuously with perennial sea ice from middle Cenozoic time to the present, and that the foram-poor layers were not typical of intervals milder than the present but actually were laid down during times when the ice cover was thicker than today's, which ranges from 3 to 4 m at winter's end to 2 to 3 m at summer's end (*8*).

Field observations and theoretical calculations indicate that sea ice reaches an equilibrium thickness at about 4 m (*9*). Furthermore, evidence exists for much drier climates during the peaks of glacial periods, probably due to a sharp drop in evaporation, reduced snowfall, and reduced moisture when ice covered extensive land and ocean (*10*), precluding the existence of a thicker ice cover than today's.

We report here on the discovery of calcareous nannofossils (skeletal remains of planktonic unicellular photosynthetic golden brown algae) in sedimentary cores from the crest and flank provinces of the Alpha Cordillera raised by Lamont-Doherty Geophysical Observatory (LDGO) scientists, on drifting ice platforms (Table 1 and Fig. 1). This discovery supports the hypothesis of an episodic warmer, possibly ice-free Arctic Ocean. Foraminiferal data and magnetic stratigraphy have been published (*5, 6, 11*) for most cores. Within the time interval of ~ 4.5×10^6 years, recorded in the longest core, three major climatic regimes are recognized, represented here by climatic units I, II, and III (Fig. 1). Thirty-one samples taken from eight cores were examined, six of which contained nannofossils (Fig. 1); these samples were selected from core tops and from downcore levels representative of the three climatic regimes. The earliest unit (III) consists of fairly well sorted manganese micronodule–bearing red clays with small but significant amounts of ice-rafted minerals (*12*). The planktonic foraminifera are dominated by polar, left-coiling *Globigerina pachyderma* complex, some of which are corroded. Benthonic foraminifera are represented by deep-water elements (*5, 6*). Neither coccoliths nor discoasters were found in these red clays. The boundary between units II and III coincides with the Gauss-Matuyama boundary (*6, 11*) (Fig. 1) and is defined by lithological and faunal changes. The change from "red clays" to tan silts with abundant coarse, ice-rafted debris is accompanied by faunal change. The planktonic foraminiferal fauna is dominated by the extant, solution-susceptible *Globigerina egelida* and *G. quinqueloba*, which constitute up to 99 percent of the fauna of the shallower cores (< 2400 m). Today, *G. egelida* inhabits the Labrador Sea during summer and the North Atlantic slope water in winter (*13*). *Elphidium*, endemic to continental shelves, constitutes up to 50 percent of the benthonic foraminiferal fauna, further evidence of the large-scale ice-rafting during the Matuyama. We believe that these changes ~ 2.4×10^6 years ago record a drastic alteration in the oceanographic regime, namely, the initiation of density stratification, a precondition for the formation of sea ice.

One specimen each of *Dictyococcites minutus*, a small cosmopolitan species ranging from Eocene to Pleistocene, and *Discoaster woodringi*, a generalized Eocene to Pliocene representative of the thermophilic discoasters, were found in core T3-67-9 at 238 to 239 cm. They come from the same level in which warm-water planktonic foraminifera were found (*5, 6, 11*) and probably represent Tertiary forms ice-rafted along with *Elphidium* spp. from shallow-water outcrops by drifting ice. The sediments of unit II were deposited during the Matuyama epoch, a time of low global temperatures, milder than those of the following Brunhes epoch (*5, 6, 11, 14*). The boundary between units I and II, defined by both faunal and lithological changes, occurs near the Brunhes-Matuyama boundary (Fig. 1). Five of the six nannofossiliferous samples are within unit I. Another climatic threshold was crossed about 0.9×10^6 years ago when perennial sea-ice cover developed over the Arctic Ocean, as indicated by the first occurrence of a "*G. pachyderma*-rich" layer similar to that being deposited today on the floor of the Arctic basin. Brunhes sediments are composed of alternating foram-rich and foram-poor layers. We interpret the foram-rich layers as representing conditions similar to those prevailing today (perennial sea-ice cover) and the foram-poor layers as indicative of short, mild, possibly seasonally ice-free, lower salinity intervals, comparable to those of the Matuyama epoch. The planktonic fauna of unit I is dominated by the polar left-coiling *G. pachyderma* complex. However, *G. quinqueloba*, which is capable of withstanding low salinities, attains high frequencies near several of the boundaries between foram-rich and foram-poor layers. Benthonic foraminifers are varied, and ice-rafted debris is scattered throughout Brunhes sediments (*6, 11*).

Coccoliths occur very sparsely ($\simeq 1$ per 10^4 silt-size grains) in five foram-poor layers and in one foram-rich sample transitionally above a foram-poor bed (Fig.

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