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SPECIAL TOPIC ON REGIONAL CLIMATE CHANGE IMPACTS AND ADAPTATION

Impacts of Climate Change on Forest Ecosystems in Northeast China

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Abstract

This paper reviews the studies and research on climate change impacts on the forest ecosystems in Northeast China. The results show that in the context of global and regional warming, the growing season of coniferous forests has been increasing at an average rate of 3.9 d per decade. Regional warming favors the growth of temperate broad-leaved forests and has a detrimental effect on the growth of boreal coniferous forests. Over the past hundred years, the forest edge of the cool temperate zone in the southern Daxing'anling region has retreated 140 km northward. From 1896 to 1986, the northern boundary of broad-leaved forests in Heilongjiang province has extended northwestward about 290 km. Future climatic changes (until 2060) may lead to the northern deciduous needle forests moving out of China's territory altogether. The occurrence cycles of pests and diseases have shortened; their distribution ranges have expanded. The life cycle of tent caterpillars (*Malacosoma neustria testacea* Motschulsky) has shortened from 14–15 years in the past to 8–10 years now. The pine caterpillar (*Dendrolimus tabulaeformis* Tsai et Liu), which has spread within western Liaoning province and the nearby areas, can now be found in the north and west. Lightning fires in the Daxing'anling region have significantly increased since 1987, and August has become the month when lightning fires occur most frequently. Overall, the net primary productivity (NPP) of forest in Northeast China has increased. The NPP in 1981 was around 0.27 Pg C, and increased to approximately 0.40 Pg C in 2002. With the current climate, the broad-leaved Korean pine forest ecosystem acts as a carbon sink, with a carbon sink capacity of 2.7 Mg C hm^{-2}. Although the carbon sink capacity of the forest ecosystems in Northeast China has been weakened since 2003, the total carbon absorption will still increase. The forest ecosystems in Northeast China are likely to remain a significant carbon sink, and will play a positive role in the mitigation of climate change.

Keywords: Northeast China; forest ecosystem; climate change

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1 Introduction

Northeast China is located at the higher latitudes of the eastern end of the Eurasian continent. It contains Daxing'anling, Xiaoxing'anling, the Changbai Mountains, and other important forest regions (Fig. 1). Northeast China is an ecologically important forest region, a strategic forest resource reserve and an important ecological green barrier for China. Climate research for nearly a hundred years show that Northeast China is very sensitive to global warming and is one of the most significant warming areas in both China and the world [*Sun et al.*, 2006]. Studies have suggested that, as one of the main terrestrial ecosystems, forest ecosystems are extremely sensitive to climate change, and climate change impacts are very significant [*Zhao*

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et al., 2009d]. In this paper, the research progress in climate change impacts on the forest ecosystems in Northeast China is reviewed. The major technical methods used for climate change impact assessment and prediction, the major findings and the countermeasures to adapt to climate change are summarized. Study areas, such as plant phenology, vegetation compositions and distributions, pests and diseases, forest fires, vegetation productivity and ecosystem carbon budgets are also presented. The uncertainty in current researches is analyzed. Forest ecosystem research that should be strengthened in the future are discussed in order to provide a reference for formulating proper climate change policies.

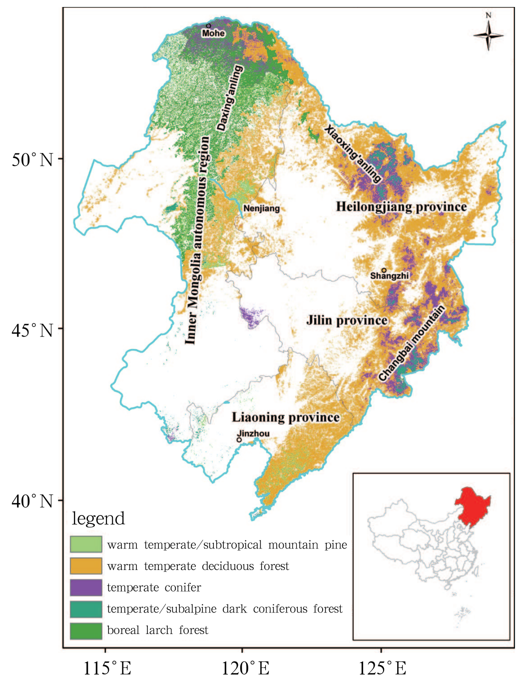

Figure 1 The location and distribution of main forests in Northeast China (based on www.geodata.cn)

2 Main methods used in climate change impact assessment and prediction

2.1 *Phenology*

Two methods have been used to study climate change impacts on plant phenology in the forests of Northeast China. The first one is the statistical analysis of long-term phenological observation data [*Zheng et al.*, 2002; *Xu et al.*, 2006; 2008; *Li and Zhou*, 2010]. The second method is the spatial analysis using a geographic information system (GIS) in conjunction with the statistical analysis of the vegetation index from satellite remote sensing data [*Guo et al.*, 2010a; 2010b]. In studies applying the above mentioned methods, two problems were identified. First, the ground phenology observation data is very limited. Second, the ground observation data are often used to validate the remote sensing data, which inhibits inconsistent scale problems.

2.2 *Vegetation composition and distribution*

Studies on timberline change are mainly based on transect investigations and tree ring analyses [*Wang et al.*, 2004]. The major methods used to study vegetation composition and distribution change include transect investigations [*Zhou et al.*, 2002] and the reanalysis of data from historical forest maps [*Chen*, 2000]. Methods for future predictions include related models based on field observations [*Mu*, 2003], statistical models [*Leng et al.*, 2007], biogeographic models, e.g. MAPSS, life zone classification and climate classification [*Zhao et al.*, 2002; *Wu*, 2003; *Wu et al.*, 2003; *Liu et al.*, 2007; *Li et al.*, 2006], and forest gap models, e.g., FAREAST, LINKAGES and BKFP [*Cheng and Yan*, 2008; *Zhou et al.*, 2007; *Liu and Jin*, 2005; *Hao et al.*, 2001]. Different climate scenarios have been used to predict forest succession dynamics and vegetation distribution trends in Northeast China.

2.3 *Pests and forest fires*

So far, studies on forest pests in Northeast China mainly used the pest monitoring data [*Zhao et al.*, 2003; *Zheng and Wang*, 2004]. Information on forest fires in Northeast China mostly comes from the government and forestry fire departments or from remote sensing data.

2.4 *Productivity and carbon budgets*

Model simulations are often used to study the productivity and carbon budget of forest ecosystems in Northeast China. Models used include biogeochemical model, e.g., Sim-CYCLE (simulation model of Carbon

CYCLE in land ecosystem) [*Tang et al.*, 2009], and forest gap model, e.g., FORCCHN (FORest ecosystem Carbon budget model for CHiNa) [*Zhao et al.*, 2009c].

Each model has its own advantages and disadvantages. The main problems with statistical models are that they are empirical models, so there is little emphasis on the responses of vegetation or ecosystems to climate change and their results cannot be easily extrapolated. Biogeographic models are equilibrium vegetation models and are mainly used to simulate the potential and natural distributions of vegetation types at large scales, e.g., global or continental, and therefore may not be suitable for simulating small-scale changes. Biogeographic models ignore the delay phenomenon shown by vegetation and cannot consider the feedback effects on vegetation. Biogeochemical models are not able to simulate the impacts of biogeochemical processes on vegetation distribution or the effect of changes in vegetation distribution on the climatic system [*Peng et al.*, 2005]. In contrast, the forest gap model is a small-scale model, which exhibits problems when it is applied at regional scale.

3 Major findings on climate change and its impacts

3.1 *Observed climate change*

From 1961 to 2010, the annual mean temperature increased approximately at the rate of 0.35°C per decade in Northeast China. This was higher than the worldwide and natimal average rate. The increase is most significant in the northern Xiaoxing'anling (0.61–0.64°C per decade). The seasonal mean temperature showed a significant upward trend, which was most obvious in winter (0.55°C per decade), followed by spring, summer and autumn, respectively. The annual precipitation showed a weak decreasing trend. The number of precipitation days showed a significant downward trend, with a rate of 2.4 d per decade [*Zhao et al.*, 2013].

3.2 *Impacts on plant phenology*

Changes in plant phenology can directly provide evidence for regional climate change, especially for global warming [*Lu et al.*, 2006]. According to *Xu et al.* [2006], the phenological observation data from tree species in Shenyang city showed that, once the annual mean temperature rose 1°C, the start of bud germination would move forward 9 d, the begin of leaf development would move forward 10 d, and the begin of flowering would advance 5 d.

There are significant differences between responses of different species to climate change in Northeast China. According to *Guo et al.* [2010b], the start date of the growing season for coniferous forests advanced at an average of 2.5 d per decade from 1982 to 2003. The end date delayed at an average rate of 1.4 d per decade, so the whole growing season was extended at an average rate of 3.9 d per decade. The start date of the growing season for mixed coniferous and broad-leaved forests in Northeast China delayed at an average rate of 2.1 d per decade; the end date was earlier with an average rate of 1.7 d per decade; the whole growing season was shortened at 3.8 d per decade over the same timescale. The start date of the growing season for broad-leaved forests in Northeast China was earlier on average at 0.6 d per decade and the end date was earlier at 0.1 d per decade. These small changes meant that the whole growing season was affected in significantly.

The seasonal effects of climate change on different tree species in Northeast China varied. From 1982 to 2003, the earlier start of the growing season for coniferous forests in Northeast China was mainly caused by rising temperature in spring (March–May). However, the earlier start of the growing season for mixed coniferous and broad-leaved forests was significantly influenced by rising temperatures in April. The earlier start in the growing season for broad-leaved forests was mainly caused by rising temperatures in March and April, while temperature in May had little effect on it. Increasing precipitation in spring might have influenced the delay of the coniferous forest growing season, while it has no obvious effects on the phenologies of the other species [*Guo*, 2010a].

3.3 *Impacts on vegetation composition and distribution*

The intensification of human activities, such as land reclamation, mining, and road construction as well as frequent forest fires, combined with climate warming, has resulted in the gradual decline of the forest area in the northern permafrost region of Northeast China. The original *Larix gmelinii* of the cool temperate zone is under serious threat [*He et al.*, 2009]. During the period 1902–2002, the forest edge of the cool temperate zone in southern Daxing'anling region retreated 140 km northward. The tree species composition in the Daxing'anling region in 2002 was significantly different to that in 1962. The proportion of coniferous forests decreased and that of broad-leaved forests increased. The area of *Larix gmelinii* and *Pinus sylvestris* var. *mongolica* Litvin fell by more than one third. Compared with 1962, the stock of coniferous forests decreased from 580 million m^3 to 360 million m^3 in 2002, with a decrease of 37.9%. In contrast, the stock of broad-leaved forests increased from 110 million m^3 to 360 million m^3, with an increase of 26.4%. The ratio of the dominant species (*Larix gmelinii* and *Betula platyphylla*) changed from 7:1 to 2.6:1 in the Daxing'anling region between 1962 and 2002. The area of original forest (mature forests) in the Daxing'anling region dropped from 4 million hm^2 in 1949 to 2 million hm^2 in 2002. During this period, the stock volume of the original forest decreased from 480 million m^3 to 200 million m^3 [*Wang*, 2005].

Significant warming has caused the island-shaped permafrost, located in the low-lying valleys of the Xiaoxing'anling region, to melt and disappear. Correspondingly, the forest ecosystems relying on the permafrost habitats, for example, *Picea abies*, have declined [*Guo et al.*, 2001].

Using a GIS, *Chen* [2000] studied five kinds of forest landscapes from the forest distribution maps for Heilongjiang province from 1896 to 1986. The results showed that during these 90 years, the total areas of spruce-fir (*Picea abie*), fir (*Pinus sylvestris* var. *mongolica* Litvin) and mongolian scotch pine (*Pinus koraieusis* Sieb. et Zucc.) fell by 87%, 40% and 84%, respectively. The area of broad-leaved forests north of 51°N increased by 500% and the northern boundary extended about 290 km northwestward.

The timberline has undergone significant changes. Studies on the diameter-class distribution of *Betula ermanii* at three sites, i.e., the typical distribution zone of *Betula ermanii*, the *Betula ermanii-tundra* ecotone and the transition edge, showed that the *Betula ermanii* population has migrated upwards with the rising temperature. They have moved from an altitude of 1900–1,950 m to 2,150 m, a retreat of 200–250 m. This migration is more pronounced in the Betula ermanii-tundra ecotone [*Zhou et al.*, 2002]. During the peroid 1967–1999, the warming in the Dahailin region in Heilongjiang province had great impacts on the treeline structure of the Laotudingzi Mountains. The warming increased the survival ratio of seedlings and saplings, which increased the upper forest line. Forest density also increased by more than 5,000 seedlings per hectare and the average tree age declined to below 20 years. The age structure is an aggregated reverse J-shape, distribution. At the lower forest line, seedling regeneration is rare and the forest is mainly middle-aged (60–90 years) with a scattered distribution and a density of 2,000–4,000 trees per hectare. Climate warming has increased tree diameter growth and moved the forest line forwards in the Laotudingzi Mountains. The tree ring index, which is the ratio of the actual width of tree rings to the expected one, has increased at an average rate of 0.01 per year and this upward trend is consistent with the temperature change in this region over the last 30 years [*Wang et al.*, 2004].

Mu [2003] studied the succession of *Larix olgensis* and *Betula platyphilla* marsh ecotone communities in the Changbai Mountains of Northeast China. He concluded that the existing trend in regional warming would accelerate the mesophytization process in the forest-marsh ecotone. The ecotone communities would eventually change into forest communities within a relatively short period of 50–60 years.

Based on a modified MAPSS biogeographic model, the prediction results by HadCM2 for future climate change, and the impact of future elevated atmospheric CO_2 concentrations, *Zhao et al.* [2002] suggested that future climate change (until 2060) may lead to a serious decline in the spatial extent of northern deciduous forests, so that it may become almost extinct in China.

The distribution range of broad-leaved Korean pine forests in Northeast China significantly declined under dry and warm climate conditions, and its ability to adapt to new ecological situations also reduced

[*Wu*, 2003]. Using general circulation models (GCMs), *Wu* [2003] used a temperature-moisture function to evaluate the impact of doubled CO_2 levels on the eco-climatic suitability of the distribution area of broad-leaved Korean pine forests in Northeast China. The results show that under the GISS (NASA) scenario, the core distribution area of broad-leaved Korean pine forests was about 11.7×10^3 km^2, with a decrease of 83.6%, and was mainly distributed north of 46°N in the Xiaoxing'anling region. The suitable distribution area of the broad-leaved Korean pine forests reduced to 94.7×10^3 km^2, a decrease of 22.8%, in which the southern boundary moved northward near 42°N. The marginal distribution area was 167.9×10^3 km^2, a reduction of 18.5%. The total area was about 274.3×10^3 km^2, with a decline of 31.4%. The western boundary in the southern distribution range moved significantly to the east and the southern boundary moved about 1° latitude northward. Under the OSU (Oregon State University) scenario, the core distribution area for Korean pine was 202×10^3 km^2, with a decrease of 71.7%, and was mainly distributed in Zhangguangcailing and north of the Xiaoxing'anling region. The area of the broad-leaved Korean pine forest was 108.6×10^3 km^2, a decrease of approximately 11.5%, and was mainly distributed in the region north of 42°N. The marginal distribution area was 187.2×10^3 km^2, with a decrease of 9.1%. The total area decreased by 21% and its southern boundary moved approximately 1° latitude northward.

If climate warming continues, the proportion of the coniferous forests will decline and the proportion of broad-leaved forests will increase in Northeast China. The stronger the warming, the more obvious the trend [*Cheng and Yan*, 2008]. The HadCM3 and HadCM3 scenarios, show that as the climate warms, the proportion of larch in the *Larix gmelinii* forest communities in Mohe and the Turi River regions will decrease over the next 100 years, while hardwoods, such as birch and Mongolia oak, will increase. The HadCM3 scenario with the strongest warming suggests that birch and Mongolia oak will occupy an important position in the forest communities. A certain amount of linden trees will also exist in the forest communities. The numbers of larch and pine conifer will decrease, but for hardwoods, such as birch, Mongolian oak, linden, and ash, will increase in the Nenjiang River region, which is located at the southeastern Daxing'anling region. The proportion of Korean pine in the coniferous and broad-leaved mixed forest communities in the Xiaoxing'anling region, the Changbai Mountains, and in the Shangzhi region will decline significantly. Under the more substantial warming predicted by HadCM3, the survival of Korean pine is uncertain. The proportion of the deciduous broad-leaved forest, containing for example linden, ash, and maple wood, will increase. With the same level of warming, spruce-fir will almost disappear in the Shangzhi region. Based on the analysis of forest responses to regional warming, it has been suggested that the forest lines will shift upward in Xiaoxing'anling, the Changbai Mountains and the Shangzhi region [*Cheng and Yan*, 2008].

The Logistic Regression model, which artificially sets climate change scenarios, indicates that once the temperature rises by 1°C the proportion of *Larix gmelinii* will decline by 12%, that of *Larix olgensis* var. *Changpaiensis* will increase by 23%, and that of *Larix principis-rupprecntii* will increase by 500%. When precipitation increases by 10%, *Larix gmelinii* will decline by 12.5%, *Larix olgensis* var. *Changpaiensis* will increase by 64%, and *Larix principis-rupprecntii* will decrease by 15%. With warmer and dryer climate conditions (i.e., +5°C and –30%), the area of *Larix gmelinii* will shrink about 100 km northwestward, the area of *Larix olgensis* var. *Changpaiensis* will extend about 100 km northwestward, and the area of *Larix principis-rupprecntii* will extend 800 km northeastward. With warmer and wetter conditions (i.e., +5°C, +30%), the area of *Larix gmelinii* will increase 400 km northwestward, the area of *Larix olgensis* var. *Changpaiensis* will extend westward by 550 km, and the area of *Larix principis-rupprecntii* will increase 320 km northeastwards [*Leng et al.*, 2007].

3.4 *Impacts on forest pests and diseases*

Regional warming expands the distribution area of forest vegetation and forest pests. With increasing warming, the emergence time of forest pests will be earlier, the number of generations will increase, the scope and degree of harm will rise, the overwintering generations of pests and diseases will move northwards, the wintering bases will increase, and the migration range will extend [*Li et al.*, 2010; *Wei et al.*, 2013]. Climate change leads to a shortening of the pest and disease cycles, which will become more frequent. Normally the occurrence cycle of tent caterpillars (*Malacosome nentria testacea* Motschulsky) was 14 or 15 years, but recently, this cycle was shortened to 8–10 years. Outbreaks of this pest occurred in 1965, 1974, 1984 and 2002 in Baicheng, Jilin province [*Zhao et al.*, 2003].

Due to temperature changes and the increase of effective accumulated temperature, the distribution range of regional insect fauna has moved northward. The pine caterpillar (*Dendrolimus tabulaeformis* Tsai et Liu), which was distributed in western Liaoning province, now has moved further northward and westward. *Hyposipalus gigas* L., *Monochamus alternates* Hope, *Blastophagus minor* Hartig, and *Tomicus piniperda* L., which are common pests in the hilly region of southeastern China, now cause serious harm in Liaoning and Jilin provinces. *Semanotus sinoauster* Gressitti has gradually spread northward into Liaoning province [*Zhao et al.*, 2003]. The worldwide quarantine pest, *Hyphantria cunea*, generally has two generations per year. Nowadays, three generations of larvae occur in western and southern Liaoning province, but most of them die about 5 years later and therefore do not complete their lifecycle. Due to the high temperatures in 1994, three generations of this pest appeared in Jinzhou city of Liaoning province [*Zhao et al.*, 2003].

Warm winter allows pests and diseases to live through winter, which prolongs the pests and diseases hazard period [*Zhao et al.*, 2003]. Spring droughts, caused by warm winters, lead to an increase in defoliating insect populations. In 2002, tent caterpillars (*Malacosome nentria testacea* Motschulsky) emerged and devastated an area of 1.38 million hm^2, including the majority of forests in Heilongjiang, Jilin, Liaoning and Inner Mongolia provinces. Especially hard hit was the forest area in the southern Daxing'anling, Aihui, the Nenjiang River and the adjacent regions. The affected area was nearly 240,000 hm^2, the worm strain rate was 70%–90% and the population density was 140–180 heads per individual tree on average in the Daxing'anling region [*Zhao et al.*, 2003; *Zheng and Wang*, 2004].

3.5 *Impacts on forest fires*

As temperature rises, drought periods get longer, and the reduction in air humidity can lead to a longer fire season, which starts earlier and ends later. As a result, the forest fire frequency and intensity, and the proportion of burned area will increase [*Zhao et al.*, 2009a]. Studies have shown that frequent and sustained high temperature and droughts in summer have led to frequent occurrence of summer forest fires in the Daxing'anling region, which rarely occurred before [*Zhang and Feng*, 2005]. An analysis of the forest fire data in Heilongjiang province from 1980 to 1999 showed that the spatial volatility of forest fires was particularly sensitive to temperature. When temperature is higher, the fire ignition centers move northward and westward [*Wang et al.*, 2003]. After 1987, under dry conditions, lightning fires increased significantly, with August becomming a new lightning fire-prone month in the Daxing'anling region [*Zhang and Hu*, 2008].

Until 2100, it is predicted that climate change will lead to an increase in the number of forest fires, in the number of days with extreme fire behavior, and in the severity of forest fires [*Tian et al.*, 2005]. The extension of the fire cycle will influence the distribution of some tree species in Northeast China, and will extend the distribution range of spruce forests in the Daxing'anling region [*Tian et al.*, 2005]. Although improvements in fire prevention can effectively control forest fires in small areas, in the context of extreme weather increases, the risk of forest fire is increasing, with the rising risk of large area and high intensity [*Tian et al.*, 2005].

3.6 *Impacts on vegetation productivity and ecosystem carbon budget*

Forest carbon stocks can ameliorate the increasing atmospheric CO_2 concentration and play an important role in the mitigation of climate change [*Zhao et al.*, 2009c]. Studies show that from 1981 to 2002, the total net primary production (NPP) of the forest area in Northeast China was 0.27–0.40 Pg C per year, and that from soil respiration was 0.11–0.27 Pg C per year [*Zhao et al.*, 2008]. During the period 1981–2002, the NPP in Northeast China showed an upward trend. The NPP was approximately 0.27 Pg C in 1981, and rose to 0.40 Pg C in 2002. The forest ecosystems in Northeast China act as a carbon sink. The total amount of carbon reserves is about 12.37 Pg C per year, in which the carbon storage by vegetation and soil are 4.01 and 8.36 Pg C per year, respectively. Both the vegetation carbon stocks and the soil carbon storage showed an upward trend from 1981 to 2002. The contribution of rising temperature to the increase in carbon stocks in the forest ecosystem of Northeast China is larger than that of precipitation changes. The forest area in Northeast China accounts for 31.4% of the whole China. Its vegetation and soil carbon storages account for around 74.3% and 63.9%, respectively of national forests. Its vegetation and soil carbon densities are 2.1 and 1.2 times as those of the national forests, respectively [*Zhao et al.*, 2009b].

Under the current climate conditions, the broad-leaved Korean pine forest ecosystem acts as a carbon sink, with a carbon sink capacity of 2.7 Mg C hm^{-2}, but its carbon sink role will gradually weaken with the increase in carbon stocks [*Tang et al.*, 2009].

Predictions show that until 2049, the forest ecosystem in Northeast China will remain a significant carbon sink, but the intensity will decrease under the A1B scenario based on the Flexible Global Ocean-Atmosphere-Land System Model (FGOALS). Until 2049, the total amount of carbon stored by the forest ecosystem in Northeast China will increase from 14.46 Pg C per year to 16.72 Pg C per year, and soil carbon storage will change slightly from 9.73 Pg C per year to 9.78 Pg C per year. Vegetation carbon storage will change from 4.73 Pg C per year to 6.94 Pg C per year, an increase of 46.7%. It is mainly the decrease in soil carbon stocks that causes the decrease in carbon absorption capacity of the forest ecosystems in Northeast China. However, the increase in vegetation carbon will slow down this process [*Zhao et al.*, 2009c].

Predictions show that under the A1B scenario until 2049, the NPP and soil respiration will show an upward trend in volatility before reaching the saturation status with increases of 10.8% and 134.4%, respectively. The increase in soil respiration is far higher than the increase in NPP. Until 2049, the forest ecosystems in Northeast China are likely to remain a significant carbon sink, but the intensity is predicted to decrease by 95.6%. Between 2003 and 2049, although the carbon sink capacity of the forest ecosystem in Northeast China is predicted to decline, the total amount of carbon absorption will still increase, which indicates that the forest ecosystems in Northeast China will play a positive role in reducing the concentrations of greenhouse gases in the atmosphere and in mitigation of climate change [*Zhao et al.*, 2009d].

4 Uncertainties of climate change impact assessment and prediction

Because of the limited knowledge on the mechanisms of the regional climatic system, the forest ecosystems, and the interactions between these systems, uncertainties exist in the impact assessments of climate change on the forest ecosystem in Northeast China [*Peng et al.*, 2005; *Zhang*, 2007; *Wang et al.*, 2008; *Anne et al.*, 2010]. Some bottleneck problems are described in the following.

(1) Accuracy in climate predictions: The prediction accuracy of existing regional climate models is not high. The predictions of different climate models vary considerably. The different climate scenarios used lack comparability. These inaccuracies increase the overall assessment uncertainty.

(2) Ecological assessment model: Some mechanistic ecological models lack reliability, because there is a lack of reliable test data, and most of the parameters and assumptions are based on models from other regions. The climate variables are often the mean values of assessment studies, which do not really express the actual situation. Furthermore, the influences of various disturbances, such as extreme weather events, fires, pests, and diseases, are not considered effectively.

(3) Vegetation self-regulation and feedback: Forest ecosystems are influenced by changes in the climate system. Internal competition, succession, self-regulation and adaptation processes of the ecosystems also affect the climate system. However, in the exist-

ing climate change impact assessments, the feedback and adaptation of vegetation to climate change are rarely taken into consideration.

(4) Scales: Different scales are used throughout all studies on climate change assessment. Scales can be broadly divided into timescale and spatial scale. First, changes in the climate system usually occur over a long time, with a timescale of 100 to 1,000 years. The response time of forest ecosystems to climate change is different because there is some lag-time to be considered. Currently, the records of monitoring, observation and control experiments are too short compared with the time length needed for climate changes. Therefore, observations cannot completely reflect the long-term adaptation and responses of forest ecosystems to climate change. Second, the spatial scale is unequal due to the highly complex, nonlinear and heterogeneous nature of forest ecosystems. The spatial discrepancies do not necessarily follow the same rules across different hierarchical scales as the timescales. Existing assessment models were developed for studies on local and small scales. Often, without rigorous scaling-up, these models are used at regional scale (e.g., for Northeast China), which increases simulation and prediction uncertainties.

(5) Validation: Currently, due to a lack of observation data, the validation for simulations is a comparison with simulations from other models. Furthermore, because of different scales, it is also difficult to validate the model at the regional scale.

(6) Systematic concept: The interactions between forest ecosystems and climate system are multi-factor, multi-process, and multi-level participation. They constrain factors and processes, and are involved in maintaining a stable state of the whole ecosystem. If we only emphasize the effects of one factor or certain factors on forest ecosystems and ignore the effects of other factors, such as nutrient conditions, population competition, vegetation succession, human activity, forest fires, pests and diseases, then the model may incorrectly amplify the impacts of the considered factors on the forest ecosystems.

(7) It is difficult to distinguish the impacts attribution from natural change and from human activities. Both the impacts of human activities and natural change can have multiple impacts on forest ecosystems.

5 Suggestions on mitigation of climate change

Many experts have put forward constructive comments and suggestions on how to mitigate climate change [*Li et al.*, 2007; 2009; *Zhu et al.*, 2009; *Wei et al.*, 2013; *Tian et al.*, 2005]. Forest management in Northeast China should be comprehensively strengthened in order to improve forest quality and to enhance the ability to respond to climate change.

(1) The concept of forest health needs to be strengthened, which implies improvements in the tolerance ability and stability of the forest ecosystem in Northeast China. The index system of sustainable management should be improved in order to comply with the requirements of the regional forestry development plan and to support sustainable forest management. In order to increase the annual growth of forest resources and improve the forest's ecological functions; the overall quality of the forests should to be improved to maximize the benefits of different approaches.

(2) The probable impacts of future climate change on the forest ecosystem in Northeast China should be taken into account in forestry development plans. A warming may negatively impact the coniferous and deciduous broad-leaved Korean pine ecosystem, which in contrast may be beneficial to the development of temperate broad-leaved forests, and should be considered in forestry development plans. There should be an improvement in provenance selection so that tree species can be bred to adapt to pests, higher temperatures, and drought. There is a need to improve the competitive ability of species so that they can adapt to the changing environments.

(3) Mitigation of future climate change on forest fires should be improved in order to minimize and control the frequency and size of forest fires. Carrying out small controlled fires at proper ranges should be allowed in order to maintain the stability and the biodiversity of forest ecosystems.

(4) Forest pest prevention and control measures should be implemented in advance. Forest pest moni-

toring and early warning systems should be enhanced. The scientific effectiveness and accuracy of monitoring and forecasting at the regional monitoring centers should be improved.

(5) The abilities of forest ecosystems to withstand meteorological disasters and to respond to climate change should be improved to protect regional ecological security.

(6) Scientific and technological infrastructure and platforms need to be improved in order to provide favorable conditions for studies on climate science and technologies.

6 Conclusions and Discussion

In this paper, we show the progress in the research of climate change impacts on forest ecosystem in Northeast China. Although significant improvements have been made, we are far from having a clear understand of the mechanisms of the regional climatic system, the forest ecosystems, and the interactions between these systems in Northeast China. The impact assessment of climate change on forest ecosystems is closely related to our knowledge of forest ecosystems. In addition to improve and enhance the prediction accuracy of the regional climate model, as far as forest ecosystems are concerned, the following areas should be focused on:

(1) The establishment of a long-term and fixed-point observation network is needed in order to create a basic database and to carry out data assimilation studies. Long-term observations should be carried out, and standardized observation rules (e.g., international standards) should be implemented. A reliable database of longer period will improve basic data for climate change impact assessments. The available multi-source ground and spatial data should be concluded, so that data fusion aspects of forest ecosystems at different temporal and spatial resolutions can be explored. A more rigorous data validation is also needed.

(2) The thresholds for physiological and ecological responses of forest vegetation to climate change should be improved and scientifically comparable when carrying out model simulation and evaluation in Northeast China. The existing thresholds are focused on leaves and time of leaf-fall at small and local scales. Studies at regional scale should be further improved in order to accurately compare the results at other spatial scales. For example, in the context of climate change, how much warming is needed to cause the melting of large areas of permafrost in Northeast China, thus changing the permafrost conditions and resulting in the decline or possible extinction of *Larix gmelinii*? With continuous warming, the forest ecosystems in Northeast China may become a carbon source rather than a carbon sink, which will exacerbate global warming even more. The above-mentioned problems are also affected by physiological, ecological, and other related factors. There is still a great deal of detailed work for accurately answering these questions. In future studies, the vegetation thresholds in model simulations should consider the impacts of climate change.

(3) In model simulations, feedback from vegetation on climate change should be fully considered. Drawing on the development ideas of the dynamic global models [*Anne et al.*, 2010], the integrated dynamic ecological models should be explored using a more coherent and integrated platform at regional scale. They also need to fully consider the vegetation competition and succession, the plant physiology, the ecological and land surface processes, the carbon/nitrogen/water cycles, the vegetation dynamics, forest fires, and pest disturbance processes. Coupling techniques between regional climate models and regional dynamic ecosystem models need to be developed and improved. The feedback effects of regional vegetation dynamics or land use change on climate change should also be quantitatively evaluated. New models should fully consider the impacts of extreme weather events, the lag phenomena in the vegetation responses to climatic changes, and different response of species to climatic changes.

(4) With regards to the scaling issues, the importance and recommendations of theoretical studies should be strengthened. Due to costly experimental expenses and limited technology, control experiments at regional scale are not undertaken in Northeast China, which may not be improved for a long time.

(5) Comprehensive observations and experiments

should be undertaken. They need to fully consider the combined effects of multiple parameters, including air temperature, precipitation, and CO_2 fertilization. The responses of different species to climate change should be fully taken into account. Uniform sampling methods and international standards need to be developed or enhanced to allow comparison of data from different sites.

(6) More studies on natural ecological zones, such as the high mountain timberline and the forest vegetation ecotone between the Daxing'anling and Xiaoxing'anling regions, which are less impacted by human activities, should be undertaken in order to determine the contribution of natural change impacts.

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