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Introduction

Enhancing forest carbon sequestration in China: Toward an integration of scientific and socio-economic perspectives

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Abstract

This article serves as an introduction to this special issue, "China's Forest Carbon Sequestration", representing major results of a project sponsored by the Canadian International Development Agency and the Chinese Academy of Sciences. China occupies a pivotal position globally as a principle emitter of carbon dioxide, as host to some of the world's largest reforestation efforts, and as a key player in international negotiations aimed at reducing global greenhouse gas emission. The goals of this project are to develop remote sensing approaches for quantifying forest carbon balance in China in a transparent manner, and information and tools to support land-use decisions for enhanced carbon sequestration (CS) that are science based and economically and socially viable. The project consists of three components: (i) remote sensing and carbon modeling, (ii) forest and soil assessment, and (iii) integrated assessment of the socio-economic implications of CS via forest management. Articles included in this special issue are highlights of the results of each of these components.

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1. Introduction

China is a country of unique importance in the context of global climate change and carbon sequestration (CS). Geographically, China occupies approximately one 15th of world land area and one 25th of world forest area (UN FAO, 2006). China is one of the few nations to encompass nearly the earth's entire range of climate zones, with temperature regimes ranging from tropical to alpine/boreal, and precipitation regimes from humid to arid. Land-use change in China has been characterized by drastic alterations of landscapes over centuries of human activities. During the early-mid-20th century, large areas of China were deforested as a result of political instability, land conversion, and population increase in forested areas. Forest degradation reached a peak during the "Great Leap Forward" (1958–1960) when government policies encouraged intense logging to provide fuel for backyard steel furnaces. However, there has been an enormous change in the fate of China's forests over the last two decades of rapid economic growth. Since the early 1980s, the Chinese

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government has implemented some of the world's largest reforestation programs. Total forested area increased from 122 to 159 million ha from the late 1970 to 2001 (China's Year Book, 2002).

Current and future trends in land use in China are of clear significance to the global carbon budget (Houghton and Hackler, 2003). Recent studies based on China's forest inventory program have quantified forest biomass carbon stock (Fang et al., 2001), and estimated China's forest carbon budget (Pan et al., 2004). While of great value, such assessments exclude land areas not encompassed by forest inventory programs, and are also not readily verifiable by those outside China. This is an important consideration in the broader political context. China approved the Kyoto Protocol on August 30, 2002, with the provision that it would not apply to the special autonomous regions of Hong Kong and Macau. As a non-Annex I country under Kyoto, China is not required to meet any emission targets within the first commitment period, but can participate in clean development mechanism (CDM) projects under which Annex I countries may earn certified emission reductions credits by implementing projects in non-Annex I countries. Although the Kyoto framework is likely to evolve substantially through and following the first commitment period (2008–2012), comprehensive and transparent assessments will continue to be critical to all internationally coordinated efforts to encourage forest CS.

The implementation of the Kyoto Protocol has come at a time when China faces critical decisions on the future of reforestation and forest protection initiatives. Major reforestation programs in China include "Grain-for-Green", in which landowners are compensated with rice for converting their agricultural lands to tree plantations (Yan-qiong et al., 2003), and the Three-North, and Upper and Middle Reaches of the Yangtze River Shelterbelt projects (e.g., Ma, 2004). In addition, the Natural Forest Conservation Program was initiated in 1998 to expand natural forests, increase plantation extent and productivity, and protect existing forests from excessive cutting (Zhang et al., 2000). A major motivation for these programs, in particular "Grain-for-Green", was over-production of and downward price pressures on key agricultural commodities (SCPRC, 2000; Zhang 2003). Recent reductions in agricultural outputs relative to demand have already resulted in some modifications in these programs. In addition, much of the marginal agricultural land in many regions of China has already been converted to forest plantation cover. China's major reforestation and forest protection programs are thus entering a period of policy re-evaluation and uncertainty.

To date, CS has not figured as a major objective of China's reforestation and forest protection programs, which were rather initiated with the main aims of erosion control, flood mitigation, wood supply, and agricultural commodity price control. However, large-scale reforestation, conversion from agricultural land uses to forest cover, and forest protection measures are precisely the sorts of the policy initiatives that also serve to enhance forest CS. China's prior programs also represent an important opportunity to assess, retrospectively, the implications of large-scale reforestation initiatives to CS, and the social and economic impacts of these programs.

The project entitled "Confronting global warming: enhancing China's capacity for CS" was developed to address these issues. Its primary goal is to enhance CS in China's ecosystems through developing tools to better make land-use decisions that are scientifically sound and economically and socially viable. The project has the following specific objectives:

1. to facilitate the transfer of knowledge and technology in geographical information systems (GIS) and remote sensing applications related to ecosystem carbon cycle monitoring and modeling in order to better estimate the potential for CS in China's forest ecosystems;
2. to undertake forest and soil assessments in pilot ecological zones in China in order to validate and adapt existing carbon cycle models to Chinese ecosystems and to examine the potential for developing balanced afforestration policy regimes; and
3. to conduct integrated assessments (IAs) on various forest CS options by comprehensively considering their social, economic and environmental impacts in order to develop carbon-favorable and sustainable land-use options. Of particular concern are the potential impacts of policy decisions to women and minority groups.

Over 50 Chinese and Canadian scientists participated in this 4-year project from 2002 to 2006. The Canadian participating institutions were (1) Institute for Environmental Studies, the Faculty of Forestry and the Department of Geography of the University of Toronto (U of T), (2) Adaptation and Impacts Research Group (AIRG), Environment Canada, and (3) Canada Center for Remote Sensing (CCRS), Natural Resources Canada. The major Chinese participating institutions included: (1) Beijing Institute for Geographical Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences (CAS); (2) Nanjing Institute of Soil Sciences (NISS), CAS; (3) Lanzhou Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), CAS; (4) Beijing Normal University (BNU); (5) Nanjing University (NU); (6) Nanjing Agricultural University (NAU); and (7) Nanjing Forestry University (NFU). These institutions contributed various expertise towards achieving project objectives.

2. Project components

The project was structured toward achieving the aforementioned project objectives with three main components (Fig. 1):

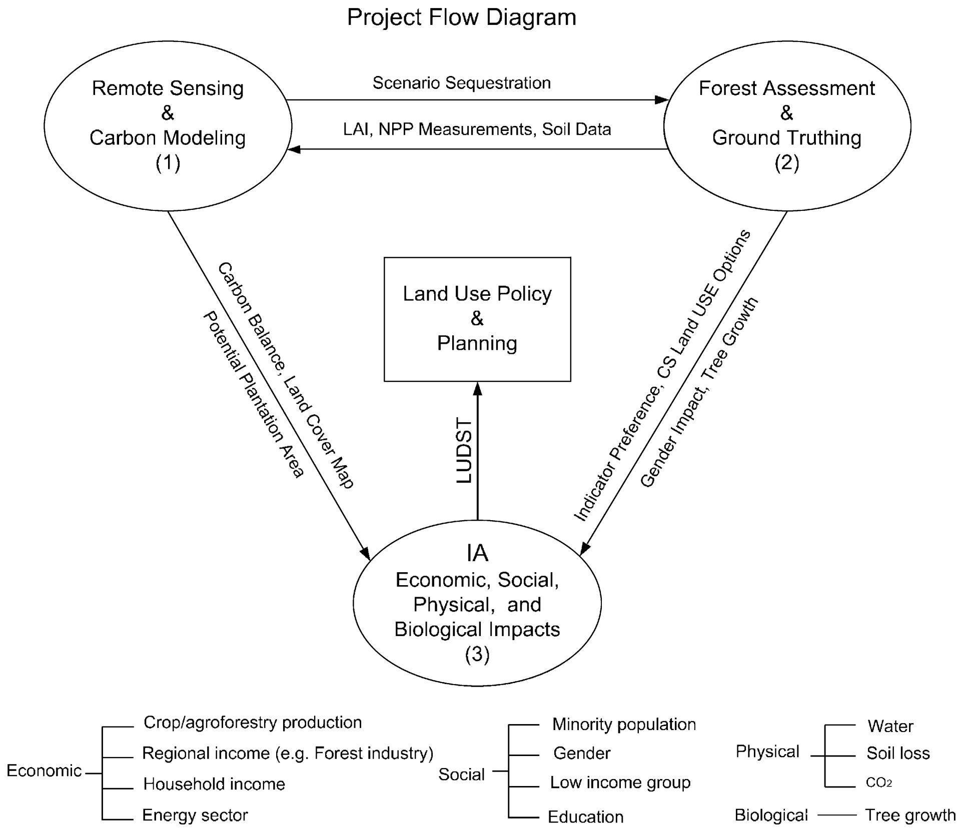

Fig. 1. Project components, information flows among them, and factors considered in integrated assessment (IA). The outcome of IA provides the basis for formulating land use policy and planning, and this process can be further assisted using the land-use decision support tools (LUDST) developed through this project.

2.1. Remote sensing and carbon modeling

In this component, a Canadian terrestrial carbon cycle monitoring and modeling framework based on remote sensing and GIS techniques was transferred to China in order to estimate the potential for CS in China's forest ecosystems. The CCRS developed and commercialized a satellite image processing system named GEOCOMP-n which produces data products useful for terrestrial ecosystem monitoring and carbon cycle modeling (Cihlar, 1996; Cihlar et al., 1997a, b, 2002). Scientists of CCRS and U. of T., in collaboration with the Canadian Forest Service and Meteorological Service of Canada, developed remote sensing-based carbon cycle models, namely the Boreal Ecosystems Productivity Simulator (BEPS) for short-term (several years) carbon cycle modeling in daily time steps (Liu et al., 1997, 1999; Chen et al., 1999) and the Integrated Terrestrial Ecosystem Carbon Model (InTEC) for long-term (a few centuries) carbon modeling in annual time steps (Chen et al., 2000; Chen et al., 2003). They also developed a ground-based optical instrument, named Tracing Radiation and Architecture of Canopies (TRAC) (Chen and Cihlar, 1995a, b; Chen et al., 1997) for measuring forest structural parameters in support of remote sensing algorithm development. GEOCOMP-n, BEPS, InTEC and TRAC represent some of the existing Canadian technologies and methodologies useful for large area carbon cycle estimation, and they were introduced to China through this project.

Based on remote sensing and ground data (component 2), two levels of carbon cycle estimation were conducted: (1) country-wide, moderate resolution (1 km) mapping of carbon cycle components, and (2) county-level, high resolution (20–30 m) mapping of carbon cycle components. Country-level maps provided regional forest carbon budget estimates, which are useful not only for global climate research but also for state level planning and policy-making. County-level maps (particularly in combination with topographical maps) can serve several purposes including (i) validation of country-wide maps; (ii) implementation of local CDM projects; and (iii) IAs of land-use options.

2.2. Forest assessment and ground-truthing

In this component, sampling of forests and soils in pilot ecological zones were conducted in order to provide input parameters for ecosystem models used, and to test remote sensing-based modeling results. In addition, component studies were carried out to examine afforestation and other management options for enhancing CS. The remote sensing-based carbon models, BEPS and InTEC, were developed in Canada based on data from boreal and cold temperate ecosystems. Although physical and biological principles imbedded in these models are in principle applicable to other ecosystems, confident applications of these models to China's ecosystems with a large latitudinal range must be accompanied by careful ground validation in a range of ecological conditions. The key purposes of this component were (1) to determine the validity of overall CS estimates by these Canadian models, (2) to provide a compartmentalized budget indicating the respective carbon pools in the forest ecosystem, with particular attention to the effect of forest dynamics and species composition on these pools, and (3) to obtain site-level biophysical parameters as input to the models and for remote sensing algorithm development. Ground observations made at local sites also provide invaluable data for input to the analysis of the potential impact of forest management on CS in China. Specifically, they provided guidance on which tree types are optimum for CS, how carbon storage is likely to be affected by changing the forest age structure, and how the storage may be affected or enhanced by changes in silvicultural practices, such as timber harvest interval. These results will be invaluable input to Chinese authorities in developing forest policy and management strategies for maximizing and sustaining CS.

2.3. Integrated assessment (IA)

In this component, the economic, social and environmental impacts of land-use scenarios designed to increase CS in China were assessed using state-of-the-art IA methods that had been tested in Canada and elsewhere (Yin and Pierce, 1993; Yin, 1999; Yin et al., 2000). IA activities were carried out in three selected counties in China (see Section 3) and engaged local stakeholders in such a way that the project promoted linkages between CS land-use plans and local sustainability in rural China. The IA framework also included consideration of poverty reduction, gender equality, ecosystem health, economic development, food production, resource management, and other regional concerns. Two questions were intensively addressed in these IA activities:

(i) How will CS strategies or policies affect local sustainability and livelihoods?
(ii) How could CS plans be better integrated into sustainable development strategies in China?

The IA work adopted a systems analysis approach assisted by multi-criteria decision making tools. Many different computer-based and participatory methods were used, including the multi-criteria policy evaluation (MCPE) (Yin and Cohen, 1994). The MCPE was carried out to identify desirable CS plans or policies by which decision makers can increase CS and take the advantage of positive impacts associated with land-use change in the region. To select desirable CS plans among alternatives, multi-stakeholder consultation (MSC) and MCPE provided a means to relate impact information to decision making requiring subjective judgment and interpretation. The results of various impacts generated were used as references for ranking the performance of each CS plan against each sustainability indicator. These indicators are used as multiple criteria by which the strengths and weaknesses of the various CS plans were evaluated.

Components 1 and 2 were linked interactively (Fig. 1), with component 1 providing spatial information for ground assessments and component 2 providing ground-truthing data for remote sensing algorithm development and carbon modeling. Results from components 1 and 2 were then used in component 3 in addition to social and economic data, to achieve the goal of producing recommendations of land-use options for enhancing CS.

3. Study sites in pilot ecological regions

Five main locations were initially chosen as the project's key research areas based on different ecosystem and land conditions (Fig. 2). Changbaishan Biosphere Reserve, Liping County and Heihe River Basin are the core sites, while Xingguo County and Baoying County are auxiliary sites. In the three core sites, all three project components were conducted. Two auxiliary sites were included to augment components 1 and 2. During the project implementation, several other minor auxiliary sites were also used for various purposes: (i) Dunhua County near the Changbaishan Biosphere Reserve in Jilin Province was added for comparison between natural forests and plantations ; (ii) Taibai County in Qinling Mountain in Shanxi Province was later selected to study hydrological effects on the carbon cycle; and (iii) Jianyin County of Jiangsu Province was used to study carbon dynamics associated with rapid land-use changes:

(1) Changbaishan (Jilin Province, Northeast China) is a forested area, consisting of both natural forests and plantations (larch (*Larix* spp.), and Korean pine (*Pinus koraiensis*)), representative of the northeast temperate forests of China. A micrometeorological flux tower for measuring carbon, water and energy fluxes using the eddy covariance technique is being operated by the Chinese Academy of Sciences and these data were used for validation of carbon cycle models.
(2) Liping County (Guizhou Province, Southwest China): This site is one of 10 largest forested areas in China, and includes mostly plantations (Chinese fir (*Cunninghamia lanceolata*) and Masson pine (*Pinus massonii*) of various ages with some native mixed hardwood forest. It is representative of 60–70% of plantations in southwest China, with a karst landscape and relatively uniform soils.
(3) Heihe River basin (Ganshu Province, Northwest China) is in a semi-arid region on the Yellow Plateau with large areas of forest plantations and some natural

Fig. 2. Locations of project core sites (Liping County, Heihe River Basin and Changbaishan Biological Reserve) and auxiliary sites (Xinguo County and Baoying County).

forests. Many international research projects have been conducted here resulting in a variety of accumulated data sets for its ecosystems. Extensive IA work was also previously done by CAREERI.

(4) Xingguo County (Jiangxi Province, Central China): This area has large areas of plantations of Masson pine and slash pine (*Pinus elliotii*), representative of large areas in Jiangxi and neighboring provinces.

(5) Baoying County (Jiangsu Province, East coast) includes about 4000 ha of hybrid poplar plantation. A 10-year-old plantation has been intensively studied by NFU. The area represents a prior conversion from agriculture, and is underlain by a fluvial clay soil.

Forest structural parameters (leaf area index, foliage clumping index), land cover, biomass, net primary productivity (NPP), and profiles of soil texture and carbon were measured at the five sites. The total soil carbon was separated into fast, slow and passive carbon pools through laboratory incubation studies for the purpose of validating the InTEC model. At the three core sites, social and economic data were collected and household surveys were conducted for IAs.

4. Highlights of project outcomes

The articles included in this special issue provide the outcomes of this project in remote sensing and carbon modeling, forest and soil assessments and IA. Although details of these outcomes are given in the individual articles, highlights are summarized here.

4.1. Carbon modeling

Using the InTEC model, Wang S. et al. (2007c) produced the first ever series of maps showing annual carbon source and sink distributions in China's current forest areas from 1901 to 2001. This represents the first time that forest age structure information is considered in carbon sink estimation for all of China's forests. Important non-disturbance factors, including climate, nitrogen deposition and CO_2 fertilization, are also considered in the model. The results show that China's forests were carbon sinks of 213 ± 60 Tg C $year^{-1}$ during 1984–2001, as a result of the large area plantations established since the late 1970s. The estimated sink magnitude including soil organic matter change is larger than that of Fang et al. (2001) which considered biomass change only.

Ju et al. (2007) extend Wang et al.'s historical model results to the future 100 years using two climate scenarios with two levels of climate warming and two regimes of precipitation redistribution. They conclude that without climate change, China's forests would continue to increase in carbon sink strength until 2015 to a level of 300 Tg C $year^{-1}$ and then the sink would gradually decrease to a level of near neutral in 2100 because of the age-related forest growth dynamics. In both high (5 K) and low (3 K) warming scenarios, China's forests would become a carbon source in the second half of the 21 century if the CO_2 fertilization effect is not considered. After incorporating a CO_2 fertilization effect, model output suggests that China's forests would remain as a carbon sink in both high and low warming scenarios, although the magnitude would be considerably smaller than scenarios not including climate change.

In support of the above carbon cycle modeling studies, Feng et al. (2007) conducted China-wide NPP modeling at daily time steps for 2001 using the BEPS model. This is the first ever process-based modeling using remote sensing inputs for China's entire landmass and many useful spatial details are shown. The annual NPP map in 2001 provides a key benchmark in annual NPP modeling for the 1901–2001 period using the InTEC model.

As country-wide NPP and full carbon cycle modeling was conducted at a moderate resolution (1 km), high-resolution (20–30 m) NPP modeling activities were carried out for several ground sites, in order to link ground plots to moderate resolution pixels. Zhou et al. (2007c) produced and validated a high-resolution NPP map for the Qilian Mountain in the upstream portion of the Heihe River Basin. The procedure for creating such high resolution NPP mapping involved the following major steps: (1) measuring LAI and NPP of ground plots; (2) developing remote sensing algorithms to map LAI and land cover; (3) using the BEPS to model the spatial distribution of NPP based on remote sensing, soil and daily meteorological inputs; and (4) validating NPP mapping using ground plots. The validation at this site was satisfactory ($r^2 = 0.70$, $n = 14$, RMSE = 14%). Similar steps were followed at the Changbaizhan and Dunhua sites (Wang P. et al., 2007b), and after increasing the NPP dynamic range by combining results from these two sites and the Heihe site, the regression results between modeled and measured NPP values improved significantly ($r^2 = 0.90$, $n = 29$). Chen et al. (2007) also used the same procedure to acquire NPP of ground plots in the Qinling Mountain in Shanxi Province. In order to consider hydrological effects (lateral ground water flow) on NPP distribution, Chen et al. (2007) coupled BEPS with the hydrological model TerrainLab (Chen et al., 2005), and showed the importance of considering various effects of topography on the carbon cycle. Xu C. et al. (2007) applied BEPS to Jianyin County, Jingsu Province, and demonstrated the effectiveness of BEPS in capturing the spatio-temporal dynamics of rapidly changing rural landscapes.

4.2. *Remote sensing in support of carbon modeling*

Based on ground measurements of LAI, many similar but fine-tuned remote sensing algorithms for LAI mapping were developed at various sites including Changbaishan and Dunhua (Wang P. et al., 2007b), Heihe (Zhou et al., 2007c), Liping (Zheng et al., 2007; Jin et al., 2007), Xingguo (Tian et al., 2007), and Qinling (Chen et al., 2007). LAI maps produced for these sites using high-resolution optical remote sensing images provided critical inputs to NPP estimation and were also useful for country-wide LAI algorithm validation (Liu R. et al., 2007; Tang et al., 2007). Based on LAI and forest age data, an algorithm was developed by Zheng et al. (2007) for mapping forest biomass, and they demonstrated that biomass mapping using optical remote sensing could be considerably improved when forest age information was available. Unfortunately, independent spatially explicit forest age information was not available and was derived from LAI data in their study. Jin et al. (2007) conducted a study to upscale high-resolution LAI images from Landsat ETM + at 30 m resolution to 1 km resolution, and developed a scaling methodology to correct errors in MODIS LAI images at 1 km resolution according to subpixel land cover information. This study paved the way to improved regional LAI mapping.

Regional remote sensing methods were developed in support of country-wide carbon cycle modeling. Tang et al. (2007) developed a new LAI algorithm using directional remote sensing information. Parameters of a kernel quantifying the distributions of surface reflectance in red and near infrared wavebands with view (satellite sensor) and illumination (Sun) directions were extracted from standard MODIS products and used to derive LAI. Compared with ground data at Heihe and Changbaishan, Tang et al. (2007) demonstrated that LAI derived using the directional information was more accurate than the standard MODIS LAI product. Principles and methodologies of GEOCOMP-n have been used in a Chinese system named MODISOFT (Liu R. et al., 2007). This system also incorporates another new LAI algorithm developed as part of this project (Deng et al., 2006), and the results compare well with high-resolution LAI maps derived using ground-based LAI data at Heihe and Changbaishan (Liu R. et al., 2007). This system can now routinely produce LAI coverages for China for ecosystem monitoring and modeling.

4.3. *Forest and soil assessments*

All estimates of forest CS rely on accurate values for the carbon content of wood and other vegetation parts. Although the figure of 50% wood carbon content has been very widely used in the CS literature, Thomas and Malczewski (2007) emphasize that wood carbon content actually varies substantially among tree species, and present empirical data for wood carbon content for species from northeastern China. They also show that the volatile fraction of wood carbon, which is typically lost during oven drying of wood, is a non-negligible fraction of total wood carbon content, averaging 2.2% for the species examined. Carbon content values for Chinese species surveyed ranged from 48.4% to 51.0%, being significantly higher in conifer than hardwoods.

A very small fraction of China's ~2500 tree species are currently planted in reforestation efforts, with larch (*Larix* spp.) predominant in northern China, hybrid poplar along the eastern seaboard, and Chinese-fir (*C. lanceolata*) and Masson pine (*Pinus massoniana*) in southern China.

Thomas et al. (2007) present a comparative analysis of potential growth and CS of 14 native tree species in northeastern China, based on tree ring analyses and simulations using a forest growth model coupled to the InTEC carbon process model. Results indicate very high potential for a number of native hardwood species in CS forestry. The authors argue that increased use of a wider variety of native tree species in reforestation efforts in China promises additional benefits in terms of forest environmental services, biodiversity protection, and economic diversification.

Soil organic carbon represents a carbon sink of at least as much importance as live biomass. Baseline data on soil carbon is essential for any assessment of forest CS, and depends critically on such as parent material, texture, and depth, as well as forest cover and management practices. Yu et al. (2007) utilize a recent comprehensive spatial data set for soil properties in China at 1:1,000,000 scale, in conjunction with a recently completed soil organic carbon measurements at more than 7000 sites distributed throughout China, to develop the most detailed spatial data set for soil organic carbon in China to date. The results highlight differences among soil and forest types, and the importance of soil carbon stores in China's far north and forest alpine systems. The results provided another critical input to full carbon cycle modeling (Wang S. et al., 2007c; Ju et al., 2007).

Understanding and predicting future trends in soil organic carbon depends critically on the underlying susceptibility of soil carbon to decomposition processes. Thirty soil samples were acquired from Changbaishan, Qilian Mountain, and Liping, and sub-tropical forests at Yujiang County (Yang et al., 2007). These samples were analyzed to obtain the total soil carbon, and the total carbon was separated into fast, slow and passive pools through laboratory incubation studies. These total and separated carbon pools provide an excellent test against the InTEC model simulation (Shao et al., 2007). The correlation coefficients (r^2) were 0.63 ($N = 16$) and 0.76 ($N = 14$) between the simulated and measured total soil carbon in Liping and Changbaishan, respectively. These successful tests of the InTEC model without modifying the decomposition coefficients of the various carbon pools in these two contrasting climate conditions gives us increased confidence in applying InTEC to all of China's forests.

Kang et al. (2007) assessed vegetation and soil conditions in various vertical zones of the Heihe River Basin and zonal CS potentials in relation to water resources. They also suggested different carbon management strategies in different vertical zones. These results are particularly useful for western China where water is the main limiting factor for forest CS.

4.4. Integrated assessment

In the IA part of this volume, Yin et al. (2007) introduce the IA component in the context of the project and identify major concerns in forest CS decision making. An IA approach was described for applications at three sites to link forestry CS land-use policies with local sustainability. Other IA papers present case studies in each of the three sites. Zhou S. et al. (2007) describe a case study in Liping County. Based on data collected from two sets of household surveys, the county-wide economic impacts of Grain for Green and carbon uptake amounts were calculated using a benefit–cost analysis method and an average carbon flow method. The paper concludes that implementation of reforestation options (using any of 11 tree species) on sloping uplands would be desirable for farmers with or without government subsidies. Using only two tree species and different assumptions from those employed by Zhou S. et al. (2007), Caldwell et al. (2007) conclude that if government subsidies under Grain for Green end after 8 years (the anticipated end of the program), farmers will suffer significant decreases in income that cannot be compensated by perpetual harvesting of the timber planted on converted agricultural lands. The spatially disaggregated, GIS-based IA model constructed by Caldwell et al. demonstrates that the income effects and CS effects of Grain for Green vary considerably by township, leaving many farmers worse off and some better off than before the Grain for Green program. Xu W. et al. (2007) discuss social impacts associated with forest CS land-use scenarios in Liping County. The results of this study reveal that socio-economic changes associated with the government-financed reforestation project are multifaceted and profound. With the financial subsidies provided by the central government, the national Grain for Green project in many aspects can be regarded as a poverty reduction measure in poor rural areas. A majority of peasant households have benefited from their participation in the Grain for Green program. The reforestation project with continued financial support also contributes to the social transformations of traditional rural society in remote areas to a more mobile, less subsistence agriculture based, and open society. The paper by Wang C. et al. (2007a) describes an IA case study in Dunhua County that combines measures of the cost-effectiveness of Grain for Green with estimates of the CS co-benefits of the program. Major findings of this case study include (1) the Grain for Green program, in many cases, did not give adequate consideration to land productivity and environmental heterogeneity when selecting plots; (2) more than half of reforested plots were on flat cropland; (3) in most townships, the economic impacts of Grain for Green on farmers will be positive at the end of 8 and 40 years; (4) the Grain for Green program could generate substantial co-benefits for the state if carbon credits from reforestation and afforestation are recognized under the CDM. Peng et al. (2007) describe applications of an IA approach in the Zhangye Prefecture within the Heihe River Basin in a semi-arid region. Some socio-economic and ecological impact results of forest CS land-use scenarios are presented in the paper. The case study also applied the fundamental orientation theory to estimate social sustainability impacts of Grain for Green land-use options. The paper suggests that, in Zhangye Prefecture, the Grain for Green project could enhance the sustainability and stability of local society, increase peasants' net income, and protect ecosystems.

5. Conclusion

In the concluding article of this special issue, Cihlar (2007) makes the following comment:

> The economic, environmental and policy roles of the terrestrial carbon cycle will increasingly demand availability and use of tools that are demonstrably capable of accurate, timely, and cost-effective estimates of the carbon budget and its components.

This project tested and fine-tuned several tools for application to China's forest ecosystems. Both short- and long-term carbon cycle models, BEPS and InTEC, were shown to perform well in comparison with ground measurements of NPP and soil carbon, respectively. These models can be cost-effective tools for future use. In this project, we also explored, for the first time, IA methodologies that consider not only social and economic impacts of land-use options but also CS potentials of these options. We also pioneered the methodology of combining spatially explicit carbon cycle estimation with township-level social and economic data for a county within a GIS system (Caldwell et al., 2007). Although these models and methodologies were tested and fine-tuned for applications in China, they should also be useful for other regions in the world.

In order to sustain the impact of the outcomes of this project, a "Land Use Decision Support Tools" package has been developed. The package includes four carbon cycle models (BEPS and InTEC for stand-level and regional applications separately) and a set of IA tools. The package effectively links carbon cycle estimation with IA within a user-friendly interface. The stand-level BEPS and InTEC models can be implemented easily in new locations with the simple replacement of an input climate file and new specifications of soil and plant types. The regional BEPS and InTEC models can also be used by non-specialists with basic knowledge of image file formats. IA tools have a user-computer interactive system that can collect scenario preference data from individual users directly. This package will be further tested by the newly established Carbon Project Office at the Chinese State Forestry Administration. It can be made freely available through contacting the lead author.

With a large number of ecological, economical and social data sets collected and produced in this project, much further analysis is possible. Important priorities include (1) conducting further assessments of the suitability of planting tree species with the highest CS potentials identified by Thomas et al. (2007), (2) using site-level LAI and NPP measurements in all sites for validating country-level LAI and NPP maps through the spatial scaling methodology developed by Jin et al. (2007), and (3) processing the latest forest inventory data for forest age structure information within each polygon to improve the estimation of China's forest carbon budget associated with forest age dynamics, and to include spatially explicit disturbance effects on the carbon source and sink distribution.

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