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Toward a general evaluation model for soil respiration (GEMSR)

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Soil respiration is an important component of terrestrial carbon budget. Its accurate evaluation is essential to the study of terrestrial carbon source/sink. Studies on soil respiration at present mostly focus on the temporal variations and the controlling factors of soil respiration, but its spatial variations and controlling factors draw less attention. Moreover, the evaluation models for soil respiration at present include only the effects of water and heat factors, while the biological and soil factors controlling soil respiration and their interactions with water and heat factors have not been considered yet. These models are not able to accurately evaluate soil respiration in different vegetation/terrestrial ecosystems at different temporal and spatial scales. Thus, a general evaluation model for soil respiration (GEMSR) including the interacting meteorological (water and heat factors), soil nutrient and biological factors is suggested in this paper, and the basic procedure developing GEMSR and the research tasks of soil respiration in the future are also discussed.

soil respiration, controlling factors, general evaluation model

Accurately evaluating global carbon budget is a key not only for estimating atmospheric CO_2 concentration and forecasting climate change in the future, but also for implementing the responsibilities from United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol. Therefore, the international joint programme, Global Carbon Project (GCP), was sponsored by International Geosphere-Biosphere Program (IGBP), International Human Dimensions Program on Global Environment Change (IHDP) and World Climate Research Program (WCRP) in 2001. The scientific aim of GCP is to accurately evaluate the temporal and spatial distributions of global carbon sources and sinks and their trends in the future.

There are various terrestrial ecosystems in China. CO_2 emission of China is secondary in the world at present, only lower than the amount of the United States of America (USA). So how to strengthen the management of terrestrial ecosystems for reducing its carbon emission or increasing its carbon sink becomes an urgent problem. To find the answer, we should correctly understand the effects of climate change and human activities on the processes and mechanisms of terrestrial carbon cycle and its interaction with environment, and accurately evaluate terrestrial carbon budget.

Soil respiration is a major flux between atmosphere and land, mainly including microbial and root respirations. Soil respiration is estimated to be 68—100 Gt C/a, being the secondary flux in the global carbon dioxide exchange, higher than net primary productivity (NPP, 50—60 Gt C/a) and lower than gross primary productivity (GPP, 100—120 Gt C/a)[1]. Studies on soil respiration and its related controlling factors will help further understand the terrestrial carbon cycle[2] and develop a general evaluation model for soil respiration (GEMSR).

Considering the importance of soil respiration in the global carbon cycle, much work has been done on the

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observation methods, involved processes and influencing mechanisms of soil respiration, as well as quantitative evaluation of soil respiration, but no GEMSR has been developed for accurately evaluating the carbon sources and sinks of terrestrial ecosystems. Here we discuss the possibility developing GEMSR based on recent findings and development in soil respiration observation and its controlling factors.

1 Soil respiration measurements

Soil respiration has been measured with different methods, mainly including alkali absorption[3], infrared gas analysis (IRGA)[4], gas chromatography[5], atmospheric composition monitoring method (measurements of CO_2 and $\delta^{13}CO_2$ or O_2/N_2)[6], and eddy covariance[7]. However, these methods are different in sampling times and sampling areas, which increase the difficulties in comparing and synthetically analyzing soil respiration at different temporal and spatial scales. The sampling time is on the diurnal scale for alkali absorption method and on the half hour and even longer for the others. The measurement area is a circle of 25 cm in diameter for alkali absorption method, a square of 50 cm×50 cm or 100 cm×100 cm for IRGA and gas chromatography, and even larger (e.g., ecosystem scale) for atmospheric composition monitoring method and eddy covariance, by which the footprint of soil respiration depends on the meteorological factors and the land surface characteristics. Thus, different methods should be selected carefully based on soil respirations at different temporal and spatial scales, in order to accurately describe the soil respiration rates and their controlling factors[8].

2 Controlling factors of soil respiration

Soil respiration is the maximum flux in terrestrial carbon exchange except for plant canopy photosynthesis. For accurate evaluation and prediction of carbon dioxide exchange between atmosphere and land, it is necessary to further understand the processes and controlling factors of soil respiration at different temporal and spatial scales[2]. Soil respiration originates mainly from biotic metabolism in soil. Thus, the factors affecting biotic activities would influence soil respiration rate, including climate factors, soil factors, plants and litter fall, etc.

2.1 Moisture and temperature related factors

Moisture and temperature are usually taken as the main factors controlling soil respiration. Soil respiration rate increases with increasing temperature[4,9]. When physiological temperature exceeds a certain threshold, the enzyme activities related to respiration in root and microorganism would reduce[4], resulting in a decline in the sensitivity of soil respiration to temperature. Meanwhile, long-term stresses at a high temperature would also increase the diffusional resistance of cellular membrane to oxygen and decrease soil respiration rate by the inhibition of plant growth[10].

The increase of precipitation (or soil water content) would generally accelerate soil respiration rate[11]. When soil water content exceeds a certain threshold, the high precipitation (or soil water content) would increase the diffusional resistance of CO_2 in soil and decrease soil respiration rate[12−13]. Moreover, soil respiration rate will decrease with increasing drought stress, which could inhibit root growth[14] and ion uptake[15], and reduce maintenance consumption[16] and transportation of photosynthetic production[17], etc.

Usually, soil respiration rate increases with increasing temperature. However, it would be inhibited by the limit of water under the conditions of higher temperature in arid and semiarid regions[11]. Furthermore, drought stress would result in decreasing root respiration rate more significantly in the high temperature zone than that in the low temperature zone[18].

2.2 Biotic factors

The effects of biotic factors on soil respiration rate include the respirations from roots and microorganisms. Root respiration rate is influenced by the root-to-shoot ratios and chemical compositions of plant species. Root respiration rate fluctuates seasonally due to the differences in quantity and quality of root secretion and the activities of rhizosphere microorganisms resulting from the seasonal changes in the biomass and the allocation of plant photosynthetic products[19]. The activities of soil microorganisms depend on the soil organic matter inputted from plant aboveground biomass and root[20]. Aboveground biomass of terrestrial ecosystems is correlated positively with the activities, quantity and biomass of soil microorganisms and enzymes[3]. The seasonal pattern of soil respiration rate could be usually expressed as a one-humped curve, with the maximum value appearing in late spring or early summer and the minimum in winter[21−23]. Microbial respiration rate has a similar seasonal dynamics[24], and its contribution to the total soil respiration rate changes with seasons[25]. Meanwhile, soil respiration rate is also controlled by above-ground biomass. For example, the removal shoots of spring wheat and soybean reduced root respiration rate[26].

2.3 Soil nutrients

Soil nutrients influence root growth and soil organic matter, which control soil respiration rate. The study on the effects of soil nitrogen and phosphorus on root respiration rate of rice seedlings indicates that soil respiration rate increases with increasing concentrations of soil nitrogen and phosphorus[27]. However, when the concentrations of soil nitrogen and phosphorus exceed 4.28 and 0.2 mmol/L, respectively, root respiration rate decreases with the increasing concentrations of soil nitrogen and phosphorus because of the inhibition of photosynthesis.

Microbial respiration rate is correlated with the quantity and the composition of soil organic matter (SOM)[28]. Generally, SOM could be divided into active, slow and passive pools based on the decomposition rate, and 80% of the microbial respiration rate comes from the active pool and 20% from the slow pool[29].

Besides the above-mentioned factors, soil respiration is also affected by soil pH value[30], atmospheric CO_2 concentration[31], grazing[32−33], deforest[34] and fertilization[35−37], which could indirectly influence soil respiration by changing moisture, temperature, biotic factors or soil nutrients.

3 Quantitative evaluation of soil respiration

In recent years, many studies on soil respiration have been done to evaluate carbon sources or sinks at the regional and global scales. A lot of soil respiration models have been established based on temperature, moisture or temperature–moisture interaction (Tables 1—3). Relationship between soil respiration and temperature could be expressed by linear, quadratic, power, exponential and Arrhenius models (Table 1). Among them, an exponential model is most commonly used. Soil respiration rate could be fitted better with the exponential model at low temperature, but worse at high tempera- ture[25,38]. Relationship between soil respiration and soil water content could also be expressed by linear, quad- ratic, cubic, logarithmic and exponential models (Table 2). Table 3 lists the relationships between soil respiration and temperature–moisture interaction, including linear, exponential, combination of exponential and power or Arrhenius models.

Table 1 Relationships between soil respiration and temperature

Equation	Example	Vegetation	Ref.
Linear	$F\ (\mathrm{g\ C\cdot m^{-2}\cdot yr^{-1}})=265.9+27.7T,\ R^2=0.83$ T: mean annual air temperature (℃)	Peat lands	[39]
	$F\ (\mathrm{mg\ CO_2\cdot m^{-2}\cdot h^{-1}})=57.626-3.544\mathrm{T},\ R^2=0.99$ T: soil temperature at 10 cm depth (℃)	*Stipa baicalensis* meadow steppe	[40]
Quadratic	$F\ (\mathrm{mg\ CO_2\cdot m^{-2}\cdot h^{-1}})=89.78+1.54T+5T^2,\ R^2=0.83$ T: mean soil temperature at the depths of 0, 5, 10 and 20 cm (℃)	Tundra	[41]
Power	$\ln F(\mathrm{mg\ CO_2\cdot m^{-2}\cdot h^{-1}})=-1.66+2.20\ln(T+10),\ R^2=0.89$ T: soil temperature at 5 cm depth (℃)	Tall grass prairie	[42]
	Farm: $F\ (\mathrm{mg\ CO_2\cdot m^{-2}\cdot s^{-1}})=1.66\times10^{-8}(T+26.5)^{4.19},\ R^2=0.90$ Forest: $F\ (\mathrm{mg\ CO_2\cdot m^{-2}\cdot s^{-1}})=2.41\times10^{-8}(T+13.4)^{4.34},\ R^2=0.86$ T: mean soil temperature at the depths of 5 and 30 cm (℃)	Farm and forest	[4]
Exponential	$F\ (\mathrm{mg\ C\cdot m^{-2}\cdot h^{-1}})=21.13\mathrm{e}^{0.1371T},\ R^2=0.80$ T: soil temperature at 10 cm depth (℃)	Mixed hardwood forest	[43]
	$F\ (\mathrm{g\ CO_2\cdot m^{-2}\cdot h^{-1}})=0.14\mathrm{e}^{0.113T},\ R^2=0.75$ T: soil temperature at 10 cm depth (℃)	Mixed hardwood forest	[44]
	$F\ (\mathrm{\mu mol\ CO_2\cdot m^{-2}\cdot s^{-1}})=0.375\mathrm{e}^{0.066T},\ R^2=0.46$ T: air temperature (℃)	Peat lands	[39]
	$\ln F\ (\mathrm{g\ CO_2\cdot m^{-2}\cdot d^{-1}})=7.069+0.133T-0.002T^2,\ R^2=0.66$ T: soil temperature at 10 cm depth (℃)	Winter wheat	[45]
Arrhenius	$F\ (\mathrm{\mu mol\ CO_2\cdot m^{-2}\cdot s^{-1}})=a\exp(-308.56/(T-227.13)),\ R^2=0.79$ T: air temperature (K); a: ecosystem-dependent variable	Different ecosystems	[46]

Table 2 Relationships between soil respiration and soil water content

Equation	Example	Vegetation	Ref.
Linear	$W < 0.12$ cm^3·cm^{-3}, F(mg C·m^{-2}·h^{-1})$=2852W-128$, $R^2=0.48$ $W > 0.12$ cm^3·cm^{-3}, F(mg C·m^{-2}·h^{-1})$= -198W+201$, $R^2=0.22$ W: volumetric water content at 0—15 cm depth (cm^3·cm^{-3})	Mixed hardwood forest	[43]
	F (mg CO$_2$·m^{-2}·h^{-1})$=58.15\mathrm{W}-105.88$, $R^2=0.85$ W: volumetric water content at 0—10 cm depth (%)	*Leymus chinensis* steppe	[9]
	F (mg CO$_2$·m^{-2}·h^{-1})$=87.94\mathrm{W}-642.66$, $R^2=0.85$ W: gravimetric water content at 10—20 cm depth (%)	*Stipa baicalensis* meadow steppe	[40]
Quadratic	F (μmol CO$_2$·m^{-2}·s^{-1})$= -7487.7+34365W-39391W^2$, $R^2=0.40$ W: volumetric water content at 0—100 cm depth (%)	Tropical forest	[47]
Cubic	Forest: F (g C·m^{-2}·h^{-1})$=1.90W^3+0.14$, $R^2=0.30$ Pasture: F(g C·m^{-2}·h^{-1})$=3.46W^3+0.09$, $R^2=0.54$ W: volumetric water content at 0—30 cm depth (cm^3·cm^{-3})	Forest and pasture	[48]
Logarithmic	Forest: F (g C·m^{-2}·h^{-1})$=-0.043\ \lg(-\psi)+0.16$, $R^2=0.31$ Pasture: F(g C·m^{-2}·h^{-1})$=-0.047\lg(-\psi)+0.19$, $R^2=0.62$ Ψ: matric potential at 0—30 cm depth (MPa)	Forest and pasture	[48]
	F (g C·m^{-2}·d^{-1})$=3.467\ \lg W-2.053$, $R^2=0.92$ W: gravimetric water content at 0—20 cm depth (%)	*Stipa grandis* steppe	[3]
Exponential	$T<10$℃, there was no significant relationship with W_{S} or W_{L} $T>10$℃, $\ln F$ (mg CO$_2$·m^{-2}·h^{-1})$=-0.019W_{\mathrm{S}}+5.31$, $R^2=0.71$ $\ln F$(mg CO$_2$·m^{-2}·h^{-1})$=-0.005W_{\mathrm{L}}+5.76$, $R^2=0.76$ T: air temperature (℃); W_{S}: gravimetric water content at 0—20 cm depth (%); W_{L}: litter water content (%)	*Eucalyptus Pauciflora* forest	[11]

4 Toward a general soil respiration evaluation model

Up to now, many studies have been done on soil respiration and its controlling factors (e.g., moisture, temperature, soil nutrients, and biological mechanisms, etc.), and lots of soil respiration evaluation models have been established based on moisture, temperature or moisture-temperature interaction. However, these relationships are based on only the average soil respiration rate and its controlling factors in the same vegetation type or ecosystem, and they do not include the effects of biotic factors (e.g., root biomass), soil characteristics (e.g., soil nutrients) and spatial heterogeneity of soil water contents. Meanwhile, the differences of soil respiration rates and their main controlling factors at different temporal scales are not taken into account from the current different measurement methods, e.g., instantaneous soil respiration rate measured by LI-6400-09, half hour values of soil respiration by gas chromatography and average values of 24 hours by alkali absorption method. The interactive processes and mechanisms among moisture, temperature, soil nutrients and biological factors are still unclear at present. Furthermore, no GEMSR including the interacting moisture, temperature, biologic processes, and soil nutrients has been established at different spatial and temporal scales. The reasons are listed as follows.

(i) Spatial heterogeneity of soil respiration and its controlling factors

Most of the current studies on soil respiration focus on a certain vegetation type or ecosystem. Spatial heterogeneity of soil respiration is avoided by stochastic samplings and calculating the mean value. The controlling factors mainly include temperature and moisture, but biotic factors, especially root biomass and soil nutrients are seldom included. Meanwhile, the standardized sampling depth and observation identifier are also not defined for temperatures (e.g., air temperature, soil temperature, etc.) and moistures (e.g., gravimetric water content, volumetric water content, water potential, and water level, etc.). Therefore, most of evaluation models for soil respiration are developed in a uniform vegetation type or ecosystem based on limited observations of moisture and temperature. These models are difficult to be applied in other ecosystems or regions because of ignoring the effects of spatial heterogeneity on soil respiration rate and the statistical relationships.

(ii) Short-term soil respiration measurement and singularity of vegetation type

Currently, most of the soil respiration studies are a certain short-term soil respiration measurement, ignor-

Table 3 Relationships between soil respiration and temperature-moisture interaction

Equation	Example	Vegetation	Ref.
Linear	F (g C·m^{-2}·d^{-1})$=0.88+0.013TW$, $R^2=0.83$ T: soil temperature at 10 cm depth (℃); W: volumetric water content at 10 cm depth (cm^3·cm^{-3})	Arid shrub steppe	[49]
	F (g CO$_2$·m^{-2}·d^{-1})$= 0.715+0.210T+0.285P_{1-3}+0.083P_{4-7}$, $R^2=0.64$ T: air temperature (℃), P_{1-3}, P_{4-7}: precipitation of 3 days and 4—7 days before experiment, respectively (cm)	Pine forest	[50]
	$W<7.5\%$, there was no significant relationship with W; $W>7.5\%$, F(mg CO$_2$·m^{-2}·h^{-1})$=-147.7+5.1W+6.0T+1.2WT$, $R^2=0.81$ T: soil temperature at 5 cm depth (℃); W: gravimetric water content at 0—10 cm depth (%)	*Leymus chinensis* steppe	[51]
Exponential	$\ln F$(g CO$_2$·m^{-2}·h^{-1})$=-2.63+0.11T+0.04MI$, $R^2=0.90$ T: mean soil temperature at the depths of 5 and 15 cm (℃); MI: moisture index	Temperate forest	[52]
	$\ln F$ (g C·m^{-2}·d^{-1})$=0.087T+0.025W-0.264$, $R^2=0.69$ T: soil temperature at 5 cm depth (℃); W: gravimetric water content at 0—5 cm depth (%)	Riparian buffers and crop fields	[53]
	$\ln F$(mg C·m^{-2}·d^{-1})$=5.86+0.01W+0.04T+0.01WT$, $R^2=0.71$ T: air temperature (℃); W: gravimetric water content at 0—20 cm depth (%)	*Leymus chinensis* steppe	[25]
Exponential-power	$W<19\%$, F(μmol CO$_2$·m^{-2}·s^{-1})$=0.33W^{0.69}e^{0.042T}$, $R^2=0.76$ $W>19\%$, F(μmol CO$_2$·m^{-2}·s^{-1})$=26.17W^{-0.82}e^{0.047\mathrm{T}}$, $R^2=0.95$ T: soil temperature at 10 cm depth (℃); W: volumetric water content at 0—30 cm depth (%)	Ponderosa pine	[54]
	F (mg C·m^{-2}·d^{-1})$=5911.65W^{0.91}e^{0.04T}$, $R^2=0.86$ T: air temperature (℃); W: gravimetric water content at 10—20 cm depth (%)	Degraded steppe	[55]
	F (mg CO$_2$·m^{-2}·h^{-1})$=1.97\times10^{-5}e^{0.045T}(W-21.42)\ (58.54-W)^{4.46}$, $R^2=0.96$ T: soil temperature at 10 cm depth (℃); W: volumetric water content at 0—15 cm depth (%)	Deciduous broadleaved forest	[56]
Exponential-Arrhenius	F(μmol CO$_2$·m^{-2}·s^{-1})$=C\times e^{(-E/RT)}\times e^{Swt}$ C: constant(μmol·m^{-2}·s^{-1}); T: soil temperature at 1 cm depth (K); R: gas constant (8.31 J·mol^{-1}·K^{-1}); E: apparent activation energy (J·mol^{-1}); $Swt=AW/(W+B)$; W: depth to water table below soil surface(cm); A and B: fitted parameters	Tundra	[57]

ing the difference at temporal scales. For example, the differences of the controlling factors at different time scales during one day and during a period of every ten days. Meanwhile, many studies are limited in a specific vegetation type or ecosystem. It is difficult to include some factors changing insignificantly with time (e.g., soil organic matter). Thus, those insufficiencies make soil respiration models only suitable at specific spatial and temporal scales, but not suitable for other ecosystem types or regions. Therefore, it is urgent to develop an integrated measurement for soil respiration and its controlling factors in various vegetation types and ecosystems, in order to acquire these parameters of GEMSR including the interacting moisture, temperature, soil nutrient factors, and biologic characteristics.

(iii) The estimation of soil respiration is mostly based on the statistical correlations with moisture and temperature, and few soil nutrients and biotic factors are included. Those kinds of soil respiration models are devoid of generality, and only suitable for each special vegetation type or site. The spatial heterogeneity and the change of biotic factors are not reflected in the soil respiration models at present, and it is difficult to get upscaled to the regional or global scales. Meanwhile, no sampling standardizations have been made for temperatures (e.g., mean annual air temperature, mean diurnal air temperature and soil temperature at 10 cm depth, etc.), moistures (e.g., gravimetric water content, volumetric water content, water potential, water level, etc.), depths (e.g., 0—5, 0—10, 0—15, 0—20 cm, etc.), and sampling times (e.g., instantaneous soil respiration rate by LI-6400-09, half hour values by gas chromatography and average values of 24 h by alkali absorption method). It was difficult to compare these soil respiration models.

Therefore, to clarify the processes and mechanisms of soil respiration responding to its main controlling factors and to establish GEMSR, we must use the similar instruments with high time resolution to observe the spatial heterogeneity and controlling factors of soil respiration in various vegetation types or ecosystems. Thus, the long-term comprehensive observation data can be obtained including soil respiration rate, moisture, temperature, soil nutrient and biological factors.

Currently, LI-6400-09 (Li-cor, Lincoln, NE, USA) has been extensively applied to measure instantaneous soil respiration rate based on infrared gas analysis method. The instrument is portable and quick in measuring (usually a measurement takes only 5—10 min), and the outputs include temperature, relative humidity and soil temperature, etc. The long-term soil respiration rate, moisture, temperature, soil nutrients and biologic characteristics could also be obtained with a set of instruments, including LI-6400-09, soil moisture measurement system (Hydrosense, Campell scientific Australia pty. Ltd.), and the corresponding measurements of above- and below-ground biomass and soil properties.

We have observed a lot of soil respiration rates with Li-6400-09 in typical grassland in Inner Mongolia (4 years)[51,58−59], maize field in Jinzhou (2 years)[60−61], reed wetland in Panjin (2 years)[62−63], different forest-land use practices of broad-leaved Korean pine forest in Changbai Mountain (3 years) including primary broad-leaved Korean pine forest, secondary mixed of *Betula platyphlla* and *Populus davidiana*, cropland, larch plantation forest, clear-cut broad-leaved Korean pine forest[64−67] since 2002. Partitioning soil respiration into root and microbial respirations, soil respiration measurements at *Leymus chinensis* populations with five planting densities (0, 30, 60, 90 and 120 plants/0.25 m^2) were made in 2003 in a greenhouse at Institute of Botany, the Chinese Academy of Sciences[69]. Many data were obtained from these studies, including soil respiration rate, air temperature and humidity, soil temperature and moisture at different soil depths, above- and below- ground biomass and soil physicochemical properties, etc. Those studies in maize field and typical grassland showed that there were linear relationships between soil respiration rate and root biomass under the conditions of constant moisture, temperature and soil nutrients[60,68−69]. The statistical soil respiration models were established based on the main controlling factors of soil moisture and temperature in the broad-leaved Korean pine forest in Changbai Mountain and in fenced and grazing typical grasslands[51,59,64]. There are no studies on the effects of soil nutrients on soil respiration rate and integrated analysis of moisture, temperature, soil nutrients, and biological characteristics yet. However, these studies provide basal data and methods for further understanding the controlling mechanisms of the main factors and establishing GEMSR including the interacting moisture, temperature, soil nutrient and biological factors.

To establish GEMSR, we must understand how to acquire the necessary observation data. We should choose various vegetation types to study the effects of soil nutrients (mainly soil carbon and soil nitrogen) on soil respiration rate. Long-term observation data of soil respiration and the related controlling factors are essential for the development of soil respiration evaluation model for soil respiration. To quantitatively describe the interactive effects of moisture, temperature, soil nutrient and biological factors (mainly soil carbon and nitrogen) on soil respiration rate, the effects of these factors at different temporal scales need to be partitioned. Firstly, the effects of biotic factors on soil respiration rate could be included based on lots of soil respiration measurements in different sampling plots at a certain time with similar environment conditions including moisture, temperature and soil nutrients. Secondly, the gradually interactive effects of biotic factors with temperature, moisture and soil nutrients on soil respiration rate will be analyzed, disclosing the processes and mechanisms of the interactive effects of belowground biomass, temperature, moisture and soil nutrients on soil respiration rate. Therefore, the cropland ecosystem (e.g. maize field) as a good experiment field with uniform soil nutrients and smaller changing among years, and others as assistant ecosystems, GEMSR including soil nutrients could be established.

Above all, GEMSR including the interacting moisture, temperature, soil nutrient and biological factors would be established as the following procedures (Figure 1):

(i) Based on the data in many measurement plots at the same time during the growing season in a certain ecosystem, keeping soil nutrients, temperature and moisture in the plots as the same, the processes and mechanisms of root biomass controlling soil respiration rate will be analyzed at different growth phases. The relationship of soil respiration rate with root biomass will be established.

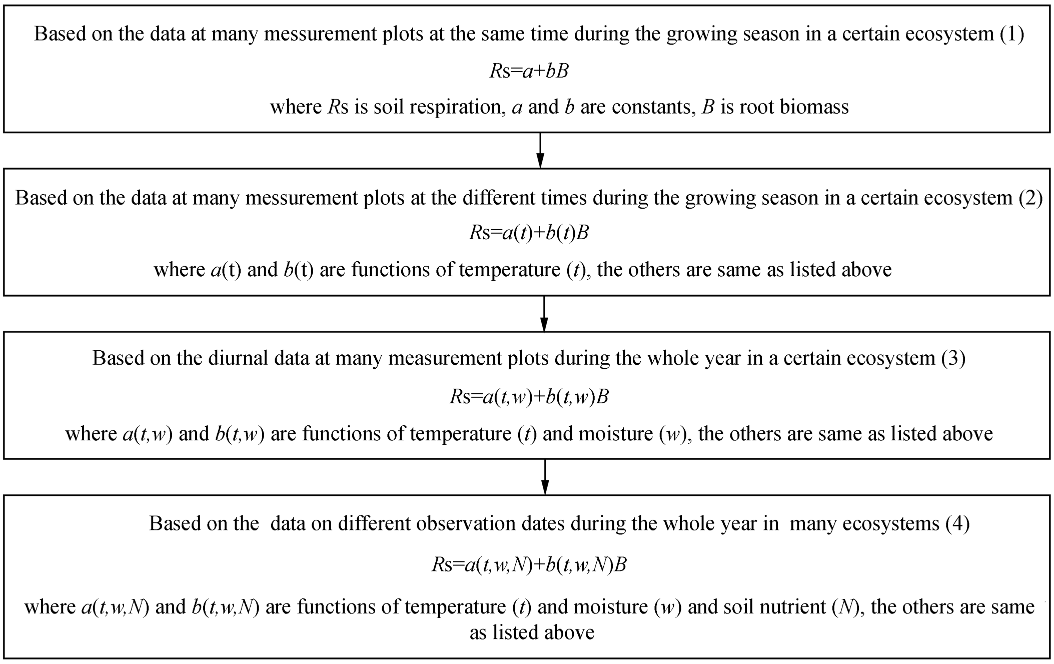

Figure 1 Procedures for developing GEMSR including the interacting moisture, temperature, soil nutrient and biological factors.

(ii) Based on the data in many measurement plots at different time scales in one day (e.g., different hours) during growing season in a certain ecosystem, maintaining soil nutrients and moisture in the plots as the same, the interactive effects of root biomass and temperature on soil respiration rate will be measured.

(iii) Based on the diurnal data in many measurement plots during the whole year in a certain ecosystem, the interactive effects of root biomass, temperature and moisture on soil respiration rate will be included. The dynamic soil respiration model including the effects of moisture, temperature and biotic factors would be established.

(iv) Based on the observation data in different time periods during an entire year in various ecosystems with different soil nutrients, the analysis would focus on the effects of soil nutrients on soil respiration rate. The dynamic soil respiration model including the interacting effects of moisture, temperature, soil nutrient, and biological factors would be obtained.

To develop GEMSR, the important studies in the future should be emphasized as follows:

(i) The responding processes and mechanisms of soil respiration to the interactions of moisture, temperature and biotic factors. We should focus on the spatial heterogeneity of soil respiration and its mainly controlling factors in different ecosystems, and analyze the processes and mechanisms of the effects of the interactions of root biomass, temperature and moisture on soil respiration.

(ii) The responding processes and mechanisms of soil respiration to the interactions of moisture, temperature, soil nutrients and biological characteristics. We should focus on the differences of the processes and mechanisms of the effects from the interactions of moisture, temperature and biotic factors on soil respiration in different ecosystems, and clarify the processes and mechanisms of the effects of soil nutrients (mainly soil carbon and nitrogen) on soil respiration rate, and eventually disclose the interactive effects of moisture, temperature, root biomass and soil nutrients on soil respiration rate.

(iii) Study on GEMSR including the interacting moisture, temperature, soil nutrients and biological characteristics. We should focus on the effects of the interaction of different factors on the processes and mechanisms of soil respiration in different ecosystems, and clarify the processes and mechanisms of soil respiration in different land use practices, and eventually establish GEMSR.

GEMSR could calculate total soil respiration including microbial and root respirations, and could also partition into two main components. The model could also evaluate soil respiration in different ecosystems and land use practices, and it could be coupled into the dynamic terrestrial ecosystem productivity model to improve the accuracy of evaluating terrestrial ecosystem carbon budget.

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