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A DISCRETE EVENT APPROACH TO POLLUTANT
TRANSPORT AND VEGETATION EFFECTS

B. D. Murphy and Kenneth R. Dixon*

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ABSTRACT

Pollutant dispersion in the atmosphere together with plant carbon assimilation has been modeled for a growing season in the vicinity of a source of ^{14}C . The modeling studies point out the importance of accounting for correlations between the dispersion climatology and patterns of plant growth processes. There are significant differences between the detailed modeling of a typical season on an hour-by-hour basis and results using yearly averaged values of atmospheric concentration.

1. INTRODUCTION

Averaged values of ambient air concentration are generally used to assess the impact of pollutants on vegetation. For instance, average ambient ^{14}C specific activity is used as an estimate of the specific activity found in growing plants under the general assumption that specific activity in vegetation tends to follow ambient atmospheric specific activity (USNRC, 1976). Likewise, average atmospheric concentrations of SO_2 and of oxides of nitrogen are used to assess growth

inhibition in exposed vegetation. Various averaging times have been in use in the assessment of these various effects. It is important, however, to choose an appropriate averaging time and this is particularly so for gaseous pollutants. Gases diffuse through a leaf's stomata and diffusion will be greatest when the stomatal openings are greatest. Thus, many commonly used average atmospheric concentrations may be unrepresentative of the pollutant exposure regimes which a plant experiences.

Because the uptake of a gaseous pollutant depends on the degree of stomatal opening, the atmospheric concentration of the pollutant during daylight hours will be of prime importance. Furthermore, the atmospheric concentration during that part of the season when the greatest growth is occurring will be of much more importance than concentrations at other times of the year. For the environs of a source of pollutants, the ground level concentrations of those pollutants are highly dependent on local meteorological conditions. Specifically, concentration values will depend on wind direction, wind speed, and atmospheric turbulence. These meteorological variables have, in general, diurnal and seasonal characteristics and hence there may be strong correlations between periods of high atmospheric pollutant concentrations and plant growth patterns. Thus, there is a need to study, in more detail, the occurrence of various concentration levels of a pollutant because the final effect on growing vegetation will be strongly dependent on when the exposure occurs and the preceding exposure history.

2. A CASE STUDY

In order to determine how the diurnal and seasonal history of atmospheric concentration influences plant uptake, it is necessary to

examine both atmospheric processes and the sequence of plant growth processes as they operate in conjunction with one another. To this end, we have modeled a situation where plants are growing in the vicinity of a source of ^{14}C and thereby studied in detail how this ^{14}C may be incorporated into plants during a growing season. This allows us to see the cumulative effect of growth rate and meteorology for the whole growing season as well as at any point during the season.

A source which emits ^{14}C in the form of carbon dioxide at a rate of $2\ \mu\text{Ci/s}$ was considered. This source was assumed to be a 100 m stack and it was further assumed that the $^{14}\text{CO}_2$ was vented through the stack at ambient temperature (i.e., no thermal rise). There was, however, a small amount of momentum rise associated with the plume.

Transport and dispersal of a gas from such a source can be estimated conveniently with a Gaussian plume model (Gifford, 1968). We made use of the Atmospheric Transport Model (ATM) of Culkowski and Patterson (1976). Such a model considers material emitted from the source as spreading both horizontally and vertically with a Gaussian distribution. The material will be carried along in the direction of the wind vector and its distribution about the plume centerline will increase with distance from the source at a rate which depends on atmospheric turbulence. Turbulence is measured in terms of stability class (Gifford, 1961) which varies from A (very unstable, giving rise to much atmospheric mixing) to F (very stable with little mixing).

In doing a detailed study in which pollutant dispersal and plant growth are considered as they vary throughout the growing season, it is not appropriate to calculate pollutant transport and dispersal in a

climatological sense. Since plant growth rates are changing throughout the season and since they also have a diurnal character, it would be desirable to represent pollutant dispersal patterns in a more detailed fashion. We have therefore attempted to model the whole process on an hourly basis. Of course, the handling of hourly meteorological data for a whole growing season would be a cumbersome matter and to do so for a number of representative growing seasons would be almost prohibitive. The present approach has, however, been chosen for the purpose of illustrating the problem. Our aim is to study plant growth during what might be a "typical" growing season and we have used monthly climatological data together with a Monte-Carlo approach to construct this typical season on an hour-by-hour basis.

Probabilities of occurrence of various stability classes¹ are usually available on a monthly basis and these in combination with wind speed and direction probabilities can give estimates of average ground level concentrations in the vicinity of the source of a pollutant. Rather than calculate such climatological averages, we have calculated the concentration values associated with specific turbulence and wind speed occurrences. The probability of occurrence of these individual events and the associated wind directions allow one to construct a hypothetical hour-by-hour concentration history for locations in the vicinity of the point source. By then studying a model of plant growth, we could follow the details of ¹⁴C assimilation by crops at those locations.

¹A number of classification schemes exists and results can vary if different schemes are used (see e.g., Portelli (1976) and Fulle (1976)).

Looking at the whole process in this way allows one to make the important distinction between daytime and nighttime atmospheric dispersion conditions. A, B, and C stability conditions are daytime in character; E and F occur at night. D conditions can occur during both day and night (Turner, 1964). For the pollutant source studied, daylight conditions gave higher ground level concentrations at locations close by (see Fig. 1). With these differences in concentration we see that the diurnal pattern in the meteorology becomes important when photosynthetic assimilation is considered.

From the meteorological data one obtains the probability of occurrence of the various stability classes during any given month. Knowing that some of these classes are daytime conditions, and knowing the number of daytime and nighttime hours, one can then calculate the probability that a given hour which is known to be during daylight will have a given stability class associated with it. Using these probabilities and a Monte Carlo procedure, atmospheric transport and plant assimilation of ^{14}C was modeled on an hour-by-hour basis under daylight conditions. The plants were not allowed to assimilate any carbon during nighttime hours although they did lose CO_2 through respiration.

The Carbon Assimilation Model, CAM, (Dixon *et al.*, 1976) considers the flux of CO_2 , F , for uptake by a hypothetical crop species according to the equations:

$$F = {}^{12}F + {}^{14}F$$

$$= \frac{({}^{12}\text{CO}_2 - {}^{12}\text{CO}_2)_a}{r_{\text{CO}_2}} + \frac{({}^{14}\text{CO}_2 - {}^{14}\text{CO}_2)_a}{r_{\text{CO}_2}}$$

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Fig. 1. Plume centerline ground level concentrations for two important atmospheric conditions occurring in the study. Class A stability is a daytime occurrence and class E a nighttime occurrence.

where

n_{CO_2a} = ambient air ^{14}C concentration ($cm^3 CO_2/cm^3$ air);

n_{CO_2c} = ^{14}C concentration at chloroplast surface ($cm^3 CO_2/cm^3$ air); and

r_{CO_2} = total CO_2 transfer resistance (s/cm).

The concentration of ^{14}C in the outside air is calculated by the ATM.

The chloroplast concentration is known under normal conditions and, for conditions of elevated atmospheric concentration, it is presumed to be in the same ratio to the atmospheric concentration as it is under normal conditions.

3. RESULTS OF SIMULATIONS

We present here the results of a modeling study for a hypothetical crop species growing in the area of Oak Ridge, Tennessee, and near to a source of $^{14}CO_2$ as described above.

Speed stability wind rose data were divided into six stability classes (corresponding to Pasquill-Gifford classes A through F) and six wind speed classes which were typified by the following values:

<u>Class</u>	<u>Wind Speed (m/s)</u>
1	0.9
2	2.4
3	4.4
4	6.9
5	9.5
6	14.0

An analysis of the speed-stability wind rose allows one to identify the most prevalent combinations of wind speed and atmospheric stability which occur in the Oak Ridge area. Calculations of ground level concentrations along the wind vector yielded the maximum concentrations for these conditions. Further analysis of the wind rose identified the wind direction associated most frequently with these occurrences.

The most frequently occurring stability classes in the Oak Ridge area during the growing season are Pasquill-Gifford classes A, D, E, and F (local temperature profile data obtained by TVA and classified as atmospheric stability according to USAEC Regulatory Guide 1.21, June 1974). Wind speed classes 1, 2, 3, and 4 are important although all speed classes are not important for all stability classes. Most frequently the wind is from the southwest. We have analyzed conditions which refer to the case of a southwesterly wind having the stability and speed characteristics noted above. Such combinations would be expected to yield the maximum opportunity for assimilation of ^{14}C in growing plants.

Using this distribution of stability classes and the ATM, three locations at different distances from the source were recognized as having large exposure histories for ^{14}C in our hypothetical example. These are shown in Table 1. Table 2 shows the probability of occurrence of the important wind speed and stability conditions associated with a southwesterly wind during daylight hours.

The hypothetical crop species was studied under the assumption that it grew at a point of 0.5 km from the source of ^{14}C (see above) this being the most severe of the situations covered in Table 1. Since one hour is a reasonable time for the persistence of a particular meteorological

Table 1. Maximum ground level concentrations of $^{14}\text{CO}_2$ expressed as fraction by volume (cm^3/cm^3). The source emits at a rate of $2 \mu\text{Ci/s}$.

Stability Class	Wind Speed Class	Distance from stack		
		500 m	1 km	10 km
A	1	1.3×10^{-14}	5.7×10^{-15}	1.5×10^{-16}
A	2	5.1×10^{-15}	2.1×10^{-15}	5.8×10^{-17}
A	3	3.0×10^{-15}	1.2×10^{-15}	3.5×10^{-17}
D	3	4.4×10^{-17}	1.4×10^{-15}	3.6×10^{-16}
D	4	3.7×10^{-17}	9.6×10^{-16}	2.3×10^{-16}

Table 2. Fractional daytime occurrence of important stability classes associated with a southwesterly wind.

Stability Class	Wind Speed Class	April	May	June	July	August	September	October
A	1	0.0	0.0136	0.0479	0.0821	0.0080	0.0084	0.0056
A	2	0.0286	0.0272	0.0592	0.0238	0.0486	0.0641	0.0084
A	3	0.0344	0.0218	0.0310	0.0207	0.0703	0.0615	0.0224
D	3	0.0072	0.0095	0.0198	0.0223	0.0027	0.0097	0.0070
D	4	0.0230	0.0149	0.0	0.0103	0.0094	0.0209	0.0112
Conditions other than above		0.9068	0.9130	0.8421	0.8408	0.8610	0.8354	0.9454

"episode," ^{14}C assimilation was examined on an hour-by-hour basis. In Fig. 2 we show the variation in plant specific activity with an hour's resolution over a five-day period. Note that for much of the time, because of the wind direction, there is no increase over background concentration of $^{14}\text{CO}_2$. Also note that only those plume events occurring during daylight are contributing to an increased assimilation of ^{14}C .

In looking at the whole growing season as illustrated in Fig. 3, we see sizable variations in plant specific activity. The values are significantly greater than that predicted by using the yearly average ground level concentration of ^{14}C . There are three distinct reasons why average ground level concentration has underestimated specific activity of ^{14}C for plant material grown near the point of emission:

- 1) Atmospheric stability classes do not occur with *a priori* equal probabilities over a 24-hour period. Classes A, B and C occur during daylight hours, E and F occur at night and D can occur during both day and night. In our simulations we assumed that D conditions occurred with equal probability during day and night. These daylight conditions will, of course, occur when plants are photosynthesizing CO_2 and hence the uptake of ^{14}C is correlated with the occurrence of A, B, C, and D stability classes.
- 2) Periods of high insolation during summer months may mean that highly unstable atmospheric conditions are prevalent and the associated ground level concentrations may be the ones of importance to the growing plants.

Fig. 2. Atmospheric concentrations of $^{14}\text{CO}_2$ and ^{14}C content of leaves for five days during the growing season. The dashed line shows ground level atmospheric concentration of $^{14}\text{CO}_2$; the solid line shows ^{14}C content of leaves. Hours of dark are represented by solid bars and hours of light by clear bars.

Fig. 3. Environmental ^{14}C specific activities. The open circles represent the ^{14}C specific activity in plant leaves (S_p) sampled every 60 hours. The horizontal line represents the yearly average atmospheric specific activity (S_a).

- 3) Because of the pattern of exposure levels throughout the growing season and because the growth rate of a plant may vary during the season, the specific activity at any point during the season may be quite variable. Furthermore the specific activity may be different in different parts of the plant. This has important implications when considering the specific activity of plant material used as food. Our modeling studies here refer to plant leaves.

The results shown here are not limited to the case of ^{14}C , although this is a convenient example with which to illustrate the phenomenon. Since carbon dioxide is so much a part of photosynthesis, the connection with the diurnal pattern of meteorological conditions is obvious. However, uptake of many gaseous pollutants (e.g., SO_2) is largely dependent on stomatal activity insofar as their effect on plants is concerned. Hence other gaseous pollutants can be expected to follow similar patterns to those illustrated here.

4. IMPLICATIONS FOR INHALATION-INGESTION OF ^{14}C

The two major exposure pathways of ^{14}C are inhalation of $^{14}\text{CO}_2$ and ingestion of food containing radiocarbon. Radiological impact should consider both the radiation dose to the maximally exposed individual (fence-post man) and the radiation dose to populations.

4.1 Radiation Dose Commitments to Individuals

The radiation dose from ingestion of ^{14}C is directly related to the ^{14}C specific activity of the food. Therefore, the dose from crops grown in the vicinity of the point source of $^{14}\text{CO}_2$ would similarly be higher using the discrete event approach.

4.2 Radiation Dose to Populations

As the distance from the point-source increases, the more dispersed is the plume and the less difference there is between discrete event calculations of ground level $^{14}\text{CO}_2$ and a long-term average. Therefore, the use of a discrete event approach may not be as important for population dose estimates. It should be pointed out, however, that variable concentrations of gaseous radioisotopes from nuclear power facilities have been measured several kilometers from the point source (Carey *et al.*, 1974; Kunz, 1976). For site-specific assessments, the use of crops grown in the vicinity of a point source by populations distant from the growing area should be considered in the calculation of population dose commitments.

SUMMARY

It has been shown by analyzing the details of atmospheric transport and plant growth mechanisms that the concentration of material assimilated by a plant can be different from that predicted by the average ambient concentration. In fact, we have calculated a value significantly higher than that implied by the average ambient concentration for an area close-by to a source. The fact that the calculated value was much higher was quite dependent on the fact that the pollutant plume had no thermal rise associated with it. For sources which have thermal rise the effective source height would be relatively greater for the highly unstable atmospheric conditions and the effect might not be so pronounced. However, in general, the concentration at a given location may be significantly different for daylight hours during the growing season from what it is "on the average" throughout the year. Or, in other words, if one is

interested in assimilation of a pollutant by vegetation, the meteorology during periods of assimilation is of greatest importance.

We have presented results for a "typical" growing season. It should be recognized that these results represent the kinds of variations in specific activity that could occur. In terms of available climatological data, however, one is probably limited to monthly averages in the characterization of any given location. It is possible to conceive of more extreme excursions but it is doubtful that the necessary climatological data are available for any location.

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