Carbon emissions and sinks in agro-ecosystems of China

LIN Erda (林而达), LI Yue'e (李月娥) & GUO Liping (郭李萍)

Agrometeorology Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China
Correspondence should be addressed to Lin Erda (email: lined@ns.ami.ac.cn)

Received March 16, 2002

Abstract Besides ruminant animals and their wastes, soil is an important regulating medium in carbon cycling. The soil can be both a contributor to climate change and a recipient of impacts. In the past, land cultivation has generally resulted in considerable depletion of soil organic matter and the release of greenhouse gases (GHGs) into the atmosphere. The observation in the North-South Transect of Eastern China showed that climate change and land use strongly impact all soil processes and GHG exchanges between the soil and the atmosphere. Soil management can restore organic carbon by enhancing soil structure and fertility and by doing so mitigating the negative impacts of atmospheric greenhouses on climate. A wide estimation carried out in China shows that carbon sequestration potential is about 77.2 MMt C/a (ranging from 26.1—128.3 MMt C/a) using proposed IPCC activities during the next fifty years.

Keywords: carbon exchange, GHG emissions and removal sinks, North-South Transect, national GHG inventories

Carbon fluxes from and into agro-ecosystems mainly include CO_2 and CH_4 emitted from cropland and grassland practices, ruminant animals and their waste treatment, biomass burning and carbon sequestration caused by corresponding land management activities. Of particular interest and importance is the role of soils in the global carbon cycle which affects the composition of the atmosphere and climate change (fig. 1[1]). N_2O is also an important greenhouse gas affected by agricultural activities. Agriculture accounts for about 70% of overall anthropogenic N_2O emission. The primary sources of N_2O come from mineral nitrogen fertilizers, legume cropping, and manure amendment.

Whether the soil acts as a source or sink of carbon gases depends greatly on the type and intensity of activities of human management on the land. Generally, intensive use of ecosystem leads to a net depletion of carbon storage compared with lightly exploited ecosystem. For example, conversion of grassland to cropland typically results in a decline in carbon stocks. Conversion of land to agricultural purposes often involves such processes due to land clearing, draining, sod breaking, cultivating, and establishing annual rather than perennial vegetation. For agricultural system, reduced tillage, reduced bare fallow, irrigation and fertilization are practices that are most likely to achieve substantial rates of carbon gain. But the net effect of the practices on climate forcing is also affected by impacts on other GHGs. For example, fertilization could increase the N_2O emission from agricultural soils[1].

Altogether, agricultural sources are estimated to contribute about 20% of the total anthropogenic emissions of greenhouse gases (fig. 2)[2]. Land use changes, often for agricultural develop-

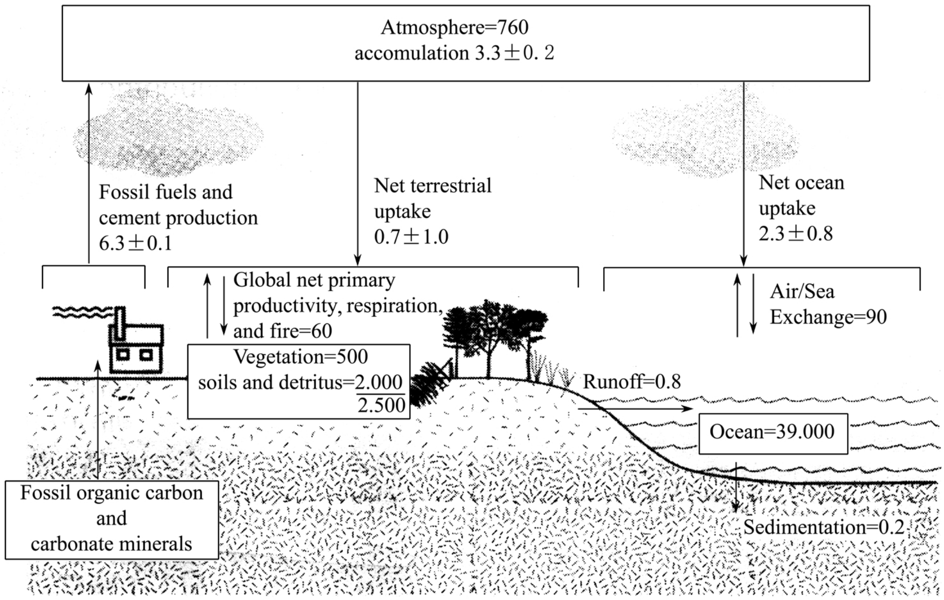

Fig. 1. The global carbon cycle, showing the carbon stocks in reservoirs (in Gt C=10^{15} g C) and carbon flows (in Gt C a^{-1}) relevant to the anthropogenic perturbation as annual averages over the decade from 1989 to 1998 (Schimel et al., 1996, tables 2.1 and 2.2). Net ocean uptake of the anthropogenic perturbation equals the net air-sea input plus runoff minus sedimentation (discussed by Sarmiento and Sundquist, 1992).

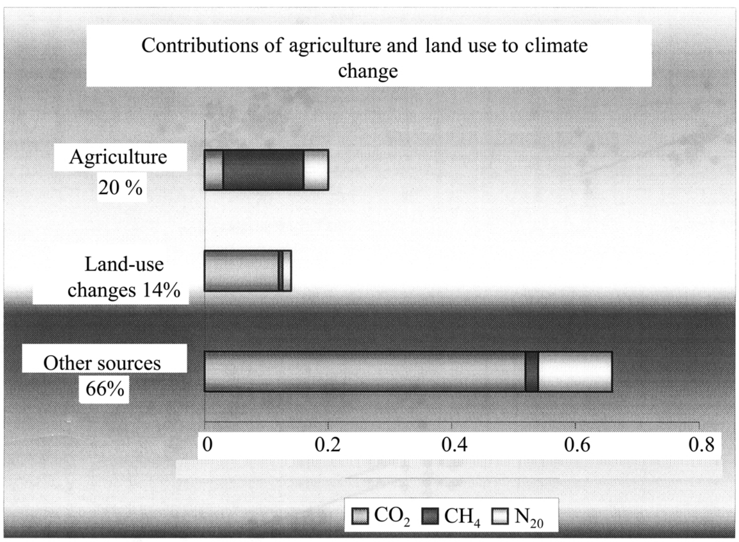

Fig.2. Contribution of agricultural and land use to climate.

ment, accounts for an additional 14%.

To understand the potential impacts of climate change on ecosystems in China, GHG fluxes were measured in the North-South Transect of Eastern China (NSTEC) driven by a gradient of temperature. This transect expands 3700 km from north to south with a 10° longitude width. The specific position of this transect is from 108 to 118°E below 40°N latitude and from 118 to 128°E above 40°E latitude in China. The climate types along this transect includes north temperate, temperate, warm temperate, sub-tropical, and tropical zones from north to south. The transect contains main agricultural ecosystems of the country, such as various forest, grassland, upland, and rice systems spacing, within the summer south-east, monsoon-dominated climate. A series of data were observed and collected on the rates of soil organic matter change and carbon emission and absorption from the different agro-ecosystems .

1 Method and materials

Gaseous fluxes were measured using the closed static chamber technique. The gas collection chamber consists of open-bottomed base unit (0.125 m in diameter by 0.2 m high, inserted 0.15 m into the soil) and removable top (0.125 m in diameter and 0.3 m high). Each base unit was pushed 10 cm into the soil before sampling. During gas collection, floodwater was poured into the base unit water through (5 cm height by 3.5 cm width) to seal the top unit to the base when sampling. The chamber was equipped at the top with a gas valve, which is closed until the sampling time. When the chamber covered the soil, the ambient above ground atmosphere was sampled. After 30 minutes, gas samples were obtained by opening the valve and attaching an evacuated 500 cm^3 sampling bag and syringe to the bag through a 3-way valve. The samples were brought to the laboratory for the analyses of CH_4, CO_2 and N_2O by gas chromatography. The gas flux was identified by the difference between ambient concentration and the concentration in the chamber after 30 minutes.

The experiment stations were located at: (i) Dalate Experimental Station (41°N,110°E), Inner Mongolia Autonomous Region, to measure the impact of land use change on GHG emissions and removals (CH_4, CO_2 and N_2O); (ii) Huangpuchuan Experimental Station (40°N,108°E), to measure the impact of the conversion of marginal farmland to grassland on GHG emissions and removals; (iii) Dinghu Mountain Station (22°N,113°E, located in subtropical zone) and Maoer Mountain Station (46°N,128°E, located in the north temperate zone), to measure GHG emissions and removals from forest ecosystem; (iv) Yingtan Red Soil Experiment Station (27.5°N, 117.5°E) and Anyang Experiment Station (36°N, 115°E) to measure GHG emissions from agricultural system. The sampling frequency in Dalate Experiment Station was once every 5 days, while in other stations, the sampling time was at the first week of January, April, July and October. The sampling time was 5 days (one sample per day) for every season. The soil temperature in the chamber, the soil temperature at 5, 10 and 20 cm depth were also measured at the same time. All sampling were carried out during 1998—2000.

2 Characteristics of greenhouse gas exchange flux along the North-South Transect of Eastern China (NSTEC)

The results showed that fluxes of C and N in the agro-ecosystems are influenced by temperature, rain pattern and management practices.

2.1 Relationship between CO_2 emissions and soil temperature

Fluctuation of CO_2 emissions from soils showed obvious seasonal variation, mainly because the soil temperature is an important factor controlling the microbial activities in grassland soils. The highest emission rate happened in summer. There was an exponential relationship between soil temperature and CO_2 fluxes of natural grassland (n = 95, $y = 1.97e^{0.0681x}$, $P < 0.01$) and also maize field in 5 cm soil depth during 1997 and 1998 in the Dalate Experimental Station (fig. 3). At

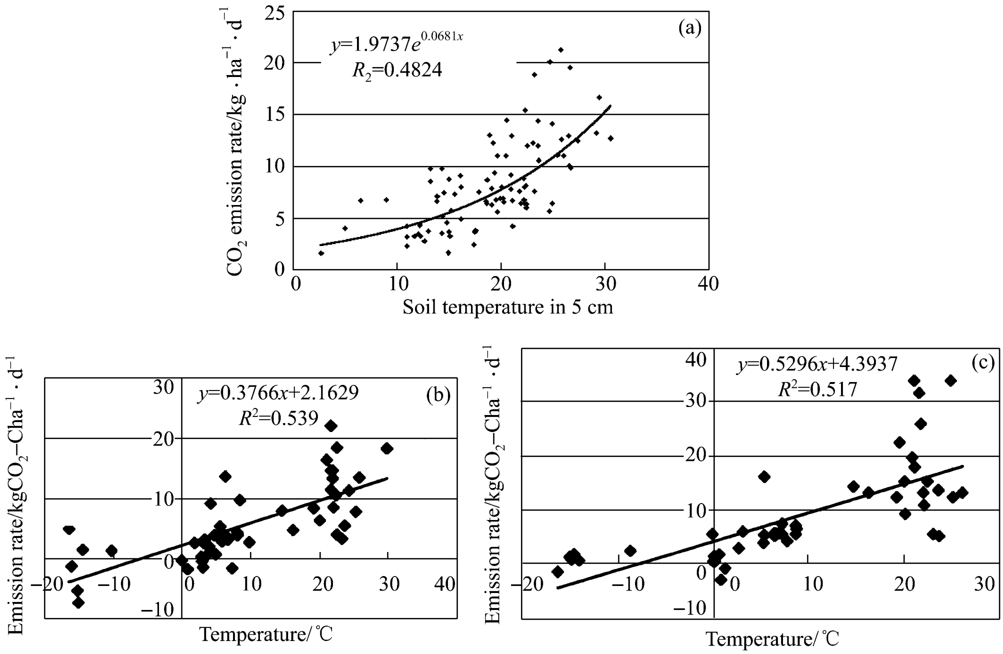

Fig. 3. Relationship between CO_2 emission flux and soil temperature in 5 cm depth. (a) Relationship of CO_2 emission with soil temperature in Dalate Experiment Station; (b) relationship of CO_2 emission with soil temperature in natural grassland in Huangpuchan Station; (c) relationship of CO_2 emission with soil temperature in restoration grassland.

Huangpuchuan Experimental Station, correlation coefficients between soil temperature and emission rates were 0.73 and 0.72 ($P < 0.01$, n = 49) for natural grassland and restoration grassland in 5 cm soil depth, respectively.

For forest soils, CO_2 emission rate is also closely related to soil temperature. At the Dinghu Mountain Station, CO_2 emission rate was higher in spring, autumn and winter than at Maoer Mountain Station because the soil temperature was lower in northern forest during these seasons than in southern forest area.

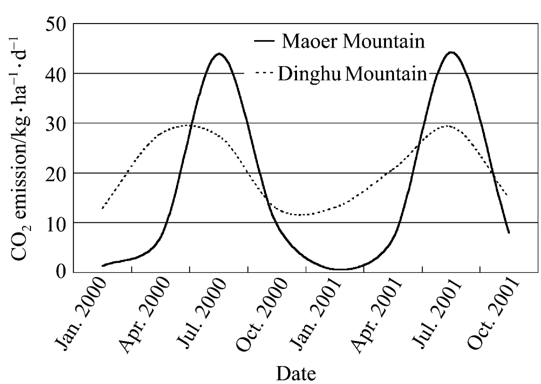

Fig.4. Comparison of CO_2 emission from two different forest systems in South-North transect along eastern China.

In the summer season, however, CO_2 emission rates were lower at Dinghu Mountain than at Maoer Mountain because of lower soil temperatures (fig. 4). The variation range of CO_2 flux in north temperate forest soils were larger than in sub-tropical forest soils due to the wider temperature differences among seasons in northern area.

Soil types, however, modulate a great of deal the relative quantitative relationship between temperature and CO_2 emissions, in addition to disturbance history, vegetation, and topography.

2.2 Impact of direct human activity on emissions and removals of GHGs

Conversion of natural ecosystems to managed systems usually results in emissions of greenhouse gases. Continuous observations of GHG fluxes were conducted in conversion lands from natural grassland to other land uses such as grazing land and cropland. In 1998 the data showed that conversion of natural grassland into farmland increased CO_2 emission. The average emission rate of CO_2 from natural grassland was 10.42 C/ha/d during the growing seasons for grasses, while it was 20.02 kg/ha/d during the growing seasons for maize six years after conversion. The emission rate increased about 100% after the native grassland was converted to farmland. In 1999 and 2000, the CO_2 emission rates from the natural grassland were 10.0 and 9.12 kg C/ha/d respectively. In a maize field, the CO_2 emissions were 14.27 and 14.20 kg c/ha/d, respectively. Conversion of natural grassland to cropland increased CO_2 emission by 43%—100% in sixth to eighth years since conversion. The conversion of natural grassland to cropland not only increased the CO_2 emissions, but also decreased the CH_4 oxidation rate and increased the N_2O emission in our observations (data not shown) and other observations[3].

The organic carbon content was decreased after the conversion of natural grassland to cropland. Nitrogen content in the soils was increased after the natural grassland was converted to maize field because of the fertilization. The soil temperature decreased during the growing season because of the much denser canopy of the cropland. Table 1 shows the changes of organic carbon and the mean soil temperatures during growing season.

Table 1 The changes of soil organic carbon content and mean soil temperatures after the conversion during the growing season in 1999

Site	Depth/cm	Organic C/g/kg	N content /mg/kg	Temp/℃
Grassland	0—5	2.9	540	22.9
Grassland	5—10	2.2	266	20.9
Maize field	0—10	2.4	420	21.1
Maize field	5—10	2.0	298	19.8

Table 2 is a case study for the land use change on overall GHG emissions in 1999, showing that both natural grasslands and maize fields are sources of increasing GHG after conversion to natural grassland.

Grazing was prohibited in the sampling grassland and it was assumed that all of the aboveground and belowground biomass were returned to the soil. Assuming a carbon content for natural grass of 45%, the carbon sequestrated by grassland was estimated to be 754.6 kg C/ha based on the grass production and belowground biomass measurements. The total CH_4 uptake was 5.1 kg CO_2-C equivalent per hectare and total N_2O emission was 62.4 kg CO_2-C equivalent per hectare. The net GHG emissions for the natural grassland was 1031 kg CO_2-C equivalent per hectare.

Table 2 The impact of land use change on overall GHG effects (case study in Dalate County in 1998—1999)

Item	Natural grassland	Maize field
A: Aboveground biomass (kg Dm/ha)	764.3	6675 (excludes the seed production)
B: Belowground biomass (kg Dm/ha)	912.5	1335
C: Carbon sequestration (kg C/ha)	754.6	941.2
D: CO_2 emission from soil (kg C/ha)	1728.2	2568.6
E: CH_4 uptake (kg C/ha)	5.1	2.3
F: N_2O emission (kg C/ha)	62.4	140.5
G: Net GHG effect (kg C/ha)	1031.0	1765.6

The conversion of grassland to maize field can increase the production of aboveground and belowground biomass. About 10 percent of aboveground biomass was returned to the soil, all of the seeds were removed out of the site, and all of the belowground biomass remained in the soil. Assuming a carbon content for the maize crop straw was 47%[2], the carbon sequestrated by corn was 941.2 kg C per hectare. The maize crop can sequestrate about 200 kg C/ha more than that by grassland (table 2). The total CO_2 emission from the maize field was 2568.6 kg C/ha while the total net GHG emissions were 1765.7 kg CO_2-C equivalent per hectare. From these figures, we conclude that the higher plant production of the maize crop cannot compensate for the higher GHG emissions, resulting in a 71% increase in total GHG due to conversion. The figures given in table 2 are calculated as follows:

$$\text{Net GHG effects } (G) = D + F - A \times f1 \times f2 + B \times f2 - E,$$

where D is CO_2 emission from soil; F, N_2O emission from soil; A, aboveground biomass; B, belowground biomass; E, CH_4 uptake by the soil; $f1$, the fraction of biomass returned to the soil; $f2$, the carbon content in the biomass.

Measurements at the Yingtan Red Soil Experiment Station during the growing seasons showed that large CH_4 emission occurred from rice flooded soils. These emissions are in striking contrast with those from upland and forests (*Pinus massoniana*) in the same experiment station which absorbed CH_4 from the atmosphere (fig. 5). Even upland and grassland acted as CH_4 sink during the period of measurements, although uptake strength decreased by 41%—56%[4] when grassland was converted into farmland.

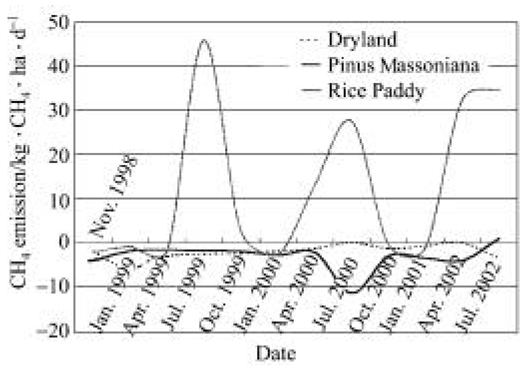

Fig. 5. Effect of direct human activities on CH_4 emission and removal.

The observations along the North-South

Transect of Eastern China showed that sensitivity of soil GHG emission to temperature, water regime and direct human induced activities under current climate condition would hold in a warmer climate.

3 Carbon sequestration potential of land use management practices in China

When land is first converted into agricultural uses, such as conversion of grassland to cropland, conversion of forest to grassland[5,6] or conversion of forest to cropland[7] the organic matter in the soil is oxidized quickly at the beginning and gradually later[8,9]. In addition, much of the originally existing vegetative biomass is released to the atmosphere as CO_2. Deforestation, biomass burning, drainage, plowing, cultivation, and overgrazing all promote the decomposing of organic matter and the release of CO_2 into atmosphere[10]. Soil degrading processes, such as erosion, crusting and compaction, acidification, and salinification, further exacerbate the loss of soil carbon.

Because uptake of methane and carbon in soils vary across the NSTEC, we believe that a substantial part of this loss can be recovered over a period of decades with the best crop management practices, which may include conservation tillage, frequent use of cover crops in the rotation cycles, establishment of agro-forestry, appropriate use of fertilizers and organic material amendments, site-specific management, soil water management that involves irrigation and drainage, and improved varieties with higher biomass production. In rice field systems, appropriate water and fertilizer management can increase carbon storage, but in calculation of the net effect we must consider simultaneous changes in CH_4 and N_2O emissions. In general, management practices to enhance carbon sequestration in croplands should also meet the need for increasing food production.

The national soil surveys has been made twice in China, the first survey was during 1958—1961 and the second one during 1979—1982. The continuous observational record from the observation network established after the mid-1980s by the former National Soil Survey Office of China, indicated that soil organic carbon increased by appropriate management practices through 1985—1995 in cropland soils. Results showed that soil organic carbon (SOC) increased at a level of 11.6 g/kg in the plowing layer during the period. SOC increased in 22% of the area in China[11]. These observed data and other long-term experiments scattered around China[12] suggested that the appropriate management in cropland could indeed increase soil carbon stocks. As for grassland and forest soils, the SOC increased in most intensified management areas, even in some grassland plots subject to overgrazing and cutting. Although conversion of native ecosystems to managed systems generally quicken the depletion of original soil organic carbon, rational crop management could decrease the further loss of soil carbon

We calculated the potential for agricultural and forest management activities to sequester carbon in the next fifty years in China (table 3). For short of long-term continuous observation at

Table 3 Carbon sequestration potential of land use practices in China in next fifty years

Activities	Area/ Mha	Feasibility /% of area	Rate (t C/ha/a)	Duration /a	C gain Potential /Mt C a^{-1}	Other GHGs	Confi-dence
A	B	C	D	E	F=B*C*D	G	H
Cropland management							
Boreal	18.2	30	0.3—0.6	40	1.6—3.3	$+N_2O$	M
Temp. dry	23.7	30	0.1—0.3	30	0.7—2.1	$+N_2O$	H
Temp. wet	18.7	30	0.2—0.6	25	1.1—3.4	$+N_2O$	H
Tropical wet	9.4	30	0.2—0.8	15	0.6—2.3	$+N_2O$	M
Sub-total	70.1				4.0—11.1 (7.5)		
Rice paddy management	9.4	30	0.2—0.8	25	1.5-6.0 (3.7)	$+N_2O$ $++CH_4$	L
All agroforest							
shelter-belt forest	10.0	30	0.1—2.5	50	0.3—7.5	$+N_2O$	M
Economic forest	14.9	30	0.1—1.3	8	0.4—5.8	$+N_2O$	M
Sub-total	24.9				0.7—13.3 (7.0)		
grassland management							
Tempt. wet	35.5	15	0.4—2.0	50	2.1—10.7	$-N_2O-$	M
Tempt. dry	257.7	15	0—0.3	50	0—11.6	CH_4	M
Tropical wet	66.6	15	0.3—3.0	40	2.0—30.0	$-N_2O-$ CH_4	M
Sub-total	360.0				4.1—52.3 (28.2)	$-N_2O-$ CH_4	M
Forest management							
Cold temperate	38.8	20	0.1—0.8	80	0.8—6.2		L
Warm temperate (wet)	8.2	20	0.1—3.0	50	0.2—4.9	$+N_2O$	L
Warm temperate (dry)	16.6	20	0.1—0.8	80	0.3—2.7	$-CH_4$	L
Tropic and sub-tropic	49.7	20	1.6—3.8	60	15.9—37.8		L
Sub-total	113.3				17.2—51.6 (34.4)		L
Total					26.1—128.3 (77.2)		

the national level, we employed the rates of carbon gain of various activities of IPCC[1] and the corresponding area data of China to get the future carbon sequestration potential listed in table 3. Given that grasslands in northern China are subject to desertification, the IPCC guidelines for management implementation are less feasible and a 15% reduction is adopted. For forestland and cropland it is easier to adopt appropriate management practices to decrease the loss or even increase the accumulation of soil carbon, and 20% and 30% are adopted as feasibility of possible practices on forestland and cropland systems respectively. The estimation shows that carbon sequestration potential is about 77.2 MMt C/a (ranging from 26.1—128.3 MMt C/a) for these activities during the next fifty years in China. The sustainability of carbon accumulated by management practices will strongly depend on the situation in which they are implemented and the duration of these activities, because unsustainable activities will result in the loss of earlier stored carbon. Due to the wider range of carbon aging rate and initial assumptions used to make these calculations, the uncertainty may be great (listed in the last column of table 3). At most of time, activities that decrease the loss or increase the stocks of carbon affect the emissions or removals of other greenhouse gases such as CH_4 and/or N_2O; relative influence of these activities on other greenhouse gases are also addressed in table 3.

4 Outlook on national greenhouse gas inventories

Based on the National Communications delivered to UNFCCC, table 3 shows the inventory of GHG emissions from the agricultural sector and carbon sequestration by land use changes and forestry for selected Asia counties. The emission sources in table 4 mainly include enteric fermentation and rice cultivation (CH_4), manure management and biomass burning of agricultural residues and grassland (CH_4, N_2O), nitrogen fertilizer (N_2O); the CO_2 sinks mainly include land use changes and agricultural soil. The large differences and changes among national inventories of all countries delivered to UNFCCC have resulted in a wide window of estimates of the soil carbon sequestration even for some countries under similar agricultural condition. Different estimates also show that methodology should be improved in order to get comparable results among different countries. The estimates of carbon emissions and removals can be improved through the following practices: (i) basing on the same definitions of land use types; (ii) basing on comparable methodology among countries; (iii) basing on consistent methodologies over time; (iv) both CO_2 and non-CO_2 greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change and forestry should be considered, (v) using the country specific rates.

Table 4 GHG emissions and removal from agriculture and by land use changes in selected Asia counties, 1994 (Gg)

Country	Proportion of GDP (agro/total)	CH_4	N_2O	CO	CO_2 By LUCF
Indonesia	17.4%	3244	53	331	156
Japan	(13.7%)	849	9	172	–83
Jordan	4.5%	27	0.01		–1455
Kazakstan	14.9%	827			–6627
Malaysia	11.5%	329	0.054		–67
Philippines	21.7%	990	40	435	–126
R. of Korea	6.4%	595	1		–26235
Uzbekistan	34.5%	377	481		

The data came from the initial national communications for individual countries to the Framework Convention on Climate Change (http://www.unfccc.de).

5 Summary

From the observations along North-South transect across eastern China, CO_2 emission flux shows seasonal variation and is positively correlated with soil temperature at 5 cm soil depth. Terrestrial ecosystems can absorb large quantities of the carbon dioxide from atmosphere, but some observations suggest that land use changes are greatly impairing this ability. The emission of CO_2 from soils in northern ecosystems showed a wider range than southern ecosystems. Conversion of natural grassland to cropland increased CO_2 emission by 43%—100% and decreased CH_4 uptake by 41%—56% in sixth to eighth years since conversion. Intensified management on ecosystems could increase soil carbon stocks, with potential carbon sequestration for selected activities in the main land use systems from 26.1 to 128.3 MMt C/a in China. Due to great uncertainties, especially for Carbon losses and removals, national GHG inventories in Asian Countries still need to be improved. Estimates of carbon emissions and removals can be improved through: (i) basing on the same definitions of land use types; (ii) basing on comparable methodology among countries; (iii) basing on consistent methodologies over time; (iv) both CO_2 and non-CO_2 greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change and forestry, (v) adopting the country specific emission or absorption rates.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 39899370-03), the Key Project of Chinese Academy of Agricultural Sciences, and the Foundation of Red Soil Ecological Experiment Station of Chinese Academy of Sciences (2000-03).

References

1. IPCC Special Report of Intergovernmental Panel on Climate Change——Land-Use Change, and Forestry (eds. Watson, R. T., Nobel, I.R., Bolin, B. et al), Cambridge: Cambridge University Press, 2000, 4.
2. Li Y.E., Lin, E. D., The impact of grassland conversion on CO_2 emission and CH4 uptake, in Non-CO_2 Gases: Scientific Understanding, Control and Implementation, in Proceedings of Second International Symposium (eds. Van Ham et al.), Dordrecht: Kluwer Academic Publishers, 2000, 115—120.
3. IPCC, Climate Change 1995——The Science of Climate, Contribution of Working Group I to the Second Assessment Report of the Intergovermental Panel on Climate Change, Cambridge-New York: Cambridge University Press, 1996.
4. Li Yue, Lin Erda, The effect of grassland conversion on CH_4 and N_2O emissions and removals, 2002, submitted.
5. Li, Y. E., Lin, E. D., The impact of grassland conversion on CO_2 emission and CH_4 uptake, in Non-CO_2 Gases: Scientific Understanding, Control and Implementation, in Proceedings of Second International Symposium (eds. J. Van Ham et al.), Dordrecht: Kluwer Academic Publishers, 2000, 115—120.
6. Lugo, A. E., Brown, S., Management of tropical soils as sinks or sources of atmospheric carbon, Plant and Soil, 1993, 149: 27—41.
7. Neili, C., Melillo, J. M., Steudler, P. A. et al., Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern brazilian amazon, Ecological Applications, 1997, 74(7): 1216—1225.
8. Eswaran, H., Van den Berg, E., Reich, P., Organic C in soils of the world, Soil Science Society of America, 1993, 57: 192—194.
9. Arrouys, D., Mariotti, J., Girardin, C., Modelling organic carbon turnover in cleared temperate forest soils converted to maize cropping by using ^{13}C natural abundance measurements, Plant and Soil, 1995, 173: 191—196.
10. Houghton, R. A., Changes in storage of terrestrial carbon since 1859, in Soils and Global Change (eds. Lai, R., Kimbkle, J., Levine, E.), Boca Raton: CRC Press, 1995, 45—65.
11. Lai, R., Kimble, J. M., Follett, R. F., Agricultural practices and policies for carbon sequestration in soil, in Recommendation and Conclusions of the International Symposium, 19-23 July 1999, Columbus, OH, USA, 12.
12. National Agricultural Technology Extension and Service Center of China (NATESC), in Proceeding of Soil Amending and Measurement (in Chinese), Beijing: China Agricultural Press, 1998.
13. Guo, L. P., Lin, E. D., Carbon sink in cropland soils and the emission of greenhouse gases in paddy soils: A review of work in China, Chemosphere: Global Change Science, 2001, 3(4): 413—418.