Reports

Atmospheric Input of Carbon Dioxide from Burning Wood

Abstract. *The atmospheric input of carbon dioxide from burning wood, in particular from forest fires in boreal and temperate regions resulting from both natural and man-made causes and predominantly from forest fires in tropical regions caused by shifting cultivation, is estimated to be 5.7 × 10^{15} grams of carbon per year as gross input and 1.5 × 10^{15} grams of carbon per year as net input. This is a significant amount as compared to the fossil fuel carbon dioxide produced from the utilization of oil, gas, coal, and limestone, and bears on the hypothesis of the enhanced sedimentation of marine detritus as a removal mechanism of excess atmospheric carbon dioxide.*

Earlier work on the anthropogenic production of CO_2 has focused on releases from fossil fuel sources, such as oil, natural gases, and coal, and from limestone (*1*, *2*). The contribution from changes in the land biota arising from forestation, deforestation, and wood burning has been recently emphasized (*2*–*4*). My purpose here is to estimate, in a very speculative way, the importance of forest fires as an additional source of atmospheric CO_2 and to generalize on the total contribution from nonfossil wood burning as an upper limit.

The amount of CO_2 produced by fires on forested and nonforested areas is exceedingly difficult to estimate either because statistics are lacking or because there are uncertainties in the available statistics. However, there exists plenty of scattered information on fire losses. Some Canadian statistics (*5*) on fire losses are shown in Table 1. In Canada, an annual average (1959 through 1968) of 0.433 × 10^{10} m^2 of forested land and 0.458 × 10^{10} m^2 of nonwooded area were burned. Moreover, there is a seasonal variability, with about 90 percent of the area burning during the dry summer months from May to September. There is also a year-to-year variability with million-acre (4 × 10^9 m^2) fires occurring in disastrous years—for example, two such fires in the 1920's, five in the 1930's, four in the 1940's, and a fire that consumed 8 × 10^9 m^2 in British Columbia in the 1950's. In the United States, forest fires burned an average of 1.05 × 10^{11} m^2 $year^{-1}$ prior to 1940 (*6*), with one of the most spectacular fires, the Peshtigo fire in Wisconsin and Michigan in 1870, scorching 1.5 × 10^{10} m^2 (*7*). In 1940 through 1950 and 1950 through 1960, the losses were reduced to about 1.2 × 10^{10} m^2 $year^{-1}$ (*6*), as a result of improvements in preventive measures. A graph of the forest area burned annually in Canada and the United States [from White (*8*)] is shown in Fig. 1.

Table 1. Annual average fire losses in Canada (1959 through 1968) (*5*).

Type	Area burned (10^{10} m^2)
Vegetation	
Salable timber forest	0.235
Young growth	0.198
Cutover land	0.056
Nonforested area	0.402
Causes	
Man-caused	0.436
Lightning	0.562

To assess the amount of CO_2 released into the atmosphere per year by burning, two parameters must be known: the amount of carbon converted by burning into CO_2 in each type of biome and the biome area burned, as summarized in Table 2.

The amount of phytomass burned, M_b (in grams of carbon per square meter), may be calculated by

$$M_b = E \times \alpha \times M_T = 0.5\, M_T$$

where E, the efficiency of burning, is estimated to be 0.75 (*9*), and α, the ratio of the aboveground phytomass to the total phytomass of a forest, is 0.64 (*10*); M_T, the total phytomass of a forest or other type of biome, is taken from Whittaker and Likens (*11*).

The areas of forested and nonwooded land burning in the boreal and temperate regions are based on statistics for Canada (*5*) and the United States (*6*), respectively. Fire statistics are not available for humid tropical forests, although it may be reasoned that natural fires may be less common for tropical forests than for boreal and temperate forests during the dry season. Forest clearing for agricultural purposes in the tropics appears to be the major cause of fire. Statistics on the area cleared are poor. Shifting cultivation, a practice of felling and burning a small area of forest or bush for agricultural uses for a few years, has been practiced widely in history and is practiced today (*2*, *12*). Earlier estimates by Bolin (*4*) and Manshard (*13*) of the annual amount of tropical forest cleared, together with the estimates derived in this report, are shown in Table 3.

The area of tropical forest cleared may be assessed in two ways. First, it may be estimated from statistics derived from a survey of wood-use trends and prospects conducted by the Food and Agriculture Organization (FAO) (*12*). Second, it may also be derived from an estimation of new land required to accommodate the annual population increase in the developing area, assuming that the rural population increase would be absorbed in agricultural practice in new forest clearings. The new land requirement, L (in square meters), may be calculated from

$$L = P \times R \times B \times \theta$$

where P is the population (*14*, pp. 331–340), R is the rate of population increase (*14*, pp. 331–340), B is the rural fraction of the population (*15*), and θ is the land requirement per capita for shifting cultivation (*16*). The total area already under

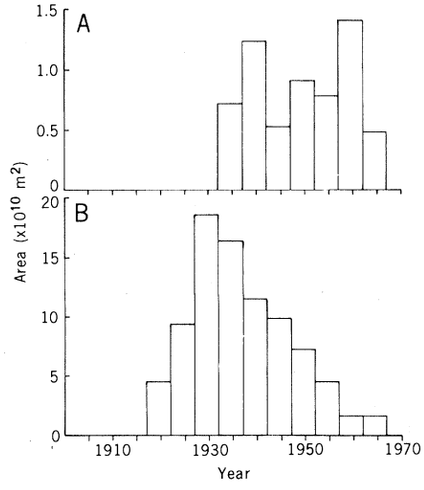

Fig. 1. A graph of the forest area burned annually in Canada (A) and in the United States (B) (5-year average) (*8*).

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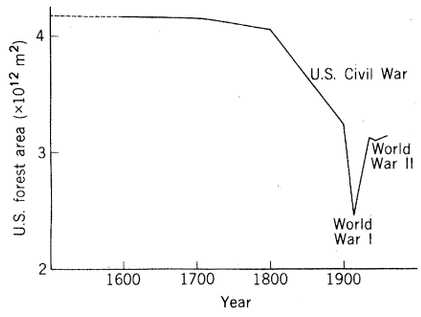

Fig. 2. Historical changes in the forested area in the United States.

shifting cultivation is much larger, estimated to be 1.03×10^{12} m² in the Far East (*12*) with about 24.5×10^6 shifting cultivators in the early 1960's, and probably the same order of magnitude, that is, 1×10^{12} m² in Africa and in Latin America. This would give a world total of 3×10^{12} m² of land in active shifting cultivation practiced by roughly 75×10^6 shifting cultivators supporting a rural population of 263×10^6 persons (*16*).

The CO_2 input into the atmosphere from forest and agricultural fires calculated from the above parameters is shown in Table 4, together with inputs from other minor sources, such as soil carbon loss in agriculture (*4*), fuel wood burning (*17*), wood and paper waste burning (*18*), soil carbon loss on burning (*19*), desertification (*20*), and urbanization of farmland (*14*, p. 84; *21*), and from other major sources, such as fossil fuel burning (*1, 2*), decomposition of land and ocean detritus (*22*), and respiration of land and ocean biota (*22*).

War may be another factor creating net CO_2 input as a result of incendiary bombing and the resultant fire storms in forests. Such fires occurred in World War II in the Black Forest of Germany during carpet bombing by the Allies; in Vietnam, Cambodia, and Laos during the Vietnam War; and in the German Hürtgen forest which was ignited in 1947 by ammunition left from World War II (*7*). About 10^{10} m² of forest cover was reported lost in South Vietnam during the Vietnam War through herbicides, bulldozing, and bombing (*23*). However, only forest fires of the magnitude of those in the United States in the pre-1940's create enough temporary increase in the atmospheric CO_2 to significantly compare to the fossil fuel input of CO_2 per year, that is, 1×10^{15} to 2×10^{15} g of carbon per year.

The atmospheric CO_2 reservoir of 670×10^{15} g of carbon is roughly in short-term equilibrium with two very large fluxes of annual gross output and input. The natural input (all CO_2 inputs here are expressed as grams of carbon), about 160×10^{15} g year^{-1}, includes respiration by the land biota at 63×10^{15} g year^{-1}, decomposition of terrestrial detritus at 37×10^{15} g year^{-1}, respiration of ocean biota at 25×10^{15} g year^{-1}, and decomposition of open ocean detritus at 35×10^{15} g year^{-1} (*22*). The nonfossil burning input, mainly anthropogenic, amounts to 5.7×10^{15} g year^{-1}, and the fire and man-made inputs total 11.0×10^{15} g year^{-1}. Corresponding input estimates by Baes *et al.* (*2*) were 7×10^{15} and 12.0×10^{15} g year^{-1}.

In contrast to the gross input, the net CO_2 input is essentially anthropogenic in nature: fossil fuel combustion at 5×10^{15} g year^{-1} and new forest clearing in the tropics at 1.5×10^{15} g year^{-1}. This figure lies between the tentative estimate of Baes *et al.* of 1.2×10^{15} g year^{-1} for prompt CO_2 release and up to 2×10^{15} g year^{-1} for delayed release as slowly exchanging wood and some humus are changed to more rapidly decomposing residues, for a 1 percent annual clearing of the forests south of 30°N (*2*, pp. 21–24). The natural net input is close to zero, because the natural carbon cycle is roughly in equilibrium. The gross natural CO_2 input by forest fires, detritus decomposition, and plant respiration is balanced by CO_2 uptake for plant photosynthesis into organic matter as the annual increment of growth of the land phytomass and tropical vegetation on land under recovering fallows in shifting cultivation rotation. Thus, the gross fluxes do not contribute to the atmospheric CO_2 increase, although the net CO_2 fluxes do.

Table 2. Parameters used in the calculation of CO_2 inputs by the burning of land phytomass.

Type	Carbon content* change on burning (10^3 g m^{-2})	Area burned (10^{10} m² year^{-1})
Boreal forest	4.5	1.2
Boreal nonwooded land	1.5	1.3
Temperate forest	7.0	4.6
Temperate nonwooded land	1.5	4.6
Tropical forest for new clearings:		
Based on FAO estimate	9	24.0
Based on rural population increase	9	7.5
Bushland already under active tropical shifting cultivation	1	300

*In the calculation, biomass values are taken from Whittaker and Likens (*11*). For boreal and temperate nonwooded land, an average of termperate grassland-shrubland biomass was used; for bushland under shifting cultivation, savanna biomass was used.

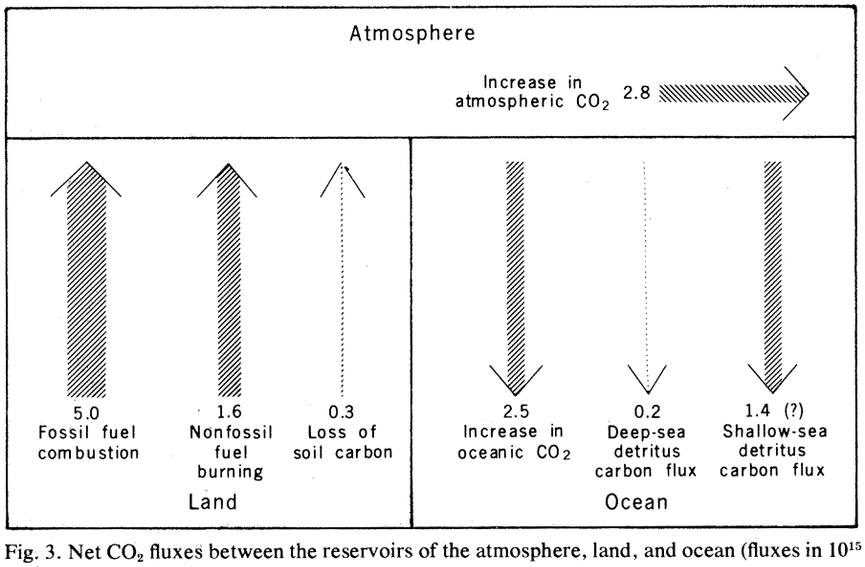

Fig. 3. Net CO_2 fluxes between the reservoirs of the atmosphere, land, and ocean (fluxes in 10^{15} g of carbon per year).

The net CO_2 input is producing a nonequilibrium situation in the atmospheric CO_2 budget. Despite a net CO_2 input of 6.9×10^{15} g year^{-1}, the documented CO_2 increase amounts to only 2.8×10^{15} g year^{-1} (*1, 2*). To account for this discrepancy, four removal mechanisms are possible: reforestation, grain storage, oceanic uptake, and the sedimentation of oceanic detritus.

Reforestation and grain storage are anthropogenic removal mechanisms. The main reforestation activity has occurred in China, where it is estimated by Persson to be about 1×10^{10} to 2×10^{10} m² year^{-1} (*24*). Canadian sources (*25*) es-

timated the reforestation in China to be about 1.9×10^{10} m^2 year^{-1}, in agreement with Persson's upper limit. Persson also derived a reforestation figure of 0.3×10^{10} m^2 year^{-1} (*24*) for other developing countries. The total reforestation is 2.2×10^{10} m^2 year^{-1} for developing areas. However, if Bolin's annual net production (*4*) of 0.5×10^3 g m^{-2} is used, a net CO_2 flux of -0.01×10^{15} g year^{-1} is obtained, which is very insignificant by comparison with Bolin's 0.3×10^{15} g year^{-1}. The historical changes of the forested area in the United States are shown in Fig. 2 (*7*) with a reforestation since World War II of about 0.2×10^{10} m^2 year^{-1}. However, this reforestation seems to have been offset by a loss to agricultural use since 1962 at the same rate per year (*3*). This result is in agreement with Bolin's conclusion (*4*) that the net change of the forests in the developed countries during the past 20 years is insignificant. The world grain harvest in 1970 amounted to about 0.55×10^{15} g year^{-1} (*11*), usually without surplus on a global basis. In recent years, such as 1975–76, the world grain surplus increased to 2×10^{13} g (*26*) or 0.005×10^{15} g year^{-1} in storage. Thus, both anthropogenic removal mechanisms by reforestation and by grain storage are unimportant.

Natural mechanisms for the removal of CO_2 are mainly oceanic, since the land biota is decreasing in size. Existing theories (*22*) suggest that oceanic uptake may account for approximately half of the fossil fuel input into the atmosphere, that is, 2.5×10^{15} g year^{-1}. The total budget of inputs (Table 4), despite its highly speculative nature, does suggest nonfossil burning to be a significant source of CO_2 compared to fossil fuel input. This result implies that the mechanism for the removal of CO_2 from the atmosphere is far more efficient than existing ones based on fossil fuel CO_2 sources only. The problem of the sinks for CO_2 is as critical as that for sources of CO_2, since such knowledge is crucial for calculating the ability of the land and oceanic environments to absorb future CO_2 increases. The present models of the role of the ocean (*4, 27*) appear to be inadequate to explain a much larger flux of CO_2 from human activities.

I propose a very speculative carbon flux model (Fig. 3), which calls for marine photosynthesis to play a larger role. The phytoplankton in the ocean has a very small biomass, perhaps 1.5×10^{15} g of carbon, but it acts as a very efficient CO_2 pump, which handles 50×10^{15} g year^{-1} with about 20×10^{15} g of detritus carbon transferred per year into a very large reservoir of dead organic detritus ($10^3 \times 10^{15}$ g of carbon) (*22*). According to the existing detritus concept, most of the detritus formed each year is decomposed and returned to the seawater reservoir, with a loss of only 1 percent or less as detritus flux into the sediment (*28*). However, it may be unjustified to assume that a particulate carbon flux of 1 percent or less of the organic production is always valid and is universally applicable to both open ocean and shallow waters. The open ocean fixation of carbon amounts to 18.9×10^{15} g year^{-1}; for shallow seas, including the estuaries, continental shelf, and coral reefs, production of 6×10^{15} g year^{-1} takes place in an area only one-tenth the size of the open ocean area (*11*), where the transit time through the water column to the bottom is about 1/20 or less than that of the deep ocean. The ratio of the detritus carbon formation rate to the primary production rate by photosynthesis is about 0.2 to 0.4 (*29*). Thus, a carbon production of 6×10^{15} g year^{-1} gives rise to 1.2×10^{15} to 2.5×10^{15} g year^{-1} as detritus carbon which will eventually settle on the shallow sea bottom. If no significant decomposition is taking place under certain sedimentary conditions, for example, high burial rates by continental materials or anoxic conditions, a maximum net transfer of 1.2×10^{15} g year^{-1} as detritus carbon flux into the sediment is possible. The assumption of negligible decomposition is certainly not quite true for the oceanic environment. However, we do not have a good idea of the magnitude of the particulate carbon flux in the coastal waters and perhaps other areas where extensive preservation of carbon may occur. Such areas may include the very productive Arctic and Antarctic waters. In particular, the Arctic waters, where a short duration of production is combined with a large input of sedimentary material from the continents, may be favorable to this carbon sink concept. Anoxic environments, such as conditions in the Black Sea, waters along the coast of California, and Peruvian waters, may be other carbon sinks.

Table 3. Estimates of new forest clearings (in 10^{10} m^2 year^{-1}) in the tropics.

Source	Africa	Latin America	Asia	Tropics
Manshard (*13*)	1.5	10	10.5	22
Bolin (*4*)	2	6	4	12
This report:				
Based on FAO (*12*)	8	7.5	8.5	24
Based on rural population increase	1.2	1.3	5.0	7.5

Table 4. Input of CO_2 into the atmosphere from nonfossil wood burning and other sources.

Source	Carbon	
	Gross input (10^{15} g year^{-1})	Net input (10^{15} g year^{-1})
Fires in boreal forests and nonwooded areas	0.07	0.0
Fires in temperate forests and nonwooded areas	0.4	0.0
Tropical shifting cultivation on land already in use	3.0	0.0
New tropical forest clearings	1.5 (0.7 to 2.2)	1.5 (0.7 to 2.2)
Fuel wood burning	0.2	0.006 (0.004 to 0.008)
Paper waste burning	0.08	0.0008
Soil carbon loss in agriculture*	0.3	0.3
Soil carbon loss on burning	0.4	0.02
Desertification	0.05	0.05
Urbanization of farmland	0.01	0.01
Fossil fuel burning†	5.0	5.0
Respiration of land biota‡	63.0	0.0
Decomposition of land detritus‡	37.0	0.0
Respiration of ocean biota‡	25.0	0.0
Decomposition of ocean detritus†	35.0	0.0
Total	~171.0	~6.9

*From Bolin (*4*). †From Keeling (*1*) and Baes *et al.* (*2*). ‡From Reiners (*22*).

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5. M. R. Lockman, *Forest Fire Losses in Canada, 1969* (Catalog Fo. 51-2/1969, Information Canada, Ottawa, 1972), p. 6. An annual average (1959 through 1968) of 0.433×10^{10} m^2 year^{-1} of the area burned in Canada was forested. The value for the boreal forest is extrapolated from a ratio of the world boreal forest area of 12×10^{12} m^2 to the Canadian boreal forest area of 4.2×10^{12} m^2. The value for boreal nonwooded land is extrapolated from an annual average (1959 through 1968) of 0.458×10^{10} m^2 of nonwooded area burned, based on the same ratio of world to Canadian area applicable also to nonwooded land.
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13. W. Manshard, *Tropical Agriculture* (Longman, London, 1974), pp. 187-189.
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15. K. Davis, in *Man and the Ecosphere* (Freeman, San Francisco, 1971), pp. 267-279. The fractions of rural population are estimated to be about 0.8 in Asia, 0.55 in Middle America and South America, and 0.87 in tropical Africa, on the basis of Davis' data on the percentage of the urban population.
16. L. D. Stamp, in *Africa: A Study in Tropical Development* (Wiley, New York, 1964), p. 144. In fertile southern Nigeria, an average family of 3.6 persons required the produce from 8×10^3 m^2 of cultivated land annually. In less fertile northern Nigeria, an average of 3.3 persons per family would be supported by 12×10^3 m^2. Thus, the average land requirement amounts to 3×10^3 m^2 per capita for shifting cultivation. The average size of family is 3.5 persons per shifting cultivator.
17. *Yearbook of Forest Products, 1963-1974* (FAO, Rome, 1976). In 1974, the world production of fuel wood and charcoal was estimated to be 1.17×10^9 m^3. Conversion factors of 725 kg m^{-3} for density, 0.5 for the dry weight of woody material, and 0.5 for the carbon content are used. Also, a total of 1.52×10^8 metric tons of paper products were produced.
18. It is assumed that half of the paper products produced (*17*) are burned as waste. The net input is calculated on the basis of a 1 percent increase in paper demand per year.
19. Loss of soil carbon in agricultural burning and forest fires is based on the following data: a total area of 350×10^{10} m^2 year^{-1} (Table 1), a fractional change of 0.08 in soil carbon before and after an experimental slash burning [R. F. Watters, *Shifting Cultivation in Latin America* (FAO, Rome, 1971), p. 43], and a soil carbon content in the top 10 cm of soil of 1.5×10^3 g m^{-2} estimated from *Soil Map of the World, North America* [(UNESCO, Paris, 1975), vol. 2]. An average area for new tropical forest clearing of 16×10^{10} m^2 year^{-1} is used for the calculation of the net input.
20. Desertification of the savanna and farmland is estimated to be 5.7×10^{10} m^2 year^{-1} (U.N. Conference on Desertification, Nairobi, Kenya, 1977), with a change in phytomass from about 1.1×10^3 to 0.3 g m^{-2} (*7*). Thus, the decrease in CO_2 uptake from the atmosphere amounts to 0.05×10^{15} g year^{-1}.
21. In California each city dweller requires an urban area of 10^3 m^2. In Great Britian the area is 6×10^2 m^2 [see also N. W. Pire, *Food Resources* (Penguin, New York, 1976), p. 39], with an average of 0.8×10^3 m^2 per urban dweller. The world's annual urban population increase, estimated from the degree of urbanization (*15*) and population increase (*14*, pp. 331-340), is about 24×10^6 persons. The urban encroachment on farmland is occurring at a rate of 1.9×10^{10} m^2 year^{-1} and, on the basis of a decrease in the phytomass CO_2 uptake from 0.5×10^3 g m^{-2} for farmland to zero for concrete paved area, a net CO_2 input into the atmosphere of 0.01×10^{15} g year^{-1} is estimated.
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29. C. S. Wong, unpublished data and personal communication with T. R. Parsons.

30. I thank Dr. R. W. Stewart for helpful comments on the first draft.

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Gyrate Atrophy of the Retina: Inborn Error of L-Ornithine:2-Oxoacid Aminotransferase

Abstract. *Cultured fibroblasts from a patient with gyrate atrophy of the retina do not convert* L-*ornithine, uniformly labeled with carbon-14, to proline. This metabolic block is caused by deficient* L-*ornithine:2-oxoacid aminotransferase activity in the patient. Her heterozygote father has intermediate activity of this enzyme.*

Gyrate atrophy of the retina is a blinding human disease characterized by progressive retinal degeneration, autosomal recessive inheritance, and an increase of ornithine in the blood and urine (*1*). We now report a specific inborn error of ornithine metabolism in this disease. A recent in vivo metabolic study (*2*) has sug-

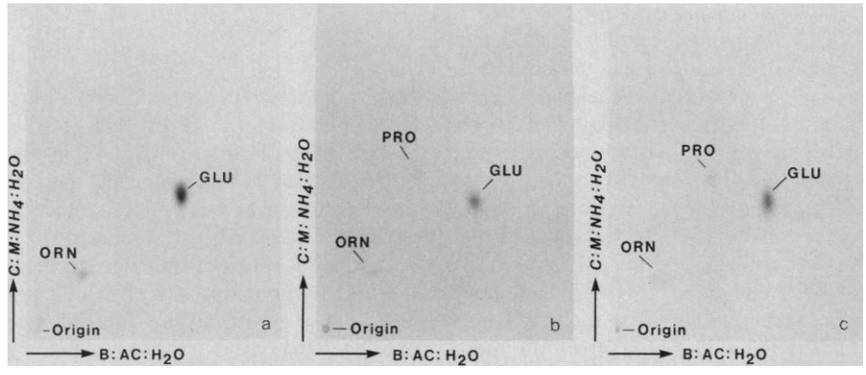

Fig. 1. Autoradiography of ^{14}C-labeled amino acids in acid soluble cell fraction separated by thin-layer chromatography. (a) Normal; (b) heterozygote father; and (c) patient. The mother was not available. Skin fibroblasts were cultured in Dulbecco's medium with 10 percent fetal calf serum in an incubator (5 percent CO_2) at 37°C. All cultures were free of mycoplasma contamination (*6*). Confluent cultures were incubated for 24 hours in media containing 0.133 μCi of L-[U-^{14}C]ornithine per milliliter (200 μCi/nmole; New England Nuclear). Cells were harvested and protein was precipitated with perchloric acid. The acid-soluble cell fraction was lyophilized and redissolved in distilled water so that 1 μl contained an acid-soluble cell fraction proportional to 11 μg of cell protein (*7*). A portion (10 μl) was applied to silica gel thin-layer chromatography plates (Analtech). The first dimension was run in a chloroform, methanol, ammonium hydroxide, water system (60:60:18:9) for 1 hour and the second dimension in a butanol, acetic acid, water system (9:3:3) for 2.5 hours. The migrations of ornithine, glutamate, and proline standards were used as controls. Autoradiography was accomplished by apposing the plates to film (Kodak NoScreen) in darkness for 1 month. The ornithine, proline, and glutamate spots identified from this autoradiography and from ninhydrin or isatin stain were scraped into vials containing 10 ml of liquid scintillation fluid (Aquasol; New England Nuclear) and 0.5 ml of water. A spot equal in size to the glutamate spot adjacent to the glutamate spot was used as a control spot. Spots removed and counted produced (counts per minute): (a) Normal; ornithine, 74; proline, 91; glutamate, 382; control, 11. (b) Heterozygote father; ornithine, 65; proline, 83; glutamate, 366; control spot, 14. (c) Patient; ornithine, 179; proline, 19; glutamate, 438; control, 13. Abbreviations: *ORN*, ornithine; *PRO*, proline; *GLU*, glutamate, *C:M:NH$_4$:H$_2$O*, chloroform, methanol, ammonium hydroxide, water; and *B:AC:H$_2$O*, butanol, acetic acid, water.

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