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Full Length Research Paper

Estimating carbon emissions from forest fires during 1980 to 1999 in Daxing'an Mountain, China

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A large number of carbons are released into the atmosphere from forest fires per year, which has a significant influence on carbon cycle and storage. In this study, we examined the spatio-temporal patterns of forest fires from 1980 to 1999 in Daxing'an Mountain of Heilongjiang Province, China and estimated the carbon emissions from forest fires based on both field research and laboratory experiments. The results show that (1) burned areas of larch (*Larix gmelinii* Rupr.), Mongolian pine (*Pinus sylvestris L.* var. *mongolica* Litv.), white birch (*Betula platyphylla* Suk.), mixed broadleaved-conifer (*L. gmelinii & B. platyphylla*) and Mongolian oak (*Quercus mongolica* Fish.) forests were 437 947, 20 939, 142 527, 168 532 and 1 375 hm^2 during 1980 to 1999 period, respectively. The fuel consumed based on these forests were 29.0 to 46.5, 16.7 to 26.5, 18.1 to 26.5, 31.9 to 51.4 and 24.5 to 40.3 Mg hm^{-2}, respectively; (2) the total carbon emissions from forest fires of the forest types in Daxing'an Mountain was 3.8 to 5.9 Tg during this period. Two thirds of the total amounts were caused by larch forests, while 1/4 came from white birch forests and the rest from other forest types; (3) the amounts of CO_2 released from forest fires for these 20 years were 13.9 to 21.6 Tg. The estimates were incomplete or could be low because the emissions from the burning of dead organic matter (litter, dead wood, etc.) were not included in this calculation and therefore, the net carbon balance was calculated.

Key words: biomass, carbonaceous gases, CO_2 emissions, forest fires.

INTRODUCTION

As the levels of atmospheric greenhouse gases continue to increase, global climate change has become one of the most serious challenges to humanity with profound consequences (Wong, 1979; Kang et al., 1996; Jiang and Zhou, 2001; Wang, et al., 2001; Zhao et al., 2007). Since the late 1970s, researchers have proposed that greenhouse gas emissions from forest fires may strongly influence global climate change (Crutzen et al., 1979; Seiler and Crutzen, 1980; Olson, 1983). Thereafter, several studies have been conducted to estimate the emissions of carbonaceous gases from forest fires in different forest regions (Goldammer, 1990; Levine, 1991, Wang et al., 1998; Choi et al., 2006). Fires occurring in tropical and boreal forest biomes have a broad impact on the global carbon cycle (Wang, et al., 2001; Page et al., 2002; Kasischke et al., 2005).

At present, the comprehensive regional or global studies on forest fires are insufficient and few of them combined field studies and laboratory experiments. In this study, we examined forest fires data from 1980 to 1999 in Daxing'an Mountain, Heilongjiang Province, China and the amounts of total carbon and carbonaceous gases released from forest fires were estimated by measuring emission factors in both laboratory experiments and field investigations. The results may provide a comprehensive estimate of carbon emissions from forest fires in the boreal region of China.

MATERIALS AND METHODS

Study site

This study was conducted in high-latitude forest areas of the Daxing'an Mountain, Heilongjiang Province (50°10′ to 53°33′ N, 121°12′ to 127°00′ E; total area: 8.35×10^6 hm^2), China. The climate is frigid-temperate continental monsoon. The mean annual temperature is -2 to 4°C. The extreme highest temperature and

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lowest temperature is 39.0 and -52.3℃, respectively. While mean total annual precipitation is 350 to 500 mm, most of which is in the form of snow during winter and early spring. The elevations in this region vary from 300 to 1400 m. Brown coniferous and dark-brown forest peat soils are the predominant soil types with a depth of 10 to 33 cm (Xu, 1998).

Daxing'an Mountain is a unique boreal forest region in China. It is mainly dominated by Dahurian larch (*Larix gmelinii* Rupr.) accompanied with white birch (*Betula platyphylla* Suk.), Mongolian pine (*Pinus sylvestris* L.var. *mongolica* Litv.) and Mongolian oak (*Quercus mongolica* Fish.). Four kinds of larch forests are widespread in this region, they are: *L. gmelinii* - *Rhododendron dauricum*, *L. gmelinii* - *Ledum palustre*, *L. gmelinii* - *Vaccinium* spp. and *L. gmelinii* - grass forests. The remaining major forest types are composed of Mongolian pine, mixed broadleaved-conifer and white birch forest. This area has an extremely high fire risk, with the highest average annual burned area in China (Hu, 1995).

Field sampling

A total of twenty 20 × 20 m standard plots in larch, Scots pine, white birch, mixed forest and Mongolian oak forests were developed by the manual sampling method which is grid investigation (Hu, 2009) (Table 1). Tree species, height and diameter at breast height (DBH) of each tree in each plot were recorded. Three samples for branches, leaves, bark and trunk from the representative trees of each species were collected. For trunk and bark, three samples were taken from the bottom, middle (at DBH) and top of a tree separately. The branch samples were consisted of both thick trunks and twigs. Leaf samples were collected at different canopy positions. All samples were taken back to laboratory for carbon content identification.

Biomass estimation

Three 20 × 20 m plots were used for estimating biomass of each forest. DBH and height of each tree in each plot were measured by field inventory. The tree biomass for larch, white birch, Mongolian pine and Mongolian oak was estimated by means of allometric equations (Zhou et al., 2006) and summed up at forest stand level.

Burned area of different forest types

The data of burned area from 1980 to 1999 came from the fire history records of Forest Fire Prevention Office, Forestry Management Bureau in Daxing'an Mountain. The area of each forest fire in the different forest types was estimated by using Geographic Information System (GIS) software. The spatial distribution map of forest fires was developed in Arcview3.3 software and superimposed onto the forest distribution map of the study area. Because of the small heterogeneity of the forests, the forest where the burned areas were less than 1×10^4 ha was used to represent the burned forest type. If the burned areas were larger than 1×10^4 ha, a buffer zone centered on the fire origin point was created, where the area was equivalent to the burned area. The approximate areas of different forests were estimated by digitizing each forest coverage and topology with ARC-INFO software (Jin, 2002).

Fire intensity

Based on parameters including fire line intensity, flame length, flame height, fuel weight and rate of spread, fire intensity was estimated (Wang, 1996). Alternatively, some measurements of burned areas were made and the severity of damage was assessed on different layers of the forest ecosystem. Although, the later got more accurate results, it was generally limited to a short time window following the fire.

Neither of the earlier mentioned methods nor a large-scale forest fire model can however, be applied to study the historical fire regime. Therefore, the fire intensity according to the burned area was defined (Frank and Elizabeth, 1995). The violent, medium and weak fire intensity and minimal burning corresponded to the different burned areas which were >1000, 100 to 1000, 1 to 100 and < 1 ha, respectively.

Fuel consumption

Fuel consumption refers to the ratio of burned biomass and total weight (Wang, 1998). It is important to estimate the amount of carbonaceous gas emissions from forest fires. Fuel consumption, however, is quite different depending on which method is used for the estimations. Some studies have reported that forest fires in Daxing'an Mountain were mainly ground fires, few crown fires and nearly no underground fires (Xu, 1998). Therefore, all forest fires in our model were considered as ground fires.

The experimental measurement of fuel consumption rate is difficult and expensive and has only been made in a few studies (Fearnside, 1990; Conard and Ivanova, 1997; French et al., 2000; Kasischke et al., 2000; Levine and Cofer, 2000). Based on actual survey work of the burned areas (Chen et al., 1987; Zhan and Wang., 1987; Hong et al.,1994; Zheng, 1994; Xu, 2004), the consumption of leaves, branches and barks was classified as follows: (1) violent burning: burning efficiencies for leaves, branches and bark were above 96, 54 and 61%, respectively; (2) medium burning: 90 to 96, 37 to 85 and 55 to 85%, respectively; (3) weak burning: 64 to 90, 30 to 65 and 40 to 65%, respectively; (4) minimal burning: 23 to 33, 14 to 25 and 22 to 25%, respectively.

Estimation of carbonaceous gases

Measurements of carbonaceous gases were conducted in a dynamic burning system, which consisted of a combustion chamber, a heating system, an electronic scale, a KM-9106 gas analyzer (KANE, UK), a collection smoke cover, a computer and the FIREWORKS gas analyzing software (Hu et al., 2009). Carbon content of different carbonaceous gases was continuously analyzed by the gas analyzer. The carbon content of different carbonaceous gases was calculated by the following equation:

$$m_i = c_i \times M_i \times F_i \quad (1)$$

Where, m_i is the carbon content of different carbonaceous gases (g); c_i is the emission concentration of different carbonaceous gases (10^{-6} mg·l^{-1}); M_i is the molecular weight of different carbon containing gases; F_i is the carbon fraction (the carbon fraction of CO_2, CO, CH_4 is 0.273, 0.429 and 0.75, respectively).

The carbon of burned biomass was assumed to be incorporated into gases and the carbon loss from burning (M_c) was calculated as:

$$M_c = C_c \times M \quad (2)$$

Where, C_c is the carbon content of samples and M is the biomass of samples (g). We used 50% as the carbon content of biomass (Gower et al., 2001).

According to the estimation model of fire-induced biomass loss (Seiler and Crutzen, 1980);

$$M = A \times B \times a \quad (3)$$

Where, M is the biomass loss from fires; A is the burned area (ha); B is the unit aboveground biomass of the particular forest type (Mg

Table 1. Basic information of the sampling plots in Daxing'an Mountain. The values in brackets are standard errors.

Forest type	Number of sample plot	Mean DBH (cm)	Mean height (m)
Birch forest	3	14.6 (1.64)	14.2 (1.71)
Larch forest	8	13.1 (1.56)	12.6 (0.69)
Mixed broadleaf-conifer forest	3	9.5 (0.50)	10.9 (1.15)
Mongolian pine forest	3	10.3 (1.53)	13.2 (0.72)
Oak forest	3	11.4 (1.01)	7.5 (1.13)

DBH, Diameter at breast height

Table 2. Burned forest areas of each forest type and fire grade in Daxing'an Mountain from 1980 to 1999 (ha). For further explanations, see text.

Fire grade	Larch forest	Mongolian pine forest	Mixed forest	Birch forest	Oak forest	Total
Minimal burning	11	0	5	2	1	19
Weak burning	106,0	0	216	154	8	143,8
Medium burning	414,4	0	155,0	580	866	714,0
Violent burning	432,732	209,39	140,756	167,796	500	762,723
Total	437,947	209,39	142,527	168,532	137,5	771,320

ha^{-1}); a is the burning efficiency.

The emission factor (EF_i) is the ratio of carbon content of a carbonaceous gas and the carbon loss after burning (Levine, 1991). The CO_2 equivalent (CO_{2e}) was estimated as CO_{2e} = (EF_{CO2} × GWP_{CO2} + EF_{CH4} × GWP_{CH4}) × M_c, where EF_{CO2} and EF_{CH4} are the emission factors of CO_2 and CH_4, respectively; GWP_{CO2} and GWP_{CH4} are the global warming potentials of CO_2 (1) and CH_4 (25), respectively (IPCC, 2001).

RESULTS

Burned areas

The total burned area of forest land from 1980 to 1999 in Daxing'an Mountain was 771,320 ha, which was composed of 437, 947 ha of larch forest, 20,939 ha of Mongolian pine forest, 142,527 ha of mixed forest, 168,532 ha of white birch forest and 1,375 ha of Mongolian oak forest. Combined with the burned non-forest land, the total burned area was 1,705 000 ha from 1980 to 1999 in Daxing'an Mountain. The burned areas of each forest type for different fire grades are shown in Table 2.

Unit biomass

The biomass per unit area of larch forest was the largest in these forest types, followed by Mongolian pine forest and white birch forest, while mixed forest has the least biomass. Among different components of a tree, the trunk accounted for most percentage of total biomass (more than 60%), while the leaf was the least (often less than 10%) (Table 3).

Estimation of fuels consumption

The burned biomass of major forest from 1980 to 1999 was estimated according to formula 3 and the consumption percentage of leaves, branches and barks for different fire grades. The mean estimated fuel consumptions in larch forest, pine forest, mixed forest, birch forest and oak forest were 29.0 to 46.5, 16.7 to 26.5, 18.1 to 26.5, 31.9 to 51.3 and 24.5 to 40.3 Mg ha^{-1}, respectively. Fuel consumptions for different fire grades were great difference. Mean estimated fuel consumptions under the minimal, weak, medium and violent fires were 1.7 to 4.8, 3.8 to 12.6, 5.1 to 15.8 and 6.5 to 18.2 Mg ha^{-1}, respectively (Table 4). The fuel consumptions for different forest types mainly came from larch and birch forests, which accounted for 51% of total amounts. For different tree components, most fuel consumptions were from branches and barks.

Carbon emissions from forest fires

According to Equation 2 and the estimation of fuels consumption, the carbon emissions from forest fires in major forest types for different components of a tree were estimated from 1980 to 1999 (Figure 1). The total carbon emission for all these forests was 3.8 to 5.9 Tg. The carbon emission from larch forests accounted for almost

Table 3. The amount of biomass for different tree components in five forest types in the Daxing'an Mountain ($Mg{\cdot}ha^{-1}$). The values in brackets are standard errors.

Forest type	Trunk	Bark	Branch	Leaf	Total aboveground
Larch forest	63 (13.4)	7.7 (1.35)	6.2 (1.77)	2.6 (0.55)	79 (16.8)
Mongolian pine forest	60 (8.19)	2.8 (0.70)	4.3 (1.07)	2.2 (0.77)	69 (7.35)
Mixed broadleaf-conifer forest	21 (9.29)	3.0 (0.12)	2.8 (0.85)	3.3 (0.38)	30 (8.45)
Birch forest	43 (6.11)	7.6 (1.08)	7.6 (0.75)	3.0 (0.51)	61 (6.14)
Oak forest	25 (7.06)	4.5 (0.42)	7.4 (1.42)	2.4 (0.20)	39 (5.96)

Table 4. The range of fuel consumption (minimum and maximum), at different forest fire intensity, in five forest types in Daxing'an Mountain ($Mg\ ha^{-1}$). For further explanations, see text.

Forest type		Fire intensity				
		Minimal	Weak	Medium	Violent	Minimum-maximum
Larch	Leaf	0.6 - 0.8	1.7 - 2.3	2.3 - 2.5	2. 5 - 2.6	7.0 - 8.2
	Branch	0.9 - 1.6	1.8 - 4.0	2.3 - 5.3	3.3 - 6.2	8.3 - 17.1
	Bark	1.7 - 1.9	3.1 - 5.0	4.2 - 6.5	4.7 - 7.7	13.7 - 21.2
	Total	3.1 - 4.3	6.6 - 11.3	8.8 - 14.3	10.5 - 16.5	29.0 - 46.5
Mongolian pine	Leaf	0.5 - 0.7	1.4 - 2.0	2.0 - 2.1	2.1 - 2.2	6.0 - 7.0
	Branch	0.6 - 1.1	1.3 - 2.8	1.6 - 3.7	2.3 - 4.3	5.8 - 11.8
	Bark	0.6 - 0.7	1.1 - 1.8	1.5 - 2.4	1.7 - 2.8	5.0 - 7.7
	Total	1.7 - 2.5	3.8 - 6.6	5.1 - 8.1	6.1 - 9.3	16.7 - 26.5
Mixed broadleaf - conifer	Leaf	0.7 - 1. 1	2.1 - 3.0	3.0 - 3.2	3.2 - 3.3	9.0 - 10.5
	Branch	0.4 - 0.7	0.8 - 1.8	1.0 - 2.4	1.5 - 2.8	3.8 - 7.7
	Bark	0.6 - 0.8	1.2 - 2.0	1.6 - 2.6	1.8 - 3.0	5.3 - 8.3
	Total	1.8 - 2.5	4.2 - 6.7	5.6 - 8.1	6.5 - 9.1	18.1 - 26.5
Birch	Leaf	0.7 - 1.0	1.9 - 2.7	2.7 - 2.9	2.9 - 3.0	8.1 - 9.5
	Branch	1.1 - 1.9	2.3 - 4.9	2.8 - 6.5	4.1 - 7.6	10.3 - 20.9
	Bark	1.6 - 1.9	3.0 - 4.9	4.2 - 6.5	4.7 - 7.6	13.5 - 20.9
	Total	3.4 - 4.8	7.2 - 12.6	9.8 - 15.8	11.6 - 18.2	31.9 - 51.3
Oak	Leaf	0.5 - 0.8	1.5 - 2.1	2.1 - 2.3	2.3 - 2.4	6.5 - 7.6
	Branch	1.0 - 1.9	2.2 - 4.8	2.8 - 6.3	4.0 - 7.4	10.0 - 20.4
	Bark	1.0 - 1.1	1.8 - 2.9	2.5 - 3.8	2.8 - 4.5	8.0 - 12.4
	Total	2. 6 - 3.8	5.5 - 9.9	7.4 - 12.4	9.0 - 14.3	24.5 - 40.3

2/3 of the total emission (2.3 to 3.6 Tg, 60.3 to 61.3%). The other four forests, Mongolian pine forest, mixed forest, white birch forest and oak forest, offered the rest 1/3 of the total emission. The mean carbon emissions for larch forest, pine forest, mixed forest, birch forest and oak forest were 3.6 to 5.8, 3.1 to 4.7, 2.2 to 3.3, 3.9 to 6.3 and 3.0 to 5.1 $Mg\ ha^{-1}$, respectively. The minimum and maximum unit carbon emission came from the mixed forest of the minimal burning and the birch forest of the violent fires respectively. The mean estimated carbon emission under minimal, weak, medium and violent fires was 1.0 to 1.9, 2.9 to 5.1, 3.9 to 6.3 and 4.4 to 8.4 $Mg\ ha^{-1}$, respectively.

Emission factor (EF)

Using the total carbon balance method described by Ward (Ward, 1980), we estimated the emission factors of different carbonaceous gases and then converted CO_2 and CH_4 to CO_2 equivalent (CO_{2e}) which is required by the UNFCCC reporting methods. The results are shown in

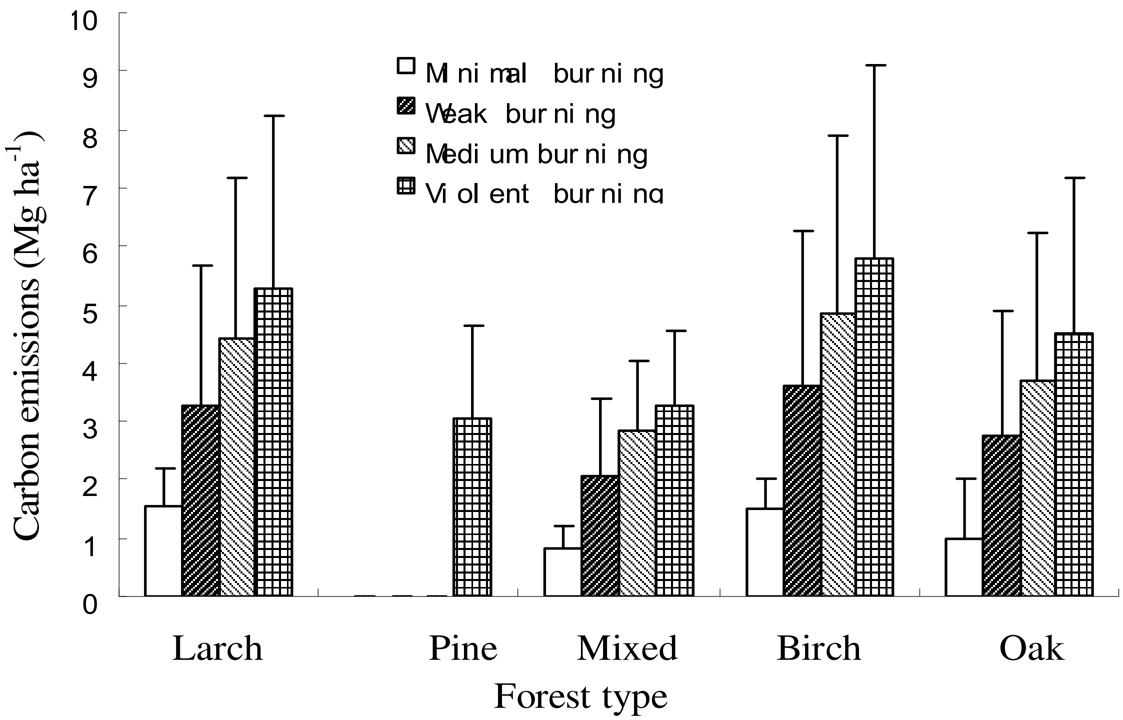

Figure 1. Carbon emission from forest fires in five forest types at different fires grade from 1980 to 1999 in Daxing'an Mountain. The vertical line on each bar indicates the difference between the estimated maximum and the minimum carbon emission.

Table 5. Carbon dioxide equivalent (CO_{2e}) when burning different tree components of five major tree species from the Daxing'an Mountain.

Forest type		CO_{2e}
Larch forest	Leaf	3.66
	Branch	3.50
	Bark	2.72
Mongolian pine forest	Leaf	3.97
	Branch	3.89
	Bark	3.42
Mixed broadleaf-conifer forest	Leaf	3.75
	Branch	3.56
	Bark	3.17
Birch forest	Leaf	3.83
	Branch	3.62
	Bark	3.62
Oak forest	Leaf	3.72
	Branch	3.63
	Bark	3.50

Table 6. Carbon dioxide equivalent (CO_{2e}) when burning different tree components of five major tree species from the Daxing'an Mountain.

Forest type	Leaf	Branch	Bark
Larch	3.66	3.50	2.72
Pine	3.97	3.89	3.42
Mixed	3.75	3.56	3.17
Birch	3.83	3.62	3.62
Oak	3.72	3.63	3.50

Table 5. In brief, the leaf component had the largest CO_{2e}, while the bark component had the least one.

Estimation of carbon equivalent (CO_{2e}) from forest fires

The amounts of CO_{2e} released from forest fires in larch forest, pine forest, mixed forest, birch forest and oak forest from 1980 to 1999 were 7.3 to 11.4, 0.2 to 0.4, 1.6 to 2.3, 3.6 to 5.6 and 0.02 to 0.03 Tg, respectively. More than 95% CO_{2e} emission was from violent-grade fires. The mean CO_{2e} emission from larch forest, pine forest, mixed forest, birch forest and oak forest is 11.5 to 18.4, 11.6 to 17.5, 8.0 to 11.6, 14.7 to 23.5 and 11.1 to 18.1 Mg ha^{-1}, respectively (Table 6; Figure 2). The mean CO_{2e}

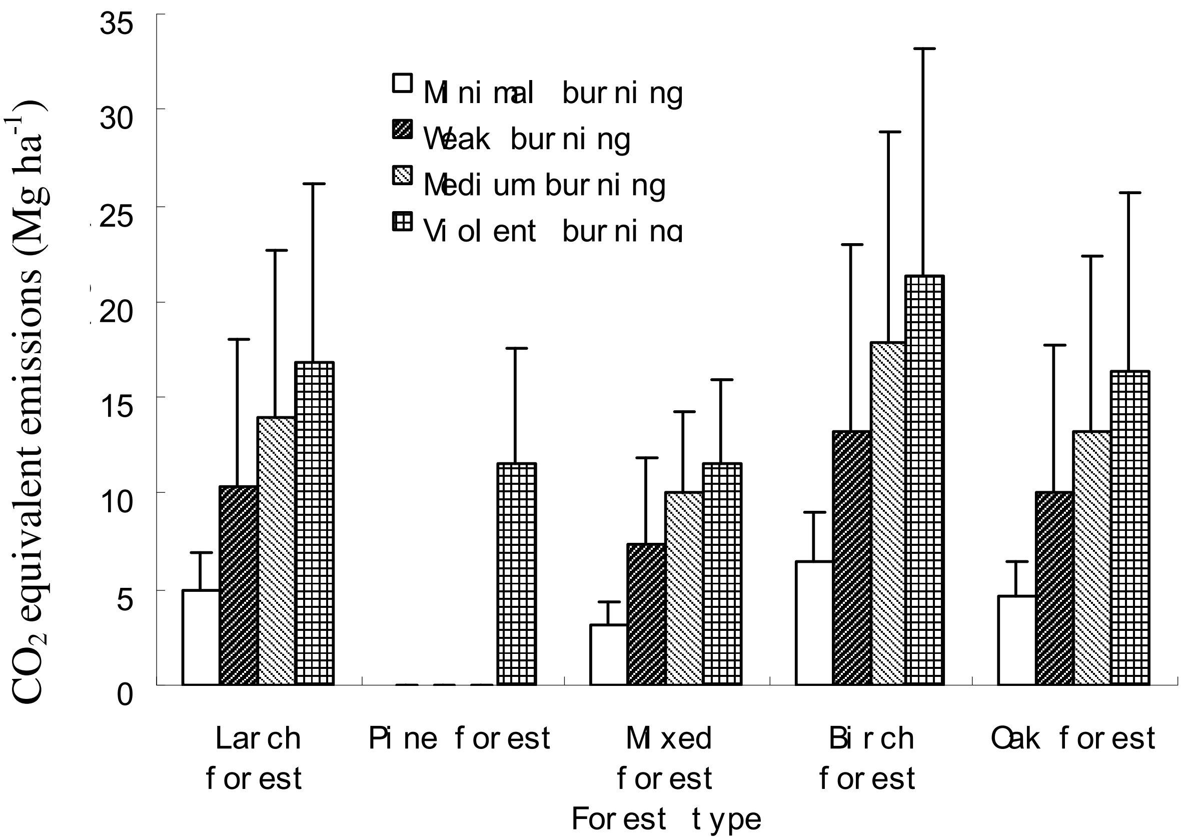

Figure 2. Carbon dioxide equivalent (CO_{2e}) emission from different forest types at different fire grade from 1980 to 1999 in Daxing'an Mountain The vertical line on on each bar indicates the difference between the estimated maximum and the minium CO_{2e} emission.

emission under the minimal, weak, medium and violent fire was 4.8 to 6.7, 10.3 to 17.7, 13.8 to 22.0 and 16.5 to 25.3 Mg ha^{-1}, respectively.

DISCUSSION

Fuel consumption is of great significance for the accurate estimation of carbon emission released from forest fires, which will be influenced by many conditions such as fire intensity, fire type, vegetation type and climate condition (Aulair and Carter, 1993). At present, few studies rigorously conducted the real investigation of the fuel consumption rate. Fuel consumption rate in different ecosystems is quite different (Levine and Cofer, 2000). For example, the largest fuel consumption rate in savannah or tropical/subtropical regions is around 0.8 to 1, while the fuel consumption rate in equatorial or boreal forests is significantly small (0.2 to 0.3). Fearnside (1990) reported that the consumption rate for tree trunks, branches and leaves in the Brazilian rain forest was 39, 92 and 100%, respectively. In this study, we examined the past forest fire records and damage reports, the fuel consumption rate which was a function of different tree components and fire grades in this area, the results were well consistent with the Fearnside's results. De Groot et al. (2007) showed that the mean fuel consumption for Montreal Lake fire was 24 Mg ha^{-1}. Amiro et al. (2001) indicated that the fuel consumption of crown fire was about 37 Mg ha^{-1}, and about 88% of the fires had some crown fuel consumption. Nalder and Wein (1999) reported that the fuel load (litter and duff) of jack pine and aspen is 26 and 56 Mg ha^{-1}, respectively. The results in our study indicate that the mean fuel consumption in violent fire was 6.5 to 18.2 Mg ha^{-1}, while all other estimated consumptions were lower than previous research results. The major reason was that the litter, forest floor or dead wood fuel consumptions were not included into the calculations. Because we only considered the above-ground forest biomass, the estimated results will be far lower than the real value.

This study indicates that the average carbon emission from biomass burning in different forests was 3.08 to 5.41 Mg ha^{-1}, which is obviously lower than other results. Shvidenko and Nilsson (2000b) estimated that 10.0 Mg C ha^{-1} burned is released from burning of vegetation during surface fires and the value is 20 Mg C ha^{-1} for crown fires. Conard et al. (2002) estimate that a total of 2.3 Mg C ha^{-1}

burned are released during low-intensity surface fires, 8.6 Mg C ha^{-1} burned are released during moderate-intensity surface fires and 22.5 Mg C ha^{-1} burned are released during crown fires. Kasischke and Bruhwiler, (2003) estimated the carbon emission from boreal forest fires in 1998, which was about 16.2 to 21.4 Mg C ha^{-1}. Turetsky and Wieder (2001) showed that an average of 22 Mg C ha^{-1} burned was released from biomass burning in four different Canadian peatland types within a 1999 fire. French et al. (2004) studied the uncertainty in carbon emissions from forest fires in Alaska, the estimate of total annual carbon emission can be as high as 10.6 or as low as 1.1 Tg C. Wang et al. (2001) showed that the carbon emission from larch forest was 19 - 36 Mg C ha^{-1} for the *Larix-Ledum*, 59 to 73 Mg C ha^{-1} for the *Larix-Rhododendron* forests. Based on the above research results, most of them considered the fire intensity had great influence on the carbon emission from forest fires at different regions.

This study describes the carbon emission from forest fires in five major forests from 1980 to 1999. Our data of carbon emission will be a good supplement to the related research on the carbon emission from boreal forest fires in China. The carbon emission from shrubs, herbs and ground cover, however, was not examined in this study due to the significant variations in sampling, data analysis and fuel consumption. In Russia, the post-fire biogenic CO_2-C emissions for 1971 to 1991 was estimated and varied from 250 to 590 Mg C ha^{-1} (Dixon and Krankina, 1993), which included the direct carbon release and indirect post-fire biogenic carbon flux. This indicates that the indirect carbon emissions will be larger than the direct carbon emissions. Future studies are needed to examine the carbon emission at a system level and consider the indirect carbon release. Finally, we should pay attention to the post-fire emissions (from the decay of trees killed by a fire) and the removals from re-growth and recovery after fires. It may provide better data to fully evaluate the impact of forest fires on global carbon balance.

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