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Tests of soil organic carbon density modeled by InTEC in China's forest ecosystems

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Abstract

The integrated terrestrial ecosystem C-budget model (InTEC) developed by Chen and co-workers has been used successfully to predict carbon dynamics of forests in Canada. It was tested here for forest soil organic carbon (SOC) density of China's northern temperate zone and southern subtropical zone. The results show that the simulated SOC density is highly correlated and in broad agreement with observations in Liping and in Changbaishan, representing the southern subtropical zone and the northern temperate zone in China, respectively. SOC density ranged from 2.2 to 11.2 kg/m^2 in Liping and from 3.4 to 14.8 kg/m^2 in Changbaishan. The correlation coefficients (r^2) are 0.63 ($N = 16$) and 0.76 ($N = 14$) between the simulated and measured data in Liping and Changbaishan, respectively. The SOC densities under different vegetation types in Liping decrease in the order of mixed forest, broadleaf forest, Chinese fir, couch grass, and Chinese redpine, and in Changbaishan in the order of mixed forest, silver fir, larch forest, and birch forest.

Keywords: Soil organic carbon density; The InTEC model

1. Introduction

Global climate change may be the most critical and complex environmental issue facing humanity over the next century. (Santer et al., 1996; Kattenberg et al., 1996). Terrestrial ecosystems and the climate system are closely coupled, particularly by cycling of carbon between vegetation, soils and the atmosphere. Ecosystem carbon fluxes are controlled by the processes of photosynthesis, plant (autotrophic) respiration and soil (heterotrophic) respiration. Among many factors affecting these processes, the most obvious at the global scale are elevated CO_2 concentration and climate change, which directly and indirectly influence and interact to control the carbon of terrestrial ecosystems (Amthor, 1995; Houghton and Woodwell, 1989).

People cannot directly and comprehensively measure the carbon cycle of ecosystems at a regional or global scale because of soil spatial heterogeneity. Ecosystem models may be the most effective way to estimate the carbon storage of soil, the atmosphere and vegetation. For example, the Carnegie Ames Stanford Approach (CASA) model is designed to estimate monthly patterns in carbon fixation, plant biomass, soil nutrient mineralization, and CO_2 exchange. Simulations of soil organic carbon were successful in crop and pasture systems using CENTURY; however, they were relatively poor under forests (Parton et al., 1987). These model studies investigated the effects of disturbances (fire, insects and harvesting) and non-disturbance climatic and atmospheric factors individually or in some combinations, but not their integrated effects at regional and global scales. The present study describes the terrestrial ecosystem carbon-budget model (InTEC), which integrates effects of all these factors on the annual C cycles of a forest region (Chen et al., 2000). InTEC is based on Farquhar's leaf photosynthesis model (Farquar et al., 1980;

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Bonan, 1995), the CENTURY C cycle model (Parton et al., 1987; Schimel et al., 1994), the net N mineralization model (Townsend et al., 1996) and an age–NPP relationship derived from forest inventory-based age–biomass relationships. To integrate these existing models, we develop a spatial and temporal up-scaling algorithm to use the instantaneous leaf-level model for a region at an annual time step; we then combine the up-scaled results with an age–NPP relationship to obtain the annual NPP of a forest region.

Although the equations for describing C cycling processes are similar between the InTEC and CENTURY models (Schimel et al., 1996), InTEC provides a better description of litter and forest soil C and N dynamics in the following respects: (1) The soil structural C pool is divided into coarse and fine components to better characterize forest detritus; (2) Disturbance effects are considered in InTEC; (3) Instead of using a constant Q_{10} to calculate the abiotic decomposition factor, we use the modified Arrhenius-type equation of Lloyd and Taylor (1994); and (4) Probably most importantly, we calculate NPP using a process-based leaf photosynthesis model. In this study, we used the InTEC model to qualify the soil organic carbon density under different climatic and disturbance scenarios. In order to validate the adaptivity of the InTEC model in China's northern temperate and southern subtropical forest zones, we will test the simulation using observation. If there is a high correlation, the model may be applied to the whole country of China (Potter et al., 2003).

2. InTEC model description

The InTEC model is a regional scale C-budget model that calculates the annual C balance of a region in year i, $dC(i)$, as the sum of changes in the size of all relevant forest C pools including biomass, $dC_{biomass}(i)$, soil, $dC_{soil}(i)$, and forest products, $dC_{product}(i)$, i.e.,

$$dC(i) = dC_{biomass}(i) + dC_{soil}(i) + dCproduct(i).$$

Changes in C pool sizes are caused by C fluxes among these pools and between the pools and atmosphere. Four biomass C pools (wood, leaf, coarse root, and fine root), six soil C pools (coarse structural detritus, fine structural detritus, metabolic detritus, microbial, slow, and passive), and three forest product C pools (fuelwood, paper products and long-term storage) are considered and separately updated at annual time steps (Schimel et al., 1996; Houghton, 1993).

The major input variables for the model include: historical green house gas concentrations (GHG.dat), CO_2 concentration (CO_2.dat); images in the reference year (2001) including NPP (npp.img), LAI (lai.img), stand age (forest_age.img), land cover type (landcover.img), nitrogen deposition (Ndep.img), and evapo-transpiration (ccet.img); historical climate data sets from 1901 to 2001 such as temperature in the growing season (ta_g.sub), the length of the growing season (length_b.sub), annual mean temperature (Ta_a.sub), and annual precipitation (app.sub); and soil texture images. Originally, all spatial data were made compatible with remote sensing imagery on a 1 km resolution grid of 5300 × 4300 pixels using a standard Albers conic equal-area projection with 25° and 47°N standard parallels and a 105°W meridian.

In this study, we collected these spatial data sets for the regions and soil C data from our field observation. The area-averaged annual NPP is the most important input into the above C–N cycles. We estimated the average NPP of China's forests in 2001 using the LAI and land cover derived from 1-km resolution AVHRR data and daily meterological data using the boreal ecosystems productivity simulator (BEPS). In the model, we corrected the effect of altitude on temperature using GPS measured elevation of each sampling site and assuming a constant adiabatic lapse rate of 6.5 °C. We substituted NPP values in the 1 km resolution image with those simulated at 30-m resolution to decrease the impact of uncertainty in NPP estimation on soil C simulation. We also modified the soil texture data using field measurements. In addition we modified the soil carbon pool decomposition rate of the model using laboratory values. The model outputs include NEP, total soil Carbon density, soil organic carbon density, total and aboveground vegetation C, and modeled annual NPP.

3. Materials and methods

3.1. Study site

Liping County (26°20′N, 109°10′E) is located in the Guizhou Province, China. The area of Liping County is 4441 km^2, 90.5% of which is mountainous, with an elevation ranging between 137 and 1589 m above sea level, Most of the area lies between 600 and 800 m and the mean annual temperature is 15 °C. The study area is in the subtropical zone, and more than half of the area is covered by forests. Chinese fir (*Cunninghamia lanceolata*) is the dominant tree species, but in some places Masson pine (*Pinus massonii*) and mixed broadleaf forest also cover a small area. There are also stands of Mo Bamboo (*Phyllostachys*), but the area is small.

The Changbaishan study area (41°42′–42°10′N ,127°38′–128°10′E) is located in the Jilin Province, northeast China, and covers a total area of 167,081 km^2. Changbaishan belongs to the coniferous and broadleaf mixed forest bioclimatic zone and the continental Temperate Zone, where the annual precipitation is in the range of 700–1400 mm, the mean annual temperature is in the range of −7–3 °C, the minimum temperature is −40 °C, and the rain period is 209 days. The dominant soils in the area are Brown coniferous forest soils, Dark-brown soils, beleached Baijiang soils, Volcanic ash soils and Bog soils. Elevation is in the range of 720–2600 m, and 4 zones of dominant vegetation are distributed based on elevation, including coniferous and broadleaf mixed forest (720–1100 m), coniferous forest (1100–1700 m), Asian birch forest (1700–2000 m) and tundra (>2000 m).

Sixteen soil profiles were collected from the Liping County in July, 2002 and 14 soil profiles were collected from Changbaishan area in July, 2003 according to the different vegetation and soil types. All replicate samples were from forest-derived soils.

3.2. Sampling analysis and calculations

In order to best represent the soil profile, we collected soil samples among trees under different vegetation and soil parent material. Sixteen and 14 samples were obtained from Liping and Changbaishan, respectively. According to different vegetation types, we collected 10 samples from yellow soil and six samples from red soils in Liping, and collected two from Volcanic ash soils, four from Brown coniferous forest soils, five from Dark-brown soils, two from Beleached baijiang soils, and one from Bog soil in Changbaishan. Soils were sampled just before leaf fall in September in Liping country and Changbaishan when the forest floor masses were at a minimum. In the laboratory, soil samples were examined in detail, and litter and remaining roots were removed by hand, and then were air-dried and sieved through a 1 mm sieve.

Soil organic carbon (SOC) was measured by wet oxidation using potassium dichromate in acid medium followed by $FeSO_4$ titration (Nelson and Sommers, 1975). Inorganic carbon is also measured through this method, however, our soil samples were not from calcareous soils. Therefore, the C content only included soil organic carbon. Soil pH was determined in 0.01 M $CaCl_2$ (vol Soil: vol Solution = 1: 5) using a glass electrode (Sparks, 1996). Bulk density can be determined by a number of different methods (Brady and Weil, 1999). We weighed a number of 5.4-cm-diameter cores obtained by hand using a hammer-driven sampling tube. Dry mass of soil per horizon and horizon depth were determined for all horizons measured. C content is expressed in terms of soil particles only.

Soil organic carbon density (C_d) (kg/m^2) refers to the soil organic carbon storage in a certain depth of the soil layer per unit area. C_d was calculated for each of the soil layers as

$$C_d = \left(\sum_{i=1}^{n} 0.58 H_i B_i O_i\right) \Big/ \sum_{i=1}^{n} H_i,$$

where B_i is the bulk density of the <2 mm fraction in $g\,cm^{-3}$, H_i is the thickness of layer i in cm, O_i is the soil

Table 1
Comparison of observed and simulated soil organic carbon densityin Liping country (0–20 cm depth)

Sample	Depth (cm)	Organic carbon ($g\,kg^{-1}$)	Bulk density (g/cm^3)	Clay(%) (<0.002 mm)	$dC_{soilorg}$ (kg/m^2) (simulated)	$dC_{soilorg}$ (kg/m^2) (measured)	Vegetation
LP1	0–30	39.80	1.21	26.4	9.3502	7.2425	Bamboo
	30–60	24.29	1.46	20.4			
LP2	0–45	37.47	0.96	17.7	11.7026	8.9923	China fir (12 year)
	45–65	16.65	1.52	18.1			
LP3	0–20	21.17	1.16	17.9	2.0132	4.4880	China fir (40 year)
	20–60	6.08	1.46	22.1			
LP4	0–8	20.92	0.83	22.0	5.4648	5.0335	Chinese redpine
	8–60	6.39	1.25	26.6			
LP5	0–15	36.89	1.17	18.9	10.5826	7.0825	Couch grass
	15–60	6.03	1.31	21.5			
LP6	0–8	25.40	1.26	17.5	7.0430	5.4591	Shrub
	8–80	5.25	1.39	21.2			
LP7	0–15	24.73	0.98	22.9	5.5045	6.1828	Broadleaf forest
	15–80	6.69	1.23	22.2			
LP8	8–25	17.45	1.03	26.1	4.5281	3.8382	China fir (8 year)
	25–80	5.24	1.26	35.2			
LP9	0–17	19.95	1.16	24.3	7.0142	4.5876	China fir (16 year)
	17–100	4.22	1.39	28.9			
LP10	0–30	24.69	1.02	22.9	5.5076	5.0369	Pine
	30–60	17.90	1.26	25.0			
LP11	0–8	48.17	1.09	16.8	9.2410	11.1752	Mixed forest
	8–60	10.61	1.22	19.5			
LP12	0–30	6.15	1.34	16.2	5.1477	3.5134	China fir (10 year)
	30–80	14.05	1.12	13.6			
LP13	0–30	4.63	1.35	21.7	6.1015	5.1436	Broadleaf forest
	30–60	23.60	1.03	19.2			
LP14	0–8	11.04	1.22	19.9	1.4018	2.2749	Chinese redpine
	8–60	3.45	1.43	21.9			
LP15	0–25	20.45	0.94	15.2	3.2736	3.9675	Couch grass
	25–60	5.53	1.04	15.5			
LP16	0–15	17.66	1.22	16.7	6.9294	4.2033	Tea –oil tree
	15–60	8.46	1.38	19.5			

Table 2
Comparsion of observed and simulated soil organic carbon density in Changbaishan (0–30 cm)

Sample	Depth (cm)	Organic carbon ($g\,kg^{-1}$)	Bulk density (g/cm^3)	Clay(%) (<0.002 mm)	$dC_{soilorg}$ (kg/m^2) (simulated)	$dC_{soilorg}$ (kg/m^2) (measured)	Vegetation
CBS1	0–11	65.03	0.43	9.39	1.834	4.416	Niupi
	11–18	12.31	0.71	4.84			
	17–48	6.35	0.97	5.57			Ericaceous
CBS2	0–19	61.46	0.51	15.10	9.903	8.44	Niupi Ericaceous
	19–36	26.82	0.83	19.50			
CBS3	0–9	138.31	0.40	18.60	11.745	7.6	Birch and silver fir
	9–30	12.33	1.01	5.84			
CBS4	0–14	33.10	0.74	6.63	5.475	4.499	Larch
	14–47	5.40	1.24	1.45			
CBS5	0–15	78.65	0.65	14.20	13.721	9.798	Silver fir and larch
	15–21	33.57	0.71	11.50			
	21–33	7.16	1.08	2.16			
CBS6	0–12	83.01	0.62	8.69	8.098	8.511	Silver fir
	12–30	14.08	0.93	5.25			
CBS7	0–12	67.89	0.60	10.20	7.312	6.444	Silver fir
	12–32	11.75	0.72	4.91			
CBS8	0–8	31.91	0.81	7.75	6.182	2.995	Birch forest
	8–24	5.16	0.99	2.87			
	24–105	2.33	0.86	3.80			
CBS9	0–9	101.90	0.46	11.50	4.717	6.275	Mixed forest
	9–25	12.10	0.93	7.86			
	25–66	5.26	1.02	5.60			
CBS10	0–7	53.12	0.43	7.18	3.316	3.47	Birch forest
	7–18	9.34	1.34	3.45			
	18–100	2.90	1.42	2.29			
CBS11	0–12	73.38	0.71	21.20	7.153	7.488	Birch forest
	12–37	4.59	1.53	25.20			
CBS12	0–9	177.49	0.38	18.40	15.792	14.815	Mixed forest
	9–16	88.01	1.06	20.15			
	16–31	10.17	1.55	21.30			
CBS13	0–10	153.79	0.36	21.40	9.042	8.799	Red pine
	10–69	19.76	0.83	24.00			
CBS14	0–11	34.93	1.10	6.82	3.783	5.352	Mei ren pine
	11–20	5.82	1.40	2.71			
	20–54	2.53	1.48	1.51			

organic matter content of layer i, and 0.58 is the coefficient of conversion from SOM to SOC. (Post et al., 1982) We substituted the mean bulk density of the soil subcategory for bulk density when the measured bulk density was not available. Soil subcategory is considered superior to great soil group for this purpose (Li and Zhao, 2001).

4. Results

4.1. Data of soil organic carbon density

Soil organic carbon density ranged widely from 2.2 to 11.2 kg/m^2 with an average of 5.51 kg/m^2 in Liping and from 3.4 to 14.8 kg/m^2 with an average of 7.06 kg/m^2 in Changbaishan (Tables 1 and 2). It was found that there were different SOC densities under different soil types and vegetation types. Generally, there is a higher SOC density under yellow soil than under red soil in Liping. SOC density under different vegetation types in Liping decreases in the order of mixed forest, broadleaf forest, Chinese fir, couch grass, and Chinese redpine, and in Changbaishan in the order of mixed forest, silver fir, larch forst, and birch forest. SOC density is the highest under the native mixed forest both in Changbaishan and in Liping County. The reason is that the amount of litter returned to the soil is the largest, and that its temperature and moisture are more conducive to formulating and accumulating soil organic matter.

4.2. Test of model predictions

It can be learned from Figs. 1and 2 that there is a correlation of $R^2 = 0.63$ in Liping and $R^2 = 0.76$ in Changbaishan between simulated and measured SOC density in the forest sites. We can see from Tables 1 and 2 that the probability of linear regression is 0.0000509 in Changbaishan and 0.000231 in Liping. The probability is less than 0.01.These data show that the simulation is highly correlated and in broad agreement with observed soil organic carbon density in the southern subtropical zone and the northern temperate zone in China. It was concluded that simulations of soil organic carbon density

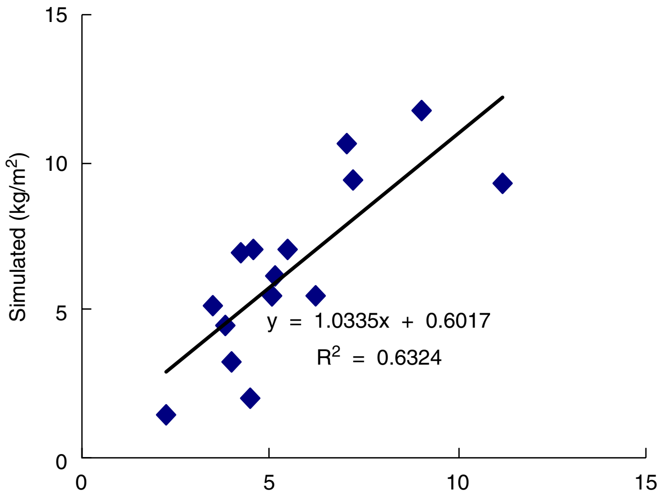

Fig. 1. Comparison of measured and simulated soil organic carbon density for sites in the Liping County (0–20 cm).

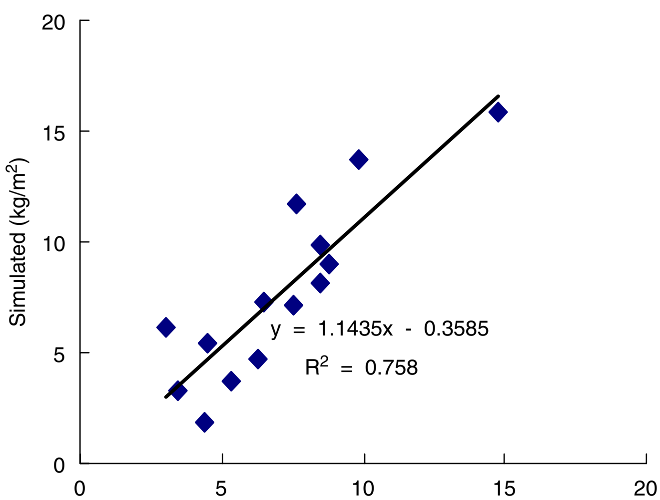

Fig. 2. Comparison of observed and simulated soil organic carbon density for sites in the Changbaishan (0–30 cm).

Table 3
The variance of linear regression between measured and simulated in Liping

Variate source	DF	SS	MS	*F*	*P*
Analysis of regression	1	159.5469	159.5469	37.5916	0.0000509
Deviation from regression	12	50.9306	4.2442		
Total variate	13	210.4775			

Table 4
The variance of linear regression between measured and simulated in Changbaishan

Variate source	DF	SS	MS	*F*	*P*
Analysis of regression	1	79.0053	79.0053	24.0827	0.000231
Deviation from regression	14	45.9281	3.2806		
Total variate	15	124.9334			

across a variety of soil types and vegetation types were relatively successful in forest systems using the InTEC model (Tables 3 and 4).

5. Concluding remarks

This paper tests predictions of forest soil organic carbon density in China's Liping and Changbaishan regions using the InTEC model. The results showed that the simulation was highly correlated and in broad agreement with observed soil organic carbon density in the southern subtropical zone and in the northern temperate zone in China. It was concluded that simulations of soil organic carbon density across a variety of soil types and vegetation types were relatively successful in forest systems using the InTEC model. In order to further improve the precision and expand its applicability at greater temporal and spatial scales, some less understood factors, such as soil degradation and a basal map of high resolution, should be considered in the model.

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References

Amthor, J.S., 1995. Terrestrial higher-plant response to increasing atmospheric CO_2 in relation to the global carbon cycle. Global Change Biology 1, 243–247.

Bonan, G.B., 1995. Land–atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. Journal of Geophysical Research 100, 2817–2831.

Brady, N.C., Weil, R.R., 1999. The Nature and Properties of Soils, 12th ed. Prentice-Hall, Upper Saddle River, NJ.

Chen, W.J., Chen, J.M., Liu, L., Cihlar, J., 2000. Approaches for reducing uncertainties in regional forest carbon balance. Global Biogeochemical Cycles 14, 827–838.

Farquar, G.D., von Caemmerer, S., Berry, J.A., 1980. A biochemical model of photosynthetic CO_2 assimilation in leaves of C_3 species. Planta 149, 78–90.

Houghton, R.A., 1993. Is carbon accumulating in the northern temperate zone? Global Biogeochem. Cycles 7, 611–617.

Houghton, R.A., Woodwell, G.M., 1989. Global climatic change. Scientific American 260, 36–47.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G.A., Metchell, J.F.B., Stouffer, R.J., Tokioka, T., Weaver, A.J., Wigley, T.M.L., 1996. Climate Models-projections of future climate. In: Houghton, J.T., et al. (Eds.), Climate Change 1995:The Science of Climate Change. Cambridge University Press, Cambridge, pp. 285–357.

Li, Z., Zhao, Q., 2001. Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. Plant and Soil 231, 175–185.

Lloyd, J., Taylor, J.A., 1994. On the temperature dependence of soil resoiration. Functional Ecology 8, 315–323.

Nelson, D.W., Sommers, L.E., 1975. A rapid and accurate method for estimating organic carbon in soil. Proceedings of the Indiana Academy of Science 84, 456–462.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society American Journal 51, 1173–1179.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and life zones. Nature 298, 156–159.

Potter, C.O., Klooster, S.V., Myneni, R.G., 2003. Continental-scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982–1998. Global and Planetary Change 39, 201–213.

Santer, B.D., Wigley, T.M.L., Barnett, T.P., Anyamba, E., 1996. Detection of climate change and attribution of clauses. In: Houghton, J.T., et al. (Eds.), Climate Change 1995:The Science of Climate Change. Cambridge University Press, Cambridge, pp. 406–443.

Schimel, D.S., Braswell, B.H., Holland, E.A., Mckeown, R., Ojima, D.S., Painter, T.H., Parton, W.J., Townsend, A.R., 1994. Climatic, edaphic, and biotic controls over carbon and turnover of carbon in soils. Global Biogeochemical Cycles 8, 279–293.

Schimel, D.S., Braswell, B.H., Mckeown, R., Ojima, D.S., Parton, W.J., Pulliam, W., 1996. Climate and nitrogen controls on the geography and timescales of terrestrial biogeochemical cycling, Global Biogeochem. Cycles 10, 677–692.

Sparks, D.L., 1996. Methods of Soil Analysis, Part III. Soil Science Society of America. American Society of Agronomy, Madison, Wisconsin.

Townsend, A.R., Braswell, B.H., Holland, E.A., Penner, J.E., 1996. Spatial and temporal patterns in potential terrestrial carbon storage resulting from deposition of fossil fuel derived nitrogen. Ecological Applications 6, 806–814.