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Simulating global soil-CO_2 flux and its response to climate change

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Abstract: It has been argued that increased soil respiration would become a major atmospheric source of CO_2 in the event of global warming. The simple statistical models were developed based on a georeferenced database with 0.5° × 0.5° longitude/latitude resolution to simulate global soil-CO_2 fluxes, to investigate climatic effects on these fluxes using sensitivity experiments, and to assess possible responses of soil-CO_2 fluxes to various climate change scenarios. The statistical models yield a value of 69 PgC/a of global soil-CO_2 fluxes for current condition. Sensitivity experiments confirm that the fluxes are responsive to changes in temperature, precipitation and actual evapotranspiration, but increases in temperature and actual evapotranspiration affect soil-CO_2 fluxes more than increases in precipitation. Using climatic change projections from four global circulation models, each corresponding to an equilibrium doubling of CO_2, it can be found that the largest increases in soil-CO_2 fluxes were associated with the boreal and tundra regions. The globally averaged soil-CO_2 fluxes were estimated to increase by about 35% above current values, providing a positive feedback to the greenhouse effect.

Key words: climatic variable; sensitivity experiment; soil respiration; statistical model

Introduction

Global climate models predict temperature increases due to enhanced greenhouse warming in the not-too-distant future (Houghton, 1990). It has been argued that one of the important effects of global warming will be to accelerate the decomposition of soil organic matter, thereby releasing CO_2 to the atmosphere and further enhancing the warming trend. Soil carbon depletion in response to the global warming has been studied by Jenkinson *et al*. (Jenkinson, 1991), Kwon and Schnoor (Kwon, 1994) and Schlesinger (Schlesinger, 1995), all of whom suggest that the efflux of carbon dioxide from soil could become a major source of atmospheric CO_2. On a global scale, soil respiration of terrestrial ecosystems has been estimated to contribute 50-77 PgC/a as carbon dioxide to the atmosphere each year (Schlesinger, 1977; Houghton, 1989; Raich, 1992; 1995; Robinet, in press). Despite its importance in the global carbon cycle, the magnitude and distribution of soil respiration over the globe and through time, however, have been poorly quantified.

The soil-CO_2 fluxes represent the sum of all soil metabolic activities in which CO_2 is produced (Lundegardh, 1927). These include root respiration and decomposition, litter decomposition, and soil organic matter decomposition. These sources of CO_2 to the atmosphere are difficult to isolate from one to another and are generally lumped together as a total CO_2 flux from the soil (Fung, 1987). This soil-CO_2 efflux, or evolution, is approximately equal to the soil respiration rate on an annual basis unless significant losses of inorganic C occur through leaching or deposition (Schlesinger, 1981; 1985; Raich, 1992) or by disturbance (Kurz, 1994). Although many climatic factors influence the biological and physical processes that control soil-CO_2 fluxes, field studies have shown that temperature and moisture are the most important factors regulating soil-CO_2 fluxes in both disturbed and undisturbed sites (Schlesinger, 1977; Ewel, 1987; Gordon 1987).

Several estimates of soil-CO_2 flux have been developed from models based on regression

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Foundation item: Canadian Government Laboratory Visiting Fellowship from the Nature Sciences and Engineering Council of Canada, and the Department of Natural Resources Canada (Canadian Forest Service); * Corresponding author analyses. Fung *et al*. (Fung, 1987) used this approach to predict monthly soil respiration in grasslands, temperate/boreal needle-leaved vegetation, temperate/boreal broad/leaved vegetation, and tropical/subtropical woody vegetation using observed air temperature as the independent variable. The correlation coefficients (r) ranged from 0.67 to 0.80. Similarly, using annual soil-CO_2 flux estimates from field studies at many sites around the globe, Raich and Schlesinger (Raich, 1992) developed several regression models describing the relationship between annual soil respiration rate and climate variables (mean annual temperature and annual precipitation) with correlation coefficients (r) ranging from 0.65 to 0.7. They estimated the mean annual global soil respiration to be 68 ± 4 PgC/a, a value obtained by multiplying the biome land areas with their estimates of mean annual soil-CO_2 fluxes. However, Raich and Schlesinger (Raich, 1992) estimate is based on mean biome fluxes and does not take into account the spatial and temporal variability in soil-CO_2 fluxes. Based on published (Raich, 1992) and unpublished database of soil-CO_2 fluxes, Raich and Potter (Raich, 1995) have recently developed a semi-mechanistic, but still empirical, statistical model to simulate the spatial and temporal patterns of soil-CO_2 fluxes. The results suggest that the soil respiration rate correlates significantly with temperature and precipitation, but does not correlate well with soil carbon pools, soil nitrogen pools or soil C/N ratio. Annual global soil-CO_2 fluxes are estimated by Raich and Potter (1995) to be 76.5 PgC/a. However, Raich and Potter's (1995) model did not considerate the potential effect of actual evapotranspiration (AET) and explained only 41% of the variability present in measured soil-CO_2 fluxes. Recently, Robinet (in press) reinterpreted the global soil respiration data sets reported by Raich and Schlesinger (Raich, 1992) to obtain different regressions of soil respiration with mean annual temperature and annual precipitation. He estimated global soil-CO_2 to be 60 PgC/a, but did not take into account the effects of human land-use on soil-CO_2 fluxes.

Brook *et al*. (Brook 1983) and Kiefer (Kiefer, 1990) also developed a regression model to analyze global relationships between average CO_2 concentration in soil and climate and found that actual evapotranspiration (AET) was the best climatic predictor of CO_2 concentration in the soil. Annual AET, which combines the availability of solar energy, the most important rate-limiting resource in photosynthesis, and soil water in one variable. It not only correlates well with net primary production (Lieth, 1972; 1975), but also correlates with litter production and decomposition, soil carbon storage (Meentemeyer, 1978; 1982; 1985) and other plant processes (Dyer, 1990; Foley, 1994). AET is influenced by soil temperature and soil moisture, both of which have significant influences on soil respiration rates. However, the explicit relationship between AET and these climatic variables has not yet been defined (Raich, 1992).

Our primary objectives in this study were to (1) reexamine the quantitative relationship between climatic variables (temperature (T), precipitation (P) and AET) and soil-CO_2 fluxes using field site data reported by Raich and Schlesinger (Raich, 1992); (2) estimate the annual global soil-CO_2 fluxes based on Olson *et al*.'s (Olson, 1985) ecosystems database (0.5° × 0.5° longitude/latitude resolution), considering the effects of human land-use and spatial variability in soil-CO_2 fluxes and comparing the new estimate to previous ones; (3) use several global circulation model (GCM) scenarios to investigate the potential effects of a CO_2 doubling and associated climate change on soil-CO_2 fluxes for the world's terrestrial ecosystems.

1 Data and methods

For a global model of annual soil-CO_2 fluxes, we need terrestrial soil-CO_2 flux values characterizing the main ecosystem types and a geographically matched set of climatic variables. To produce a geographically realistic model, data are required for virtually the entire range of terrestrial ecosystems.

1.1 Soil-CO_2 flux data

Raich and Schlesinger's (1992) summary of published estimates of soil respiration in terrestrial ecosystems provides the most complete reference at a global scale. This data set includes only those data based on full year measurements (or most of a full year), and excludes measurements made on soil cores. Also excluded are data obtained with alkali absorption technique because these data lead to modified root respiration or low estimates of soil respiration. In using these data, we have additionally excluded some sites without latitude and longitude references and have averaged the soil respiration values within the same 0.5° × 0.5° cell. This procedure yielded 150 available measurement sites which we have divided into three main groups: (1) 117 sites representing the major natural ecosystems (tundra, boreal forest and woodland, temperate grassland, temperate coniferous forest, temperate broad-leaved and mixed forests, Mediterranean woods, desert scrub, tropical savanna and grassland, tropical and subtropical dry forest,· tropical and subtropical moist forest); (2) 19 sites representing the major disturbed ecosystems (crops, settlement, field, and fringe land); (3) 14 sites representing northern bogs, mires, and marshes.

1.2 Climate data

The IIASA climatic database (Leemans, 1991) provides mean monthly values of temperature, precipitation, and cloudiness on a global terrestrial grid with a 0.5° × 0.5° (latitude/longitude) resolution. The mean annual T and annual P were calculated by averaging the twelve monthly values of temperature and precipitation. Based on the mean monthly values of temperature, precipitation, and cloudiness, the AET and PET (Potential evapotranspiration) were computed using a bucket model (water-balance model) and assuming a constant soil water capacity of 150 mm (Harrison, 1993).

Only a few of the study sites both reported soil respiration and also provided climate data such as T and P. Therefore, both T and P at most of the measurement sites and AET for all of the studies sites were interpolated linearly from IIASA global climatic database (Leemans, 1991) with a 0.5° latitude by 0.5° longitude resolution.

1.3 Ecosystem data

We use the Olson *et al.* (Olson, 1985)'s database, which defines the major terrestrial ecosystems, on a 0.5° × 0.5° grid. The major climatic, topographic and land-use patterns are reflected in the ecosystem complexes used by Olson *et al.* (1985). Ecosystems that have been modified by land-use are classified as field/woods, forest/fields and cropped lands. We slightly modified this classification by combining all human-disturbed ecosystems into a single type "crops and field". While this is recognized as a simplication of reality. There is insufficient soil-CO_2 flux measurement data to distinguish between these different types.

1.4 Development of soil-CO_2 flux models

Although soil respiration is a complex set of dynamic processes which are controlled by many environmental factors (Singh, 1977), the relationships between climatic factors and soil-CO_2 flux have been widely studied and provide a solid foundation of both theory and data upon which we based our model. We selected six climatic variables (T, P, PET, AET, soil moisture deficit (PET-AET) and soil moisture index (AET/PET)) form the set of independent variables used in this statistical analysis. Based on the statistical package of Giout (Giout, 1991), stepwise regression is performed to develop a statistical model that "explains" the largest amount of variance in soil-CO_2 flux. The results have shown that T, P and AET are correlated significantly with soil-CO_2 flux ($P < 0.001$, stepwise linear regression) and rest variables were found to be poorer predictors of soil-CO_2 flux.

1.4.1 Correlation soil-CO_2 fluxes with AET

In order to distinguish important differences in soil-CO_2 fluxes from undisturbed ecosystems, disturbed ecosystems, northern bogs and other wetlands, we calculated three regression models (hereafter called AET-models) based on the data sets of these three different groups of ecosystems. The quantitative relationship of annual soil respiration (SR) against local actual AET for measurement data in each ecosystem group can be summarized as follows:

Group A: Major natural ecosystems

$$SR = 0.42\,(AET)^{1.12}, \qquad (r^2=0.67); \tag{1}$$

Group B: Crops and fields

$$SR = 1.59\,(AET) - 410, \qquad (r^2=0.64); \tag{2}$$

Group C: Wetlands (bogs, mires, and marshes)

$$SR = 0.40\,(AET) + 1.18, \qquad (r^2=0.65). \tag{3}$$

Here, SR is the mean annual soil respiration rate (gC/($m^2 \cdot a$)), and AET is the mean actual evapotranspiration (mm).

1.4.2 Soil-CO_2 flux models

One of the best combinations of the climatic variables to simulate the soil respiration is based on a non-linear combination of T, P and AET. The combination of T, P, and AET has improved the correlation coefficient for three groups. The resulting simulation equations (which we refer to as, TPAET-models) are:

Group A: Major natural ecosystems

$$SR = 7.64\exp(0.029T)\,P^{0.171}\,AET^{0.423}, \qquad (r^2=0.70); \tag{4}$$

Group B: Crops and fields

$$SR = 0.66P + 0.95AET - 7.11T - 468, \qquad (r^2=0.71); \tag{5}$$

Group C: Wetlands (bogs, mires, and marshes)

$$SR = 0.722AET - 0.023P - 10.241T - 140, \qquad (r^2=0.74). \tag{6}$$

Global annual soil-CO_2 fluxes (SCF) are calculated by summing over the land area of each 0.5° × 0.5° cell (j) in each of the three ecosystem groups (i = A, B, C):

$$SCF = \sum\,(SR(i) \times Area(ij)). \tag{7}$$

2 Model results

2.1 Global soil-CO_2 flux and geographic patterns

As shown in Table 1 the global soil-CO_2 flux is estimated to 64 PgC/a using the calibrated AET- model (equations: (1)—(3)) and about 69 PgC/a using the calibrated TPAET-model (equations: (4)— (6)). These values are within the range of 68 ± 4 PgC/a based on extrapolating the mean biomes soil-CO_2 fluxes provided by Raich and Schlesinger (Raich, 1992), but, are 9% to 16% lower than the estimate based on extrapolating the annual soil-CO_2 flux model (a) (Raich, 1992) and the soil-CO_2 flux model (b) (Raich, 1995). The figure of 69 PgC/a, which is between the values of annual soil-CO_2 flux that are based on only AET-model (c) and both T and P(a), seems to be close to the estimate based on mean biome soil-CO_2 flux. In contrast, our global soil-CO_2 flux estimates are 7% to 15% higher than the Robinet reports (Robinet, in press). Robinet's approach, based on the 1° × 1° distribution of ecosystems published by Wilson and Henderson-Sellers (Wilson, 1985), does not recognize the disturbed ecosystems, so that the difference between this estimate and ours indicates the probable effects of spatial resolution and land-use disturbances on soil-CO_2 flux.

Table 1 Comparison of global estimates of soil-CO_2 flux

Sources	Estimates, PgC/a	Correlation, r^2
1. Raich and Schlesinger (1992)		
Mean biome soil-CO_2 flux	68 ± 4	N/A
Annual soil-CO_2 flux model (a)	76	0.50
2. Raich and Potter (1995)		
Monthly soil-CO_2 flux model (b)	77	0.41
3. Robinet (in press)		
Annual soil-CO_2 flux models	60	0.65 - 0.81
4. This study		
Annual soil-CO_2 flux (AET - model) (c)	64	0.64 - 0.67
Annual soil-CO_2 flux (TPAET-model) (d)	69	0.70 - 0.74

(a) CO_2 flux = 9.26T + 0.0127(T)(P) + 289; CO_2 flux is annual soil-CO_2 flux (gC/(m^2·a); T is mean annual temperature (℃); P is annual precipitation (millimeters); (b) CO_2 flux = 1.33 (P/(P + 1.63)) exp 0.04T; (c) AET-model represents three different ecosystems groups models according to equations (1)—(3) (see text); (d) TPAET-model represents three different ecosystems groups models according to equations (4)—(6) (see text); N/A means no available

Table 2 present the distribution of annual soil-CO_2 flux as calculated by TPAET-model (equations: (4)—(6)). The estimated soil-CO_2 fluxes differ with terrestrial ecosystems and regions. The largest annual estimated soil-CO_2 flux (1250 gC/(m^2 · a) occurs in tropical moist forests where both temperature and moisture availability are high all year-round; the lower annual estimated soil-CO_2 flux occurs in the coldest ecosystems including tundra (184 gC/(m^2·a)) and northern bogs (239 gC/(m^2·a)) due to the low soil temperature, and deserts (177 gC/(m^2·a)) due to inadequate precipitation. These geographical patterns of soil-CO_2 flux are not dissimilar to those of Raich and Potter (1995) and Robinet (inpress).

Table 2 Response of soil-CO_2 flux by ecosystem to the climate change scenarios simulated by four general circulation models (GCMs). The vegetation types and observations are taken from Table 1 of Raich and Schlesinger (1992). Increases of soil-CO_2 flux are shown as percentage change from TPAET-model (equations (4)—(6) in text) values

Ecosystem	Mean soil CO_2, gC/(m^2·α)					
	Current	Climate	Climate	Change	Scenarios	(2 × CO_2)
	Observation	TPAET-model	OSU(+%)	GFDL(+%)	GISS(+%)	UKMO(+%)
Tundra	60 ± 6	184	249(35.6)	252(36.7)	253(37.1)	262(42.3)
Boreal forest	322 ± 31	305	415(36.2)	422(38.4)	424(39.1)	443(45.2)
Temperature coniferous forest	681 ± 95	549	712(29.7)	732(33.4)	736(34.0)	749(36.5)
Temperature deciduous and mixed broad and needle leaved forest	647 ± 51	564	724(28.3)	741(31.4)	749(32.6)	756(34.1)
Temperate grasslands	442 ± 78	382	489(27.9)	496(29.8)	498(30.4)	508(32.9)
Mediterranean woodlands and heath	713 ± 88	741	928(25.3)	946(27.6)	955(28.9)	974(31.4)
Desert scrub	224 ± 38	177	214(21.0)	224(26.7)	225(27.4)	221(24.8)
Tropical savannas and grassland	629 ± 53	663	753(13.5)	792(19.4)	800(20.6)	804(21.2)
Tropical dry forest	673 ± 134	807	902(11.8)	930(15.2)	935(15.8)	947(17.4)
Tropical moist forest	1260 ± 57	1205	1321(9.6)	1348(11.6)	1352(12.2)	1406(16.7)
Wetland (bog and mires)	94 ± 16	239	313(31.0)	320(34.0)	323(35.2)	331(38.3)
Croplands and fields	544 ± 80	549	688(25.4)	693(26.3)	697(27.0)	720(31.2)

2.2 Sensitivity to CO_2-induced climate change

In order to examine how changes in temperature, precipitation and evapotranspiration would affect future soil-CO_2 flux, sensitivity experiments were performed by varying the values of temperature, precipitation, and evapotranspiration. These sensitivity experiments can be related to the simulations of changes in global average temperature and precipitation generated by GCMs that simulate the climatic consequence of effectively doubled levels of atmospheric CO_2 concentration (Houghton, 1990).

We studied the overall effect of climatic change on the soil-CO_2 flux at each grid point by successively increasing: (1) temperature (by +1.5℃, +2.5℃ and +4.5℃); (2) precipitation (by +5℃, +10℃ and +15℃); and (3) evapotranspiration (by +5℃, +10℃ and +15℃). For each sensitivity experiment, one variable was altered at each grid point by a specified amount and the others were held at their current values.

As shown in Table 3, the total simulated soil-CO_2 flux increased by about 3% for $T = +1.5$℃, 5.4% for $T = +2.5$℃, and 10.7% for $T = +4.5$℃; the total soil-CO_2 flux was only slightly affected by precipitation increases of 5%, 10% and 15%. With increases in soil-CO_2 flux ranging from 1.0% to 3.5%. An increase in actual evapotranspiration by 5%, 10% and 15% had a stronger effect on soil-CO_2 flux, leading to increases of 1.8%, 4.3% and 6.7% respectively.

Table 3 Global soil-CO_2 flux for various sensitivity experiments simulated by TPAET models (equation (4)—(6) in text). Sensitivity experiments were performed by increasing the values of temperature (+1.5℃, +2.5℃ and +4.5℃), precipitation (+5%, +10% and +15%) and evapotranspiration (+5%, +10% and +15%) with respect to the present-day data set. Changes are shown as percentage change from the current values

Sensitivity experiments	Soil-CO_2 flux, PgC/a	Change (increase %)
Current climate	69.00	
Temperature +1.5℃	71.06	+3
Temperature +2.5℃	72.76	+5.4
Temperature +4.5℃	76.37	+10.7
Precipitation +5%	69.56	+1
Precipitation +10%	70.50	+2.2
Precipitation +15%	71.44	+3.5
Evapotranspiration +5%	70.29	+1.8
Evapotranspiration +10%	71.96	+4.3
Evapotranspiration +15%	73.59	+6.7

These sensitivity experiments illustrate that the soil-CO_2 flux is sensitive to the changes in temperature, precipitation and actual evapotranspiration, but the temperature and actual evapotranspiration affect the soil-CO_2 flux more than does precipitation.

2.3 Global soil-CO_2 flux under climatic change scenarios

We used climatic change projection corresponding to a doubling of CO_2 from four GCMs (Table 4). Changes in mean monthly temperature and in precipitation were calculated for each GCM scenario at each computational grid point by taking the difference between simulated current ($1 \times CO_2$) and $2 \times CO_2$ climates. These differences were interpolated linearly from the coarser GCM grid to the finer $0.5° \times 0.5°$ model grid and then added to the global climate database (Leemans, 1991) to provide climatic change scenarios. The corresponding evapotranspiration (AET) value was derived from a simple regression equation: $AET = 0.16P + 17.21T + 340$ ($r^2 = 0.74$), which was calibrated from 150 field measurements reported by Raich and Schlesinger (1992).

Table 4 Changes in global soil-CO_2 flux under the climate change scenarios simulated by current ($1 \times CO_2$) and $2 \times CO_2$ climates from four general circulation models (GCMs). Changes are shown as percentage change from the current values

GCMs	Resolution, Lat/Lon	Change in mean global		
		Temperature, ℃	Precipitation, %	Soil-CO_2 flux, PgC/a
Current				69.00
OSU[1]	4°×5°	2.84	7.8	88.58(+28%)
GFDL[2]	4.5°×7.5°	4.00	8.7	92.40(+34%)
GISS[3]	7.8°×10°	4.20	11.0	93.68(+36%)
UKMO[4]	5°×7.5°	5.20	15.0	98.24(+42%)
Average				93.23(35%)

1. Oregon State University (Schlesinger, 1988); 2. Geophysical Fluid Dynamics Laboratory (Manabe, 1987); 3. Goddard Institute for Space Studies (Hansen, 1988); 4. United Kingdom Meteorological Office (Mitchell, 1983)

Global soil-CO_2 flux was increased under all four climate change scenarios (Table 4). The increases ranged from 28% (19.6 PgC/a) for OSU scenario to 42% (29.2 PgC/a) for the UKMO scenario. The average increase of global soil-CO_2 flux for four climate change scenarios is about 35% (24.2 PgC/a). This result is higher than the 20% increase estimated by Robinet (in press), but lower than the net loss of 61 PgC/a from terrestrial soil during the next 60 years reported by Jenkinson *et al*., (Jenkinson, 1991).

The response of global soil-CO_2 flux to the CO_2-induced climatic change varies from one ecosystem to the other (Table 2). The smallest increases were found in the tropical regions. For all four GCM climate change scenarios, the increase of soil-CO_2 fluxes predicted by TPAET models range from 13% to 21% for tropical savannas, 11% to 17% for tropical dry forest and 9% to 16% for tropical moist forest. In agreement with the results of Robinet (in press), we found that larger increases were associated with boreal and tundra regions. The predicted soil-CO_2 fluxes are increased about 35%—42% for tundra and 36%—45% for boreal forest. This is probably due to three factors. First, the soils of these regions have higher soil carbon. Secondly, in these regions temperature and moisture are the most important factors dominating soil-CO_2 flux. Finally, the projected climate changes are more pronounced in these regions (Hougnton, 1990).

3 Discussion

Annual global soil-CO_2 fluxes are highly dependent on the terrestrial areas used (Raich, 1992). Using the same rate of soil respiration, but different biome areas estimated by Whittaker and Likens (Whittaker, 1975), Ajtay *et al.* (Ajtay, 1979), Matthews (Matthews, 1983) and Olson *et al.* (Olson, 1985), Raich and Schlesinger (1992) estimated annual global soil-CO_2 fluxes at 70, 63, 72 and 68 PgC/a, respectively. If we take into account this factor, the annual global soil-CO_2 fluxes of 69 PgC/a over a terrestrial area of $132 \times 10^6 km^2$ estimated by our annual-based TPAET model is compatible with the 77 PgC/a over a terrestrial area of $149 \times 10^6 km^2$ estimated by Raich and Potter (1995). However, the latter models explained only 41% of the variability present in measured soil-CO_2 fluxes (Table 1).

There remain uncertainties in the temporal and spatial estimation of soil-CO_2 fluxes in this study. Our statistical models with a georeferenced database allow better consideration of the variability in soil-CO_2 flux due to spatial variability of climate, but temporal variations in climate are not taken into account in this study, probably leading to about 16% aggregation error in the regional estimates (Kicklighter, 1994). On the other hand, the results presented here are also limited by the paucity of available field measurements of soil-CO_2 fluxes from very dry (desert) and cold (tundra) ecosystems, as despite an abundance of soil-CO_2 flux data, global coverage is still poor. Raich and Schlesinger (1992) reported three rate of the soil respiration in deserts yielding an estimation of 224 ± 38 gC/($m^2 \cdot a$), while the average rate estimated by our TPAET model is about 177 gC/($m^2 \cdot a$) (Table 2). Both our model and observations are still lower than the value of 282 gC/($m^2 \cdot a$) estimated by model B in Raich and Potter (Raich, 1995). In reality, the low soil respiration in deserts is expected to accompany the low rates of plant productivity. Moreover, a 184 gC/($m^2 \cdot a$) of soil-CO_2 flux in tundra is similar to 217 gC/($m^2 \cdot a$) estimated by Raich and Potter (Raich, 1995), but is three times more than measured mean value of 60 gC/($m^2 \cdot a$) (Raich, 1992). Partly due to the lack of near-zero measurements in the published literature (Raich, 1995). In this respect, cold region (tundra), arid, semi-arid and desert regions should be priorities for future field research. However, total soil-CO_2 fluxes from tundra and deserts contribute only about 10% of global soil-CO_2 fluxes. Despite these limitations, it appears that the TPAET model provides good estimates of the global distribution pattern and magnitude of soil-CO_2 fluxes for major ecosystems.

The uncertainties are also associated with simple statistic model to predict future global soil-CO_2 fluxes. Regression-based models contain more empirical relationships than process-based simulation models, but are often simple to apply, and less demanding of input data than process-based simulation models. It should be emphasized that the empirical statistical models have been developed on the basis of present-day climatic conditions. Thus, one of their major weaknesses in considering future climatic changes is their limited ability to predict effects of climatic events that lie outside the range of present-day variability. However, if we can choose the proper independent variables, the correlations may approximate a cause and effect relationship. The role of statistical models in global analysis has been discussed by Raich and Potter (Raich, 1995). These empirical models can still be useful predictive tools in climate impact assessment (Jenkinson, 1991; Rizzo, 1992; Dai, 1993; Lloyd, 1994; Peng, 1995a; 1995b). The approach has been extended to the construction of global carbon cycle models (Meentemeyer, 1995; Esser, 1987; 1991; Box, 1988; Friedlingstein, 1992; 1994) and to the prediction of future vegetation redistribution under different climates using vegetation classification schemes that rely on direct correlation between vegetation and climate (Emanula, 1985; Neilson, 1993; Lenihan, 1995).

More importantly, however, climatic change and increasing atmospheric CO_2 may alter both primary productivity and litter fall characteristics, thereby effecting a change in the supply of soil organic matter (Schimel, 1990; Melillo, 1993). Future effort must be devoted to predictions of soil-CO_2 flux which explicitly take into account the changes in ecosystem primary productivity and in land-use changes (such as deforestation) over the next century. The development and application of process-based models such as CENTURY (Parton, 1987; 1988) to simulate the dynamics of soil-CO_2 flux at the regional scale seems to provide a promising direction (Parton, 1993; Vitousk, 1994; Peng, 1998a, 1998b). The direct application of process-based models to global scale questions is certainly problematic due to the lack of data (Peng, 1995a; 1995b; Raich, 1995). However, an improved inderstanding of the dynamics processes of the global carbon cycle and improved global database of environmental parameters will facility our abilities to investigate the dynamics of soil-CO_2 flux with finer spatial and temporal resolution.

Besides the major climatic factors such as temperature, precipitation and evapotranspiration which govern the rate of soil respiration, there are also other environmental factors such as: land use, CO_2 concentration, fire disturbance, soil characteristics, and substrate quantity and quality which directly or indirectly affected the soil-CO_2 fluxes in different ways. There are also important interactions among these factors (Singh, 1977; Raich, 1992; 1995). In many cases, the interactive effects of these factors on soil-CO_2 flux, which are not likely to be simple additive combination of the individual responses, are still poorly known and need for further studies.

4 Conclusions

Our sensitivity experiments suggest that soil-CO_2 flux is responsive to temperature, precipitation and evapotranspiration, but increases in temperature and in evapotranspiration affect soil-CO_2 flux more than increase in precipitation. The global soil-CO_2 flux is about 69 PgC/a calculated by our simple statistical models. Using climatic change projection corresponding to a doubling of CO_2 from four GCMs, the global average soil-CO_2 flux are estimated to be about 35% higher than present-day values. The largest increases in soil-CO_2 fluxes were associated with the boreal and tundra regions. This increase is likely to produce a positive feedback to the greenhouse effect.

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