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V.D. DANG AND M. STEINBERG

August 1980

MASTER

DEPARTMENT OF ENERGY AND ENVIRONMENT

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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WASHINGTON, D.C. 20545

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Abstract

The dispersion of carbon dioxide emitted from a 1000 MW(e) coal fired power plant is investigated. Calculated ground level carbon dioxide concentrations as a function of distance from the power plant stack is validated by the results derived from sulfur dioxide dispersion measurements. Forestation is examined as a means for removal and control of atmospheric carbon dioxide at a distance of 5 to 10 km away from the power plant stack. An equilibrium and a dynamic approach are considered. In the equilibrium case, the increase in concentration of CO₂ above background is less than 1 ppm and thus the growth rate of forests is not significantly affected by the concentration change. In the dynamic method, it is estimated that a maximum increase of 15% in CO₂ concentration above background can be obtained in the 5 to 10 km annular ring at ground level. This incremental CO₂ concentration would result in an estimated maximum increase of 15% in the growth rate of trees located in this area. For an average temperate zone forest growth rate (7.42 mg/dm² hr), the overall reduction in forested land area required to remove the equivalent of all of the CO₂ from a 1000 MW(e) power plant would be less

than 3.3% compared to removing the equivalent amount of CO₂ by planting forests remotely from the plant. If faster growing tropical plants or trees having up to 4 times the temperate plant growth rate were used, there would be a maximum savings of 15% in forested land area compared to a remote planting. This magnitude of reduction in cultivated forest area is insufficient to recommend planting forested areas adjacent to central power stations as a means of controlling CO₂ emission. Rather it is suggested to provide sufficient increased regional forested areas on a global scale for the purposes of absorbing the equivalent increase in CO₂ emission due to increased fossil fuel use.

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Introduction

Emission of carbon dioxide to the atmosphere by the consumption of fossil fuel in the USA has been reviewed in a recent report [1]. The emitted carbon dioxide interacts with the atmosphere, biosphere, and ocean. The final equilibrium concentration of carbon dioxide in the atmosphere results from about fifty percent of the original emission with the remaining absorbed by the biosphere and the ocean. Estimates for 1985 indicate that of the total carbon dioxide to be emitted to the atmosphere, the concentrated sources, which include power and industrial plants, will amount to 54.2%, while that from diffuse sources which consist mainly of automotive emissions will be 45.8% [1]. For concentrated sources, carbon dioxide can be removed and recovered by various physical and chemical techniques such as absorption/stripping, adsorption, liquefaction, etc. Another possible technique of controlling atmospheric CO₂ is through the photosynthetic process for the production of biomass which includes plants and trees. Forests can be planted to take up CO₂ and a recent workshop [3] reports the carbon dioxide exchange with existing forests.

The concentration of carbon dioxide in gases emitted from a coal fired power plant stack is about 15% and is thus a fairly concentrated source. The concentration of atmospheric carbon dioxide around a power plant could increase above background, and forestation in this region could possibly act as a control method for carbon dioxide. Coal fired power plants contribute about 25% of the total US carbon dioxide emission. Thus investigation of a control technology for carbon dioxide emission surrounding a power plant is a significant and worthwhile effort. In the following, a coal fired plant of 1000 MW(e) capacity is used for making a first order estimate of the value that forestation may have in capturing and controlling the atmospheric carbon dioxide surrounding a power plant stack.

Atmospheric CO₂ Dispersion

Measurement of CO₂ concentration away from a power plant is not as extensive as that for SO₂. From physical dispersion phenomena, from power plant stacks, it is possible to draw analogous estimates of the ground level concentration of CO₂ from SO₂ measurements. Fig. 1 shows experimentally measured ground-level SO₂ concentrations at distances away from the stack of the Dickerson power plant in Maryland [4] where H_m and h_e are the mixing length and the effective stack height, respectively. Correlation of these data has also been performed using the Gaussian plume model with various dispersion coefficients [4,5]. Solid curves in Fig. 1 are the correlation using the Brookhaven dispersion coefficients [4].

For a 1000 MW(e) coal fired power plant with an electrical power cycle efficiency of 35%, carbon dioxide is emitted at a rate of 19.32×10^6 gm/min or 1.52×10^4 m³/min at 300°F and 1 atm at the stack. The carbon dioxide in the flue gases will then be dispersed from the stack. Atmospheric dispersion of pollutants has been extensively investigated. An approximate estimate of the carbon dioxide concentration away from the stack can be obtained from the following equation [6, pp. 366-71]

$$C = \frac{2.8 \times 10^{-3}}{ud\theta h} \exp \left(- \frac{2.303H^2}{h^2} \right) \text{units/m}^3 \quad (1)$$

where H is the actual stack height, h is the plume rise, u is the wind speed, d is the distance downwind from the stack and θ is the lateral spread.

A schematic illustration of the dispersing process together with the parameters is shown in Fig. 2. For a stack height of 100 m and other conditions listed in Table 1 [6, Table VIII], one can then determine the carbon dioxide concentration C(units/m³) at four locations (0.1, 1, 10, and 100 km) from the stack. The concentration of carbon dioxide in terms of ppm is then obtained by multiplication of C in Eq. (1) and the carbon dioxide flow rate 1.52×10^4 m³/min. The carbon dioxide concentration as a function of distance from the stack is shown in Fig. 3. Experience indicates that the maximum surface SO₂ concentrations at ground level usually occurs at 5 to 10 km away from the source [7] and therefore this region is used for the CO₂ investigation. The concentration of carbon

dioxide at ground level is calculated to be between about 48 and 5.2 ppm above background (~ 330 ppm) at a distance of 5 to 10 km away from the stack. It is interesting to note that the incremental ground level concentration of CO_2 above background derived from the experimental results of SO_2 measurement [4] is 15 to 18 ppm at a distance of 5 to 10 km away from the stack which is in the same order of magnitude as calculated.

The planting of trees in an area of increased carbon dioxide concentration surrounding the source may be a useful method for improving the removal of carbon dioxide from the atmosphere. However, many factors can affect the uptake of CO_2 by trees and forests. Carbon dioxide exchange between the atmosphere and the trees varies with the season. The carbon dioxide concentration in the atmosphere is lower in summer than in spring, fall, and winter [8]. For trees of a given height (average 18 m [8]), the atmospheric carbon dioxide concentration varies in altitude from the bottom to the top of the tree. Measurements indicate that CO_2 concentration decreases when the altitude above ground increases, except in winter where the CO_2 concentration remains fairly constant with altitude. The variation of CO_2 concentration can change from 325 to 305 ppm at 3 m to 20 m above ground level in summer which has the largest variation of the four seasons. Carbon dioxide is practically constant at a value of 295 ppm at 1:00 pm but it varies between 315 and 305 ppm at different altitudes at 9:00 pm [8].

It is known that plants take up CO_2 concentration and light intensity as can be seen in Figs. 4 and 5. Full sunlight available for

photosynthesis is equivalent to an energy flux of $42 \times 10^4 \text{ erg sec}^{-1} \text{ cm}^{-2}$. The photosynthetic rate is practically independent of CO_2 concentration over 1000 ppm in the environment. Up to about 500 ppm CO_2 , the growth rate increases linearly with CO_2 concentration. At a CO_2 concentration of 378 ppm at 5 km away from the power plant, as shown in Fig. 3, it is expected that the photosynthetic rate would increase linearly with carbon dioxide concentration as seen in Figs. 4 and 5. In other words, the growth rate of trees in a 378 ppm CO_2 environment should be about 15% higher than in a 330 ppm CO_2 environment. The average photosynthetic uptake rate also varies with the type of planting as given in Table 2 [9, pp. 244-5]. The net primary productivity (NPP) of trees also varies among forests as can be seen in Table 3 [2]. In the following discussion, an average forest growth rate of $8.50 \text{ mg/dm}^2\text{hr}$ [2] is used for evaluation. Note that $8.50 \text{ mg/dm}^2 \text{ hr}$ is based on a $\sim 378 \text{ ppm CO}_2$ environment which is 15% higher than for 330 ppm CO_2 and a tree growth rate of $7.42 \text{ mg/dm}^2\text{hr}$. The latter average forest growth rate corresponds to a forest of oak trees or dogwood.

An estimate of a forest area needed to remove atmospheric carbon dioxide in a region of 5 to 10 km away from a power plant is quite complex. The fraction of the pollutant in the original source from the stack dispersed over a certain area depends on the wind speed and the characteristic time of the pollutant staying in the atmosphere.

There are two approaches that can be taken when considering forestation of land area for removal of atmospheric carbon dioxide. The

first approach is an equilibrium one. That is, the CO_2 emitted from the power plant has stayed in the atmosphere for a long enough time so that it reaches an equilibrium concentration with the surrounding air. From previous estimates [1], the annual increase in CO_2 concentration in the atmosphere due to fossil energy usage is expected to be less than 1 ppm. Thus, the increase in forest growth rate due to the effect is negligible. The forestation land area for trees with an average growth rate of $7.42 \text{ mg/dm}^2\text{hr}$ required to remove $19.32 \times 10^6 \text{ gm/min CO}_2$ from a 1000 MW(e) power plant is 1065 km^2 . Trees planted in the annular region of 5 to 10 km away from the stack will cover an annular area of 236 km^2 and thus should remove only 22% of the total carbon dioxide emitted from the stack.

The other approach involves a dynamic process where carbon dioxide is removed instantaneously by the trees while taking advantage of a higher carbon dioxide concentration due to the plume dispersion at ground level. Further description of the dispersion process is necessary before estimates of forestation land can be made. Downstream dispersion of a plume from the stack can be stable, neutral or unstable. By means of a gaussian plume dispersion model [11], it is possible to determine the average fraction of CO_2 emitted from the stack which is dispersed above the annular area of 5 to 10 km from power plant as listed in Table 4. For example, the characteristic time of SO_2 in the atmosphere is about 22 hours [13]. For wind speed between 4 to 10 m/sec and a characteristic time for CO_2 staying in the atmosphere between 0.5 to 1 yr, it is found that the average fraction of CO_2 from the stack which is dispersed above the annular area of 5 to 10 km from the power plant lies between 36 and 100%. Because of variations of different parameters such as wind speed,

light intensity, kinds of trees, etc., it is very difficult to determine a fixed area for forestation. If young trees with a growth rate of $7.42 \text{ mg/dm}^2\text{hr}$ are planted in an area of 236 km^2 to absorb the CO_2 emitted from the power plant continuously for 30 years, the trees will grow accordingly. The mass of trees that can be produced due to the output of CO_2 from the power plant is $5.3 \times 10^{10} \text{ kg}$ during a thirty year period. If the average final diameter and height of a tree is 0.76 m and 18.9 m , respectively, there should be a population of approximately 37,462 trees/ km^2 . It is noted that the density of the Eastern Cottonwood can range from 8,000 trees/ km^2 to 362,000 trees/ km^2 for tree heights in the range of 11 m to 42 m and diameters of 0.09 m to 0.7 m [12]. Hence the estimated forestation density lies within the existing forestry data.

As discussed previously, the annular ring area of 236 km^2 at a distance of 5 to 10 km away from the power plant stack can only remove 22% of the total carbon dioxide emission under equilibrium background CO_2 concentrations and an average tree growth rate of $7.42 \text{ mg/dm}^2 \text{ hr}$. Under dynamic conditions, due to the higher concentration of carbon dioxide above this area, a maximum increase in photosynthetic rate of 15% can be expected. Thus the total amount of forestry area required to remove all of the CO_2 from a 1000 MW(e) power plant can be reduced by 3.3% as shown in the following table:

	<u>Equilibrium</u>		<u>Dynamic</u>	
	<u>Land area, km²</u>	<u>Fraction removed, %</u>	<u>Land area, km²</u>	<u>Fraction removed, %</u>
Land area and fraction of CO ₂ removed in 5 to 10 km annular ring	236	22	236	25.3
Fraction CO ₂ removed outside annular ring	<u>829</u>	<u>78</u>	<u>794</u>	<u>74.7</u>
Total land area	1065	100	1030	100
Total land savings	35 km ² or 3.3% of equilibrium			

This small savings in land area is hardly worth the effort for providing a planned forest area immediately surrounding a power plant. However, provision can be made to allot areas in the country for forestation specifically assigned to remove the equivalent mass of CO₂ emitted from power plants. For the equilibrium growth rate assumed, this is equivalent to 1065 km² per 1000 MW(e). These can be planted anywhere in the country and not necessarily adjacent to a power plant.

There is also the possibility of planting fast growing tropical plants such as sugarcane, sorghum, pigweed, and sunflower that have growth rates more than four times that of 7.42 mg/dm² hr assumed above. If these are planted in the annular region of 5 to 10 km away from the power plant stack and the meteorological conditions are such that almost all the carbon dioxide emitted from the stack is above this region, these plants will tend to remove practically all the carbon dioxide emitted

from the power plant. However, even in this case the maximum decrease in land area that can be expected due to the dynamic conditions of increased CO₂ concentration would be 15%.

Summary and Conclusions

A suggested method of removing CO₂ from the atmosphere due to emission from a coal fired power plant is by forestation. Considering a 1000 MW(e) coal fired power plant, the increase in ground level carbon dioxide concentration is estimated to be between 48 and 5.2 ppm above background (~330 ppm) at a distance of 5 to 10 km away from the power plant. This increased concentration level is about the same order of magnitude derived from the results of sulfur dioxide measurements. The photosynthetic rate varies with the type of tree in different geographical areas and increases linearly with environmental CO₂ concentration up to 500 ppm. It is thus expected that a maximum increase of 15% in tree growth rate would result in the annular region of 5 to 10 km away from the plant due to increased ground level concentration of CO₂.

An equilibrium and a dynamic method for determining planting area of forests are compared. A 1000 MW(e) power plant releases 19.32×10^6 g/min CO₂. The area of trees required with an average cultivated temperate zone growth rate of 7.42 mg/km² hr to remove this emission rate is 1065 km². If trees of this growth rate are in an area of 236 km², a 5 to 10 km annular ring, only 22% of the total carbon dioxide emitted from the stack will be removed by the forests. It is thus necessary to provide another 829 km² to remove the remaining 78% of the CO₂ emitted.

Because of the increased photosynthetic rate due to increased ground level concentration mentioned above, the forestation area required for the dynamic case may be 15% less than that of the equilibrium case. This would result in a net reduction of 3.3% in land area to remove all of the CO_2 emitted from a 1000 MW(e) plant. It is interesting to note that depending on meteorological conditions, the fraction of CO_2 absorbed by tree growth which originates from the power plant can vary widely, typically ranging from 36 to 100%. For a thirty year life power plant, young trees with growth rate of $7.42 \text{ mg/dm}^2 \text{ hr}$ can grow steadily to 18.9m tall and 0.76 m diameter in an area of 236 km^2 by absorption of CO_2 emission. The total mass of tree produced is $5.3 \times 10^{10} \text{ kg}$ and the tree density is 37,462 trees/ km^2 . In comparison with existing forest data the density of the Eastern Cottonwood can range from 8000 trees/ km^2 to 3.62×10^5 trees/ km^2 at a height of 11 m to 42 m and a diameter of 0.09 m to 0.7 m, so that this kind of forest planning seems to be reasonable.

Fast growing plants such as sugarcane, sorghum, pigweed and sunflower that have growth rates more than four times the dogwood or oak trees, 7.42 mg/dm^2 , are planted in the annular region of 5 to 10 km away from the power plant stack would reduce the land requirement accordingly. However, the maximum decrease in forested land area required would be no more than 15%.

The general conclusion of this paper is that the increased growth rate and consequent reduction in forested land area that can be expected from increased concentration of CO_2 in the atmosphere surrounding a large power plant is insufficient to justify the provision of space for

planting trees adjacent to the power plant as a means of CO₂ control. Rather, it is suggested that land area in suitable regions of the country be provided to remove the equivalent amount of CO₂ emitted from power plants. On a global scale, increased areas for tropical biomass growth such as rain forests in the tropical zone to absorb the increasing emission of fossil fuel both from central and diffuse sources may be a feasible global control technique.

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Table 1

Calculation of the Distribution of Concentration from a Point
Source of strength 1 'unit'/min [6, Table VIII]

Distance d (km)	0.1	1	10	100
Effective value of h (m)	20	170	2000	2000
Lateral spread θ (deg)	120	93	67	40
Effective value of u (m/sec)	4	4	6	6
C(units/m ³)	2.89×10^{-31}	2×10^{-8}	3.46×10^{-10}	5.8×10^{-11}

Table 2A

Typical Rates of Net Photosynthesis in Single Leaves of Various Species
at High Illuminance and 300 ppm of CO₂ in Air
[9, pp. 244-5]

Species	Net photosynthesis, mg CO ₂ dm ⁻² hr ⁻¹
Maize	46-63
Sugarcane	42-49
Sorghum	55
Bermuda grass, <i>Cynodon dactylon</i>	35-43
Pigweed, <i>Amaranthus edulis</i>	58
Sunflower	37-44
Cattail, <i>Typha latifolia</i>	44-69
Tobacco	16-21
Sugar beet	24-28
Orchard grass	13-24
Wheat	17-31
Bean	12-17
Oak	10
Maple	6
Dogwood, <i>Cornus Florida</i>	7

Table 2B

Variation of Net Photosynthesis of Single Leaves within a Species at High
Illuminance and 300 ppm of CO₂ in Air
[9, pgs. 244-5]

Species	Plant compared	Range of net photosynthesis (mg CO ₂ dm ⁻² hr ⁻¹)
Maize	15 Inbreds and hybrids	28-85
Maize	20 Races	48-59
Rice	3 Varieties	12-30
Rice	50 Varieties	34.5-62
Barley	7 Varieties	17.7-21
Bean	5 Varieties	13.7-18.5
Soybean	36 Varieties	12-24
Soybean	9 Varieties	18.7-23
Soybean	20 Varieties	29-43
Gossypium	26 Species	24-40
Tobacco	3 Varieties	11-17

Table 3

Net Primary Productivity (NPP) and Energy Fixation of Major
Vegetation Units of the World.
[Leith (2)]

Vegetation unit	Area (10^6 km^2)	Range ($\text{kg/m}^2 \text{ a}$)	Approx. mean ($\text{kg/m}^2 \text{ a}$)	Total for area (10^9 mt)	Approx. Com- bustion value (kcal/g)	Mean for m^2 (10^6 cal/m^2)	Total for Area (10^{18} cal)
1	2	3	4	5	6	7	8
Forests	50			81.6			368.6
Tropical rainforest	17.0	1.0-3.5	2.8	47.4	4.1	11.5	195.5
Raingreen forest	7.5	1.6-2.5	1.75	13.2	4.2	7.4	55.5
Summergreen forest	7.0	0.4-2.5	1.0	7.0	4.6	4.6	32.2
Mediterranean sclerophyll forest (inclu- sive chaparral)	1.5	0.255-1.5	0.8	1.2	4.9	3.9	5.9
Warm temperate mixed forest	5.0	0.6-2.5	1.0	5.0	4.8	4.7	23.5
Boreal forest	12.0	0.3-1.2	0.65	7.8	4.6	3.0	36.0
Woodland	7	0.2-1.0	0.6	4.2	4.6	2.8	19.6
Dwarf and Open							
Scrub	26			2.6			11.0
Tundra	0.8	0.06-1.3	0.16	1.3	4.5	0.7	5.6
Desert scrub	18.0	0.01-0.25	0.06	1.3	4.5	0.3	5.4
Grassland	24			19.2			76.8
Tropical grassland (incl. grass- dominated Savannah)	15.0	0.2-2.9	0.8	12.0	4.0	3.2	48.0
Temperate grassland	9.0	0.07-1.3	0.8	7.2	4.0	3.2	28.8
Desert (extreme)	24						0.1
Dry desert	8.5	0-0.01	0.003	--	4.5	--	0.1
Ice desert	15.5	0-0.001	--	--	--	--	--
Cultivated Land	14	0.1-4.0	0.65	9.1	4.1	2.7	37.8

Table 3 (continued)
 Net Primary Productivity (NPP) and Energy Fixation of Major
 Vegetation Units of the World.
 [Leith (2)]

Vegetation unit	Area (10 ⁶ km ²)	Range (kg/m ² a)	Approx. mean (kg/m ² a)	Total for area (10 ⁹ mt)	Approx. Com- bustion value (kcal/g)	Mean for m ² (10 ⁶ cal/m ²)	Total for Area (10 ¹⁸ cal)
1	2	3	4	5	6	7	8
Fresh Water	4			5.0			21.4
Swamps and marsh	2.0	0.8-4.0	2.0	4.0	4.2	8.4	16.8
Lake and stream	2.0	0.1-1.5	0.5	1.0	4.5	2.3	4.6
Total for Continents	149			121.7			535.3
Open ocean	332	0.002-0.4	0.13	41.5	4.9	0.6	199.2
Upwelling zones	0.4	0.4-0.6	0.5	0.2	4.9	2.5	1.0
Continental shelf	26.6	0.2-0.6	0.36	9.2	4.5	1.6	43.1
Algae beds and reefs	0.6	0.5-4.0	2.0	1.2	4.5	9.0	3.6
Estuaries	1.4	0.5-4.0	1.8	2.5	4.5	8.1	11.3
Total Marine	361	0.002-4.0	0.161	55.0			258.2
Overall Total	510			176.7			793.5

Table 4

Fraction of CO₂ Emitted from Stack which is Dispersed Above the Annular Area at distances of 5 to 10 km from Power Plant

$u(\text{m/sec})$	0.5 hr	3 hr	10 hr	15 hr	1 day	10 day	50 days	100 days	1 year
4	0.360	0.841	0.949	0.966	0.979	0.998	1.000	1.000	1.000
6	0.504	0.891	0.966	0.977	0.986	0.999	1.000	1.000	1.000
10	0.661	0.933	0.979	0.986	0.991	1.000	1.000	1.000	1.000

Figure 1. Measured ground-level SO₂ concentration normalized by C_{max} versus dimensionless downwind distance X/X_{max} . Gaussian plume model prediction.

Figure 2. Schematic diagram of the gas plume diffusion.

Figure 3. Concentration-distance for CO₂ from 1000 MW(e) power plant.

Figure 4. Net photosynthesis of intact young spinach plants in relation to light intensity at different CO_2 concentrations (from Gastra, 1959, Ref. [10]). Leaf temperature was 21 to 24°C and irradiation is given for the range from 400 to 700 nm.

Figure 5. Net photosynthesis of intact young spinach plants in relation to CO_2 concentration at different light intensities (from Gastra, 1959, Ref. [10]). Conditions as in Figure 4 with light intensities of 3.7, 11.3, and 22.0 $\times 10^4 \text{ erg sec}^{-1} \text{ cm}^{-2}$ as shown. The normal CO_2 concentration of air is represented by the dashed line.