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Carbon dioxide released to the atmosphere by soil respiration: a global scale approach
Gaz carbonique libéré vers l'atmosphère par la respiration du sol : une approche à l'échelle globale

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1. INTRODUCTION

Among all the studies focusing on the global carbon cycle, few are concerned with the soil reservoir, and especially with the fluxes of CO_2 respired by soils worldwide. Whereas, soil respiration (heterotrophic respiration) is probably one of the largest input of CO_2 to the atmosphere with an annual flux estimated to about 68 to 76 10^{15}g.C.yr^{-1} (Raich and Schlesinger, 1992; Raich and Potter, 1995). Therefore, soil respiration must play a very important rule in the regulation of the concentration of CO_2 in the atmosphere, at least as important as the vegetation-atmosphere exchanges (net flux 50 to 60 Gt.C.y^{-1}) and the ocean-atmosphere exchanges (net flux 1 to 2 Gt.C.y^{-1}).

This study is an attempt to a global approach of temporal and spatial variation of the soil respired CO_2. In previous work, soil respiration has always been related to climate parameters, especially to the temperature and/or to and the moisture (Howard and Howard, 1979; Fung et al., 1987; Raich and Schlesinger, 1992; Raich and Potter, 1995). In this work, we try to correlate the CO_2 emitted by soil respiration with the true evapotranspiration. Thus, our study is divided in two parts: i) the construction of a database of soil CO_2 emissions worldwide from literature data and ii) the modeling approach.

2. DATABASE CONSTRUCTION

2.1 Data collection

Data of soil respiration have been collected in the literature related to field measurements on sites mainly located in natural ecosystems (i.e. not subject to a systematic exploitation by man). Thus, studies concerning laboratories experiments or calibrated field experiments have not been included in the database. However, several studies looking at the soil respiration in cultivated area or in forested sites after clear cutting have been taken into account. Data have been reported only from articles giving

the values of soil respiration but have never been deduced from figures. This way of data collection led us to exclude more than one half of the consulted literature.
Actually, the database contains about 300 values of soil respiration rates, which are related to 105 different sites.

Together with the soil respiration rates, several *environmental* parameters have also been collected each time it was possible. These environmental parameters (table 1) are concerned with the soil physical and chemical properties, the climate and the vegetation.

Table 1: different parameters taken into account in the database

SITE LOCATION	longitude, latitude, altitude
SOIL RESPIRATION	method of measurement, date of measurement, respiration rate
SOIL PARAMETERS	soil type, bedrock, temperature, moisture, bulk density, thickness, granulometry, carbon content, nitrogen content, pH
CLIMATE	mean monthly precipitation, mean monthly temperature, mean monthly evapotranspiration
VEGETATION	ecosystem, plant species

2.2 Heterogeneity of the data

The heterogeneity of the data is one of the main problems to solve in global scale studies based on field measurements. In the case of the soil respiration, this problem is really difficult to overcome. Indeed, soil respiration rates are quickly variable with time and space. Thus, depending on the kind of studies, respiration rates are representative of daily or seasonal variations and they have been measured one or two times a month for a one year period (Edwads, 1975; Gupta and Singh, 1982; Holt et al., 1990), or even continuously during 24 hours every three days for a two years period in the case of the unique work of Kucera et al. (1971). In our work, data representing seasonal variations are obviously the most important to consider. However, measurements of the soil respiration have often not been carried out for the winter because it is considered that soil respiration is very low during this season. Consequently, it becomes difficult to calculate mean annual rates of soil respiration with sufficient precision.

2.3 Spatial representativeness of the data

The spatial distribution of the 105 sites included in our database is presented in the figure 1. The representativeness is low, with no sites located in Africa and in central and east Asia. Thus, in the framework a global modeling, the database should be completed. However, climates and ecosystems of the temperate and tropical regions are quite well represented in the database. Data have been collected from forested sites (deciduous forest, evergreen forest, ...) as well as from sites located in grassland and pasture area. The represented climate are the main temperate climates (oceanic to continental climates, Mediterranean climates) and the main tropical to sub-tropical climates (tropical rainy, wet to dry tropical climates, tropical semi-desert and desert climates).

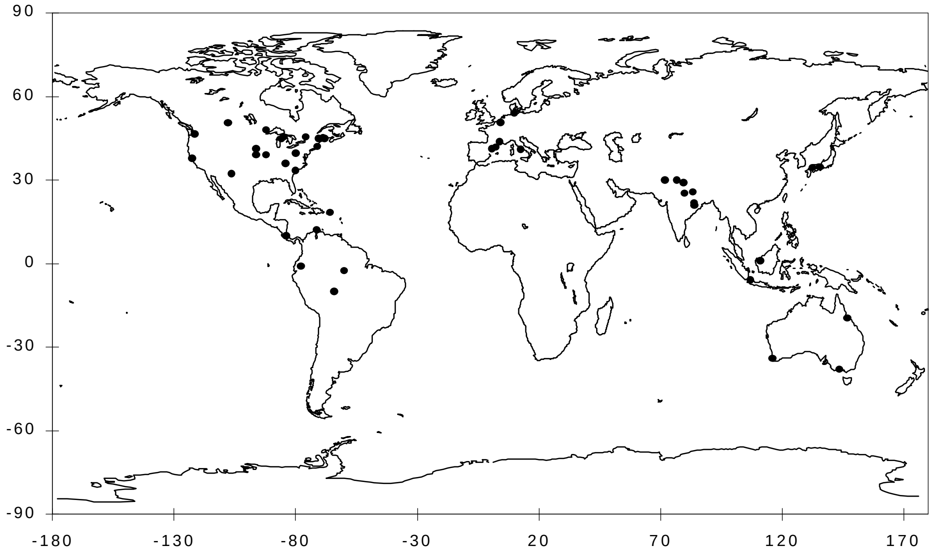


Figure 1: Spatial distribution of the 105 sites (solid circles) of the soil respiration database.

2.4 Climatic data

In order to complete the database with the necessary climatic parameters, we have used the results of the work of Willmott et al. (1985). The mean monthly precipitations, temperature and calculated evapotranspiration have been deduced for each site from the global 1° by 1° datasets of Willmott et al. (1985). These datasets result from the spatial extrapolation of observed precipitation and temperature in more than 13000 stations distributed all over the world. The evapotranspiration is calculated each month from temperature and precipitation data with a "Thornwaite based" hydrologic model.

3. SPATIAL AND TEMPORAL VARIATIONS

3.1 Daily variations

The daily variations of the soil respiration are not very well understood today. It seems to vary from one site to another and from one day to another. Kosonen (1969), Redman (1978) and Huck and Hillel (1983), among other, have observed that soil respiration was higher during the day than during the night. Whereas, Witkamp (1969), Edwards (1975) and Cavelier and Penuela (1990) have observed the opposite situation: soil respiration is higher during the night. As already stated by Grahammer et al. (1991), this inconsistency between the different observations is induced by the interactions between the soil respiration, the soil temperature, the soil humidity and the plant physiology. Thus, as it can be seen from figure 2, that, for the same site, the soil respiration can be alternatively higher during daytime or during nighttime. In this case, the soil humidity is a limiting factor and soil respiration is controlled by soil temperature as long as it remains dry.

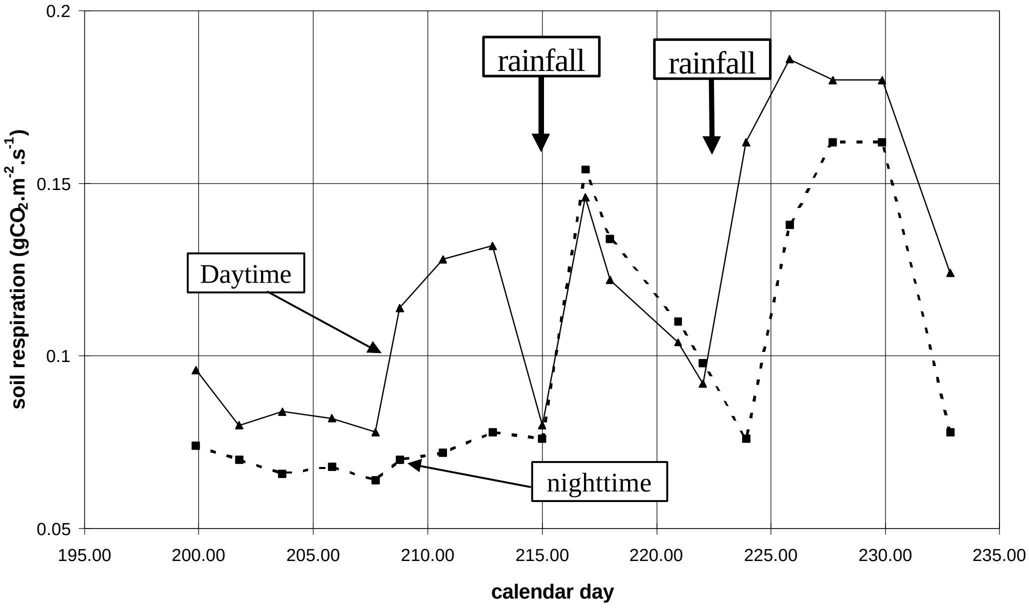


Figure 2: Daytime and nighttime soil respiration in a grassland of Kansas (USA) after Grahammer et al. (1991)

3.2 Seasonal variations

All the studies agree on the fact that soil respiration show strong seasonal variations, which can be related to the interaction between the soil temperature and the soil humidity. During winter, the rates of soil respiration are very low, ranging from 0 to about 5 $gCO_2.m^{-2}.d^{-1}$. In spring, soil respiration is increasing and varies between 4 and 8 $gCO_2.m^{-2}.d^{-1}$. Finally, the maximum rates are generally observed in summer with values up to 20 to 25 $gCO_2.m^{-2}.d^{-1}$. During autumn, rates are progressively decreasing toward the minimum of winter. Comparing one site to another, it remains difficult to evaluate for which one soil respiration is higher, because of the heterogeneity of the data and the impossibility to calculate the same mean values for almost all the studies. Thus, the only way to solve this problem is the modeling.

4. MODELING APPROACH

4.1 Previous works

All the empirical approaches previously carried out (Howard and Howard, 1979; Fung et al., 1987; Raich and Potter, 1995 among other), have led to develop quite simple models expressing the soil respiration as a function of the temperature and of the moisture. However, these modeling show very often relatively low values of *r-square* (correlation coefficient r^2) reflecting the high variability and the lack of precision of the parameters in such global studies. Thus, the attempt of Raich and Potter (1995) to include in their multiple regression models other parameters (the ecosystem type, the soil physical properties, the carbon and nitrogen pools), which are known to influence the heterotrophic respiration, was unsuccessful.

4.2 Relationships with evapotranspiration

This study is an attempt to correlate the soil respiration (SR) with the true evapotranspiration (E), assuming that evapotranspiration (E) constitute a realistic index of the combined influence of the temperature (T) and of the soil humidity (Hs) on the soil respiration (SR). Indeed, E is raising with increasing T and Hs, and becomes null for low T values and/or low Hs values. Hs acts as a limiting factor of E, as it also acts as a limiting factor of SR (Grahammer et al., 1991). Moreover, the root respiration, as part of the autotrophic respiration, is positively correlated with evapotranspiration. Therefore, there should be a positive relationship between E and SR.

Looking first at the relationship between SR and E for all the values of the database (figure 3), it can be noted that there is no very clear correlation between the two parameters. Results are not better when the same plot is performed inside each climate type or vegetation type.

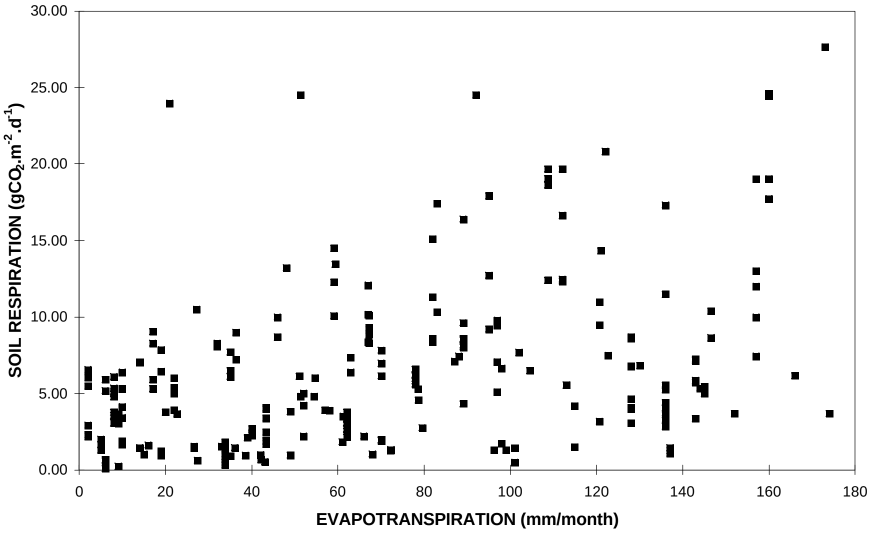
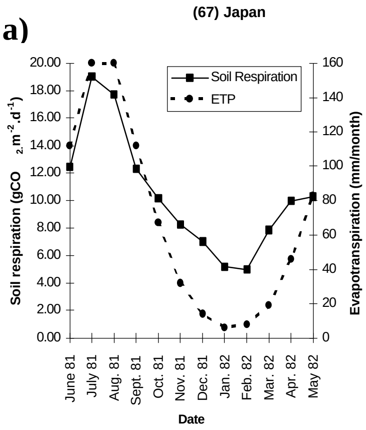


Figure 3: Plot of soil respiration versus true evapotranspiration for all data of the database.

However, looking at the seasonal variations, there is a good correlation between SR and E for each site, as it can be seen from the two examples in figure 4.

The models fitted to the relationship between SR and E are presented in table 3 for 11 different sites for which we had seasonal data. These models are mainly of linear type, excepted for the 3 Indian sites located in tropical grassland, for which models are of logarithmic type. In almost the linear models, the intercept is generally very low (between 0 and 1 $gCO_2.m^{-2}.d^{-1}$) which reflects the strong relationships between SR and E.

a)



b)

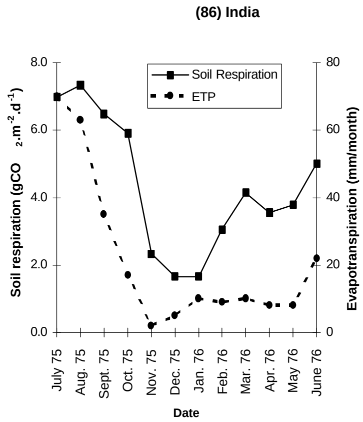


Figure 4: Examples of the relationship between the soil respiration (SR) and the true evapotranspiration (E): a) site 67, Japanese red pine forest 40 year old in Japan, SR data from Nakane et al. (1984) and E values from climatological datasets described in Willmott et al. (1985) and available from the NCAR (Boulder Colorado); b) site 86, tropical grassland in India, SR data from Gupta and Singh (1982) and E values from climatological datasets described in Willmott et al. (1985) and available from the NCAR (Boulder Colorado)

Table 2: Model fitted to the relationships between soil respiration (SR) and true evapotranspiration (E) for sites for which sufficient data were available.

site	location	model equation	r^2	climate	vegetation	ref.
6	South Carolina, USA	SR=0.0212.E+0.54	0.56	warm temperate, sub-tropical zone	long leaf pine	(1)
7	South Carolina, USA	SR=0.0222.E+0.84	0.85	warm temperate, sub-tropical zone	long leaf pine	(1)
12	Missouri, USA	SR=0.0745.E+0.86	0.89	cool temperate zones	wheat field	(2)
17	Tennessee, USA	SR=0.11366.E+0.47	0.67	cool temperate zones	mixed deciduous forest	(3)
31	Saskatchewan, Canada	SR=0.0216.E+0.25	0.56	cool temperate zones	mixed grassland	(4)
67	Japan	SR=0.0755.E+5.29	0.94	warm temperate, sub-tropical zone	Japanese red pine, 40 yr old	(5)
68	Japan	SR=0.1269.E+4.28	0.97	warm temperate, sub-tropical zone	Japanese red pine, 80 yr old	(5)
84	Queensland, Australia	SR=0.O414.E+1.6306	0.38	tropical zone, humid summer	Eucalyptus woodland	(6)
85	India	SR=1.88.ln(E)-0.12	0.82	tropical zone, wet and dry	tropical grassland	(7)
86	India	SR=1.72.ln(E)-0.13	0.78	tropical zone, wet and dry	tropical grassland	(7)
87	India	SR=1.16.ln(E)+2.08	0.36	tropical zone, wet and dry	tropical grassland	(7)

references: (1) Duholery et al. (1996) - (2) Buyanovsky et al. (1986) - (3) Edwards (1975) - (4) De Jong et al. (1979) - (5) Nakane et al. (1984) - (6) Holt et al. (1990) -(7) Gupta and Singh (1982)

5. CONCLUSIONS

The soil respiration depends from a lot of parameters among which climates factors are the most important one. As it has always been stated in previous works, the attempt to correlate soil respiration with the climatic parameters at the global scale do not give complete satisfaction, probably because soil respiration is highly variable and is significantly correlated to other parameters like vegetation types or soil properties.
The database on soil respiration developed in this study has to be improved. Indeed, the representativeness of the data remains relatively poor and the number of site measurements included in the database has to be increased.

Whereas, we have shown in this study that, in measurement site, soil respiration was strongly correlated to the true evapotranspiration. Additional information on each site is required to explain the differences between the fitted models.However, this very interesting result would means that true evapotranspiration can be a good index of the respiration rates in soil profiles and that it could be used at the global scale to determine parametric function between soil respiration and climates.

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Mots clés : cycle du carbone, respiration du sol, modélisation, base de données