CHAPTER 7

CO_2 ENVIRONMENT

7.1. INTRODUCTION

Carbon dioxide concentration in the air is another important factor for plant growth. The CO_2 concentration in the open air varies daily. On a sunny day the CO_2 level is fairly constant around 300 to 350 $\mu l/l$ due to photosynthesis by plants, and it rises to around 400 to 450 at night. The CO_2 level is more important under cover, especially in plastic houses where air exchange is normally restricted in order to raise temperatures in a cold climate. As a result, the carbon dioxide concentration falls below the outside level during the daytime due to photosynthetic CO_2 uptake. Therefore, sometimes CO_2 enrichment is conducted in plastic houses.

In CO_2 flow above the open ground in the daytime, the plant layer is a sink, and there are two sources of CO_2, one in the air layer above the plants and the other in the soil layer. In plastic houses, CO_2 is supplied from outside through ventilation instead of through flow from the air layer above the plants. CO_2 generation in soil is therefore an important source in both open fields and plastic house environments. CO_2 in soil is released through plant root respiration, microbial activity, chemical changes and physical phenomena.

7.2. CO_2 CONCENTRATION IN SOIL LAYER (**CUC70**)

There are not many reports on the CO_2 environment in soil, but Yabuki (1966) measured CO_2 concentration in soil and considered its daily and seasonal variation. In simulations by van Bavel (1951) and Ito (1979), steady-state patterns in several soil layers were demonstrated clearly, but periodic changes in CO_2 concentration were not considered. It is clear that non-linear models are needed in order to analyze the effects of soil temperature on CO_2 diffusion. Typical hourly changes and trends over three days are shown in Fig. 7.1.

Large changes at deeper soil layers are striking; it is apparent that temperature has an effect on the CO_2 concentration.

CO_2 diffusion in soil is similar to heat transfer as well as to water vapor transfer in soil. Therefore, let us consider the same model we used for soil temperature in Chapter 3. In this model, CO_2 concentration (**C1**) in the first soil layer shown in Fig. 3.10 is given as

IC1 = **DS** * (**CCF** - **C1**)*2.0 / **Z** + **DS** * (**C2** - **C1**) / **Z**) / **Z** + **gen1** (7.1)

where **IC1** is the differential form of the **C1** related equation, which is one of the equations to be solved simultaneously. **DS** is the diffusion coefficient (m^2/hr); **CCF**, **C1** and **C2** are CO_2 concentrations just above the ground, in the top layer, and in the second layer, respectively; **Z** is the depth of the soil layer; and **gen1** is CO_2 generation in the same soil layer ($m^3/m^3/hr$) derived using the following equation:

gen1 = **CCG1** * **fgen1**

where **CCG1** is the coefficient of CO_2 generation and **fgen1** is the amount of CO_2 generated in soil layer 1 by micro-organisms. It has also been found that the effect of temperature on CO_2 generation is much greater than that on the diffusion coefficient (**DS**), so **DS** is assumed to be constant in the program.

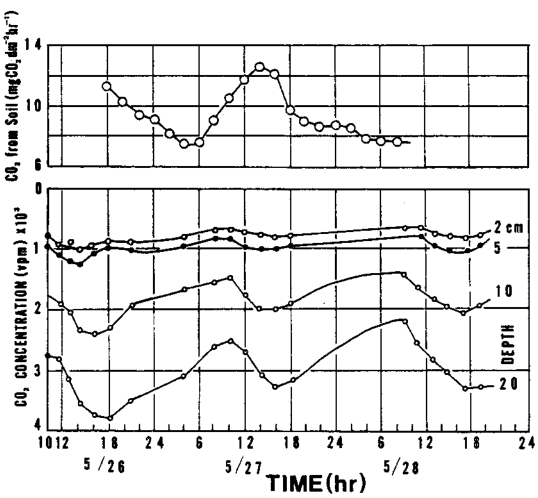

Figure 7.1. Hourly patterns of CO_2 concentration change in soil (after Yabuki, 1966).

Plant respiration is a **Q10** function of temperature; that is, for every 10°C increase in temperature, respiration is doubled (see Fig. 7.2). Therefore, it is assumed that CO_2 generation due to biological reactions is in this form, as indicated by the array of [**Xtemp**, **Yco2**] as shown in Fig. 7.3b. Non-dimensional generation is 0.0 at 0°C, 0.5 at 10°C, 1.0 at 20°C, 2.0 at 30°C, 1.5 at 40°C, 1.0 at 50°C and 0.0 at 60°C. Thus, the array of **Xtemp** is [0 10 20 30 40 50 60] and **Yco2** is [0.0 0.5 1.0 2.0 1.5 1.0 0.0]. A function for one-dimensional interpolation, **interp1**, is used to derive the amount of CO_2 generated according to the soil temperature.

fgen1 = **interp1**(**Xtemp**, **Yco2**, **T1**, 'nearest');

The third parameter is the value of Xtemp for interpolation**,** and the fourth parameter is the method used for the interpolation. The graph of [**Xtemp**, **Yco2**] and several methods of interpolation can be found in Fig. 7.6. Refer to section 7.5 of this chapter for more details.

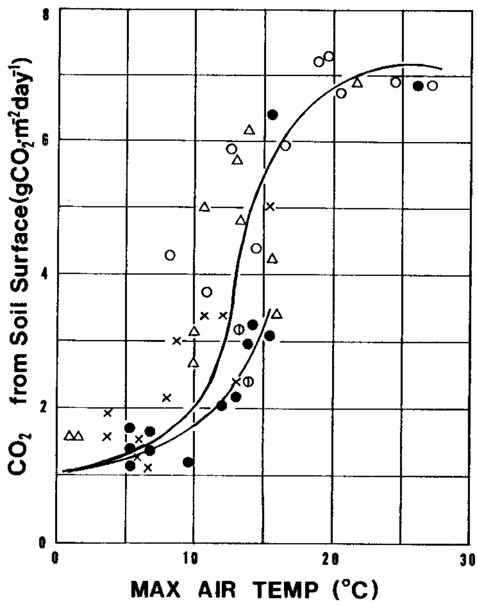

Figure 7.2. The relationship between maximum air temperature and CO2 release from soil surface (after Yabuki, 1966).

The main part of the program is more or less the same as that in Fig. 3.8. Five equations **(IC1** to **IC5**) to find the CO_2 concentration in soil layers (**C1** to **C5)** have been added with boundary conditions, one of which is a **sin** function (**CCF**) to give CO_2 variation at the soil surface.

The value for **DS** has been changed from 0.002 to 0.02 (m^2/hr). The former is close to the value van Bavel used in his simulation. When **DS** becomes larger, gas exchange is activated and the CO_2 concentration levels and amplitude of variation are decreased. This is a much faster way to obtain a steady state, and a tendency to increase or decrease without reaching steady-state is also overcome.

CO_2 generation in the soil layers is assumed to be larger in the upper soil layers than in the lower layers: the CO_2 generation rate is $1x10^{-3}$ m^3/m^3/hr in the upper two layers and 0.7, 0.5 and $0.3x10^{-3}$ in the remaining three layers. These figures are on the order of van Bavel's values (1951), and ten times smaller than those of Ito (1979).

As it is not easy to measure CO_2 generation in the soil layer, it is difficult to determine which order of magnitude is reasonable. In the present simulation, these values are assumed in order to measure periodic changes similar to those of Yabuki (1966). However, there are some data that indicate the CO_2 concentration in soil is up to ten times more than those simulated here.

A typical simulation result is shown in Fig. 7.4. Since the value of **DS** in this run is rather small (0.005), a tendency for CO_2 to slightly increase with periodic change is apparent in deeper layers. The amplitude of the CO_2 concentration in the first layer is about 1000 $\mu l/l$ (0.1%), and the CO_2 concentration changes from 5000 to 6000 $\mu l/l$ (0.5 to 0.6%). In the second layer, the amplitude is about 3000 $\mu l/l$ (0.3%), and the CO_2 concentration changes from 12000 to 15000 $\mu l/l$ (1.2 to 1.5%). Amplitudes decrease to a degree similar to the experimental data in Fig. 7.1.

```
%   Carbon dioxide concentration in the soil layer             CUC70.m
%   Generation in each layer is assumed as a function of temperature
%   Function requires: co2insoil.m
%
function cuc70(out)
clc
disp('Please wait.');
global DS
if out==1, DS=0.005;end
if out==2, DS=0.02;end
tic
tstart=0;tfinal = 48;     % Define run time
y0 = [20 20 20 20 20 0.005 0.015 0.02 0.02 0.02]' ;   % initial conditions.
[t,y] = ode23t('co2insoil',[tstart tfinal],y0);
% calling function ode23t, constants & eqs are listed in 'co2insoil.m'
% Replace ode23t with ode45 for MATLAB version prior to 5.3
% [t,y]=ode45('co2insoil',[tstart tfinal],y0);
toc
if out==1
    h1=findobj('tag','Temperature');     close(h1);
    figure('tag','Temperature','Resize','on','MenuBar','none',...
    'Name','CUC70.m (Figure 1: Temperature in soil layers)',...
      'NumberTitle','off','Position',[140,140,520,420]);
    h=plot(t,y(:,1),t,y(:,2),t,y(:,3),t,y(:,4),t,y(:,5));
    set (h,'linewidth',2);
    axis([-inf,inf,10,40]);       grid on;
    xlabel('time elapsed, hr');   ylabel('Soil temperature, ^oC');
    legend('T1','T2','T3','T4','T5');
    title('Temperature in soil layer');
    figure('tag','CO2','Resize','on','MenuBar','none',...
    'Name','CUC70.m (Figure 2: CO2 concentration in soil layers)',...
      'NumberTitle','off','Position',[180,100,520,420]);
end
if out==2
    figure('tag','CO2','Resize','on','MenuBar','none',...
    'Name','CUC70.m (Figure 3: CO2 concentration in soil layers)',...
      'NumberTitle','off','Position',[220,60,520,420]);
end
h=plot(t,y(:,6),t,y(:,7),t,y(:,8),t,y(:,9),t,y(:,10));
set (h,'linewidth',2);
axis([0,48,0,0.03]);
grid on;
xlabel('time elapsed, hr');
ylabel('CO_2 cincentration, ND');
legend('C1','C2','C3','C4','C5');
co2title=['CO_2 concentration in soil layer when DS=' num2str(DS,5) ' m^2/hr'];
title(co2title);
disp('Thank you for using ');
disp(' ');
disp('CUC70: Porgram to calculate changes of soil temperature');
```

```
disp('      and CO2 concentration in soil layers with focus on DS value.');
disp(' ');
disp('You can enter ''close all'' in the command window to close figure windows.');
disp(' ');
```

Figure 7.3a. Main program to calculate CO_2 concentration in soil **(CUC70.m)**.

```
% Subprogram to be used with cuc70 model                        co2insoil.m
function dy = co2insoil(t,y)
global DS
%[Xtemp Yco2] is the array of CO2 generated from soil;
Xtemp=[0 10 20 30 40 50 60];
Yco2=[0.0 0.5 1.0 2.0 1.5 1.0 0.0];
omega=2*pi/24;
%----------------------------------------PARAMETER---------------------
Z=0.1;         % Depth of each soil layer (m)
KS=5.5;CS=2000;
% KS=11;CS=2000;   % KS doubled
% KS=5.5;CS=4000;  % CS doubled
% KS: Soil thermal conductivity (kJ/m/C) and KS/3.6 (W/m/C)
% CS: Heat capacity of soil (kJ/m3/C)
%----------------------------------------CONSTANT----------------------
T0=25;  TU=15;  TBL=25;    % All in degree C
% T0: Avg. outside T, TU: Variation of T, TBL: Boundary soil T
%--------------------------------------------------------------------
clk=mod(t,24);
TF=T0+TU*sin(omega*(clk-8.));
%  TF: Soil temp of surface layer (C),   t: time  in hr
%  Maximum temp occurs at 2 o'clock in the afternoon
CCF=(0.04+0.01*sin(omega*(clk+6)))/100;
%  CCF: CO2 concentration in the air
%  DS=0.005;  % now a global variable
%  DS: diffusion coefficient of CO2 in soil (m2/hr)
CCG1=0.001;CCG2=0.001;CCG3=0.0007;CCG4=0.0005;CCG5=0.0003;
%  CCGx: CO2 generation coefficient in soil by microorganisms (m3/m3/hr)
%--------------------------------------------------------------------
T1=y(1); T2=y(2); T3=y(3); T4=y(4); T5=y(5);
C1=y(6); C2=y(7); C3=y(8); C4=y(9); C5=y(10);
IT1=(2*KS*(TF-T1)/Z+KS*(T2-T1)/Z)/Z/CS;
IT2=(KS*(T1-T2)/Z+KS*(T3-T2)/Z)/Z/CS;
IT3=(KS*(T2-T3)/Z+KS*(T4-T3)/Z)/Z/CS;
IT4=(KS*(T3-T4)/Z+KS*(T5-T4)/Z)/Z/CS;
IT5=(KS*(T4-T5)/Z+KS*(TBL-T5)*2/Z)/Z/CS;
%--------------------------------------------------------------------
fgen1=interp1(Xtemp,Yco2,T1,'nearest');  gen1=CCG1*fgen1;
IC1=(2*DS*(CCF-C1)/Z+DS*(C2-C1)/Z)/Z+gen1;
fgen2=interp1(Xtemp,Yco2,T2,'nearest');  gen2=CCG2*fgen2;
IC2=(DS*(C1-C2)/Z+DS*(C3-C2)/Z)/Z+gen2;
fgen3=interp1(Xtemp,Yco2,T3,'nearest');  gen3=CCG3*fgen3;
IC3=(DS*(C2-C3)/Z+DS*(C4-C3)/Z)/Z+gen3;
fgen4=interp1(Xtemp,Yco2,T4,'nearest');  gen4=CCG4*fgen4;
IC4=(DS*(C3-C4)/Z+DS*(C5-C4)/Z)/Z+gen4;
fgen5=interp1(Xtemp,Yco2,T5,'nearest');  gen5=CCG5*fgen5;
IC5=DS*(C4-C5)/Z/Z+gen5;
dy = [IT1 IT2 IT3 IT4 IT5 IC1 IC2 IC3 IC4 IC5]';
```

Figure 7.3b. Subprogram to calculate CO_2 concentration in soil **(CO2insoil.m)**.

7.3. PROGRAM EXECUTION AND OUTPUT

Enter 'cuc70(1)' in the Command Window to execute the **cuc70** program. When variable **out** equals 1 (or 2), value 0.005 (or 0.02) will be assigned to variable **DS**. Fig. 7.4a and Fig. 7.4b show the outputs of 'cuc70(1)', and Fig. 7.4c shows the output of 'cuc70(2).

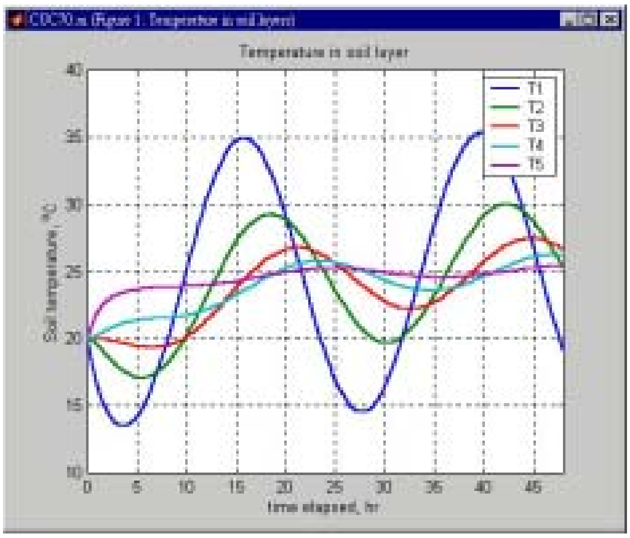

Figure 7.4a. Temperatures in soil layers when DS=0.005.

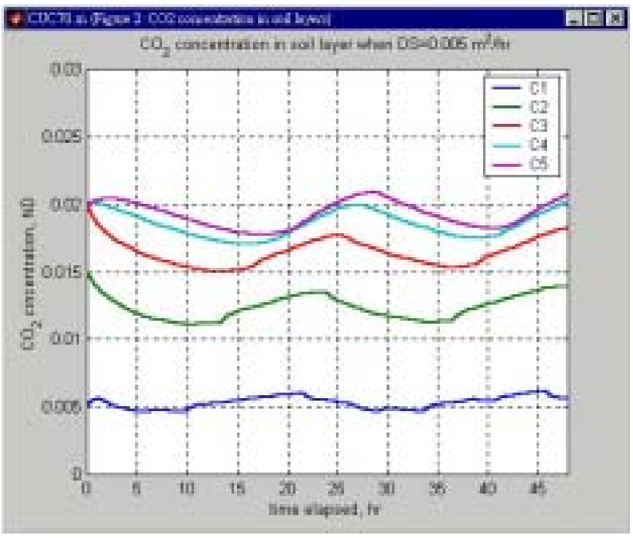

Figure 7.4b. CO_2 concentrations in soil layers when DS=0.005.

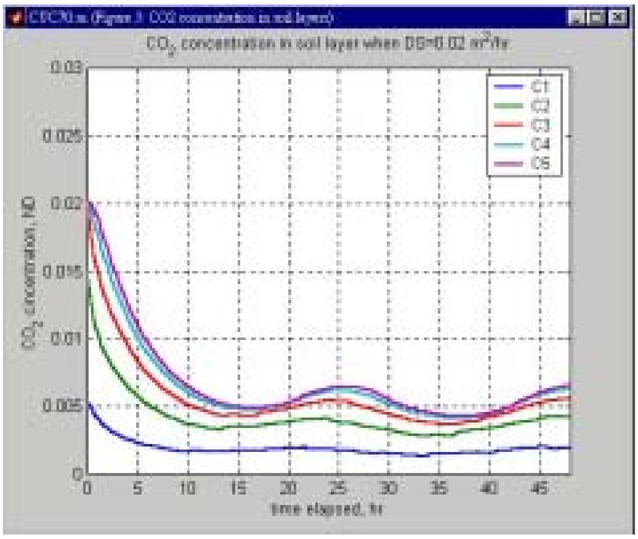

Figure 7.4c. CO_2 concentrations in soil layers when DS=0.02.

7.4. CO_2 CONCENTRATION IN A PLASTIC HOUSE AND VENTILATION

As mentioned in the introduction to this chapter, the CO_2 concentration in a plastic house is determined by the CO_2 balance in the house. There are two sources and one sink during the daytime. CO_2 brought in from the outside through ventilation and released from soil in the house are the sources, and plant photosynthesis is the sink.

Ventilation is usually defined as either a rate or an amount. Ventilation rate (**N**) is expressed in terms of the number of multiples of house volumes of air exchanged in an hour (1/hr), and ventilation amount (**Q**) is air volume per unit floor area per unit time ($m^3/m^2/min$).

Then, CO_2 balance in a house is given as

$$\mathbf{V} * (d\mathbf{CI}/d\mathbf{t}) = \mathbf{V} * \mathbf{N} * (\mathbf{CO} - \mathbf{CI}) + \mathbf{AS} * \mathbf{DS} * \mathbf{SH} * (\mathbf{CF} - \mathbf{CI}) - \mathbf{CONV} * \mathbf{PH} * \mathbf{AP} \quad (7.2)$$

where **V** is house volume (m^3); **CI**, **CO** and **CF** are CO_2 concentrations in the house, in the outside air and at the soil surface, respectively (m^3/m^3); **N** is ventilation rate (1/hr); **AS** is floor area (m^2); **DS** is diffusion coefficient of CO_2 (m^2/hr); **SH** is Sherwood number; **CONV** is the conversion factor from mg CO_2 to m^3; **PH** is photosynthesis rate (mg $CO_2/m^2/hr$); and **AP** is plant leaf area in a house (m^2). Using eq. 7.2, the model in Fig. 7.3 can be combined with the house model in Fig. 6.13, for example.

7.5. ONE-DIMENSIONAL INTERPOLATION

Several methods can be used to do the interpolation as shown in Fig. 7.5 and Fig. 7.6. The execution time follows the same order as listed in Fig. 7.5. The curves generated by the methods ‘cubic’ and ‘spline’ are much smoothes than those generated by the methods ‘nearest’ and ‘linear’. If components of the vector X are at the same interval, the speed of execution can be improved by a leading ‘*’ with a method such as ‘*linear’.

```
% Learning one-dimensional interpolation                    cuc70sup.m
%
x=0:10:60;
y=[0 0.5 1 2 1.5 1.0 0];
xi=0:1:60;
y1=interp1(x,y,xi,'nearest');
y2=interp1(x,y,xi,'linear');
y3=interp1(x,y,xi,'cubic');
y4=interp1(x,y,xi,'spline');
plot(x,y,'o',xi,y1,'g-',xi,y2,'r:',xi,y3,'c-.',xi,y4,'b--');
legend('Original','nearest','linear','cubic','spline');
```

Figure 7.5. Learning one dimensional interpolation.

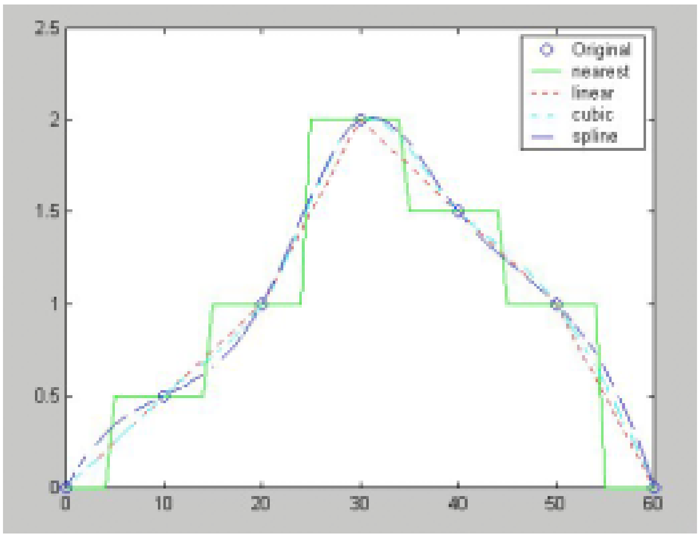

Figure 7.6. Output of program listed in Fig 7.5.

PROBLEMS

1. Consider the reason why we have a rather irregular shaped curve for the change of CO_2 concentration in the first soil layer.

2. Try to find how many days we need to get steady periodic change for both temperature and CO_2 concentration in all soil layers.

3. Rerun the program **CUC70**, assuming that the diffusion coefficient of CO_2 (**DS**) is a function of temperature; that is, **DS** = 0.005 + 0.001***TEMP**, where **TEMP** is soil temperature.

4. Change the boundary condition for CO_2 from the CO_2 concentration at the soil surface to that in the air in the program **CUC70**.

5. What is the effect of soil properties **KS** and **CS** on CO_2 concentrations in the soil layers? Note that **KS** is the soil thermal conductivity (kJ/m/C) and **CS** is the heat capacity of the soil (kJ/m^3/C). Rerun the program **CUC70** using the following 3 sets of parameter values:

   Case 1: KS = 5.5, CS=2000
   Case 2: KS = 11, CS=2000
   Case 3: KS = 5.5, CS=4000