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ORIGINAL ARTICLE

Absorption of Power Plants CO_2 Emissions by Coniferous Tree Stands

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The article reviews the ability of coniferous (common pine, siberian larch and siberian spruce) stands growing in 9 municipal districts of the Irkutsk region to absorb CO_2 technogenic emission of heat power plants. (EIGAF) index is suggested to characterize gas-absorbing (CO_2–absorbing) activity; the index reflects proportion between CO_2 technogenic emission and photosynthetic productivity (GPP) of coniferous tree stands. CO_2–absorbing capacity in 8 of the monitored districts has been shown to significantly exceed the amount of carbon dioxide emission from heat power sector. The index values EIGAF=0.01-0.97 demonstrate that CO_2 technogenic emission amounts to 1-97% of coniferous stands photosynthetic productivity in the areas under study. At the same time, the most industrially developed Angarsk district shows CO_2 photosynthetic absorption to be 8-12 times lower than technogenic CO_2 emission. Reasons of low gas-absorbing capacity of coniferous tree stands of this area are discussed.

Key words: photosynthetic productivity, coniferous stands, technogenic CO_2 emission, forest gas-absorbing capacity

Increase in atmospheric carbon dioxide concentration is commonly acknowledged to be the primary cause of global climatic changes (IPCC, 2001, 2007). Topicality of investigating processes, which account for climate change on the planet, is recognized on the intergovernmental level and expressed in the UN Framework Convention on Climate Change (1992) and in Kyoto Protocol (1997). Key activities regulated by Kyoto Protocol are industrial emissions of greenhouse gases in forest and agricultural sectors, but it also considers changes of greenhouse gases sources and runoffs in forest and agricultural sectors. Russia became a signatory to Kyoto Protocol in 2005, thus undertaking the obligation to take steps to decrease sources, increase runoffs and preserve major greenhouse gasses reservoirs (Kokorin, 2004; Zamolodchikov, 2005; Korovin, 2005; Kurganova, 2010). IPCC and many researchers recognize that by the scale of carbon absorption and, particularly, by deposition duration, forests represent the most reliable system of preventing greenhouse effect (Dixon *et al*., 1994; IPCC, 2001, 2007; Korovin, 2005; Shchepachenko *et al*., 2008; Shutov, Ryabinin, 2008).

The studies conducted by many authors in the forests of the Earth (Valentini *et al*., 2000; Liski *et al*., 2000; McGuire *et al*., 2001) demonstrate that annual carbon balance in the forests of different latitudes ranges between –6.6 t C ha^{-1} (i.e. 24 t CO_2 are absorbed by ha^{-1}) and +1.0 t ha^{-1} (corresponds to release of 3.7 t CO_2 ha^{-1}). CO_2 balance changes with the location latitude (Valentini *et al*., 2001). At that tropics are approximately neutral in terms of carbon balance, in moderate climate countries carbon balance is unstable, whereas ecosystems to the north from the tropics demonstrate stable carbon runoff (McGuire *et al*., 2001). Moderate and boreal forests of the world are classed as carbon absorbers by practically all researchers, though the evaluations vary greatly – 0.2 Pg C $year^{-1}$($0.2 \cdot 10^9$ t C) for forests of moderate belt (Heath *et al*., 1993), 0,7 Pg C $year^{-1}$($0.7 \cdot 10^9$ t C) for all moderate and boreal forests in the last 20 years (Sedjo, 1992), 0.6–0.7 Pg C $year^{-1}$ ($0.6–0.7 \cdot 10^9$ t C) for all boreal and sparse forests for the early 1990s (Goodale *et al*., 2002).

At the same time, forests are known to be able to act not only as the carbon storage (runoff, reservoir), but as carbon source as well (Carrara *et al*., 2003; Harmon *et al*., 2004) depending on natural and economic situation. With this in view, investigation of forest ecosystems ability to absorb carbon dioxide technogenic emisssion acquires particular importance. Approximately three fourths of atmospheric CO_2 concentration increment in the last few years is due to burning fossil fuels, with the remainder mainly accounted for by changes in land use management including deforestation (Fedorov, 2004; Shchepachenko *et al*., 2008). Thus, from 1980 till 1990 annual increase of carbon emission due to burning fossil fuel amounted on average to $84 \cdot 10^6$ t. From 1991 till 1996 this increase was slightly lower - $83 \cdot 10^6$ t. Global CO_2 emission in 2000 reached $6.85 \cdot 10^9$ t (Kondrat'yev *et al*., 2003; Zamolodchikov, 2005; The fifth national report ..., 2010).

Large Siberian regions including Irkutsk region are commonly characterized by distribution of vast forest areas with prevailing coniferous stands and presence of industrial centers with large-scale heat power plants. The present study aims to evaluate the ability of coniferous stands to absorb technogenic CO_2 emission from heat power plants (HPP) and boiler plants (BP) located in nine municipal districts of the Irkutsk region.

MATERIALS AND METHODS

Region characteristics. The Irkutsk region is the sixth largest region of Russia with the area of 767.9 th. km^2 (4.6% of the territory of Russia). Most of the region territory is covered by taiga forests. Coniferous forests with pine (*Pinus sylvestris* L.*)*, spruce (*Picea obovata* Ledeb.) and larch (*Larix sibirica* Ledeb.) occupy about 76% of forest-covered area. Most forested are northern and central districts. Forest-steppe vegetation is partially presented in southern districts.

The primary producer of electrical energy in the Irkutsk region is the Irkutsk Joint-Stock Company of Energy and Electrification (JSC "Irkutskenergo"). The JSC "Irkutskenergo" is the largest consumer of organic fuel in Siberia. In fuel balance of the company's power plants coal share amounts to 99.3%, black oil share – 0.7% (Functioning..., 2005). Subordinate heat power and boiler plants (HPP and BP) are located in the territory of main industrial municipal districts of the Irkutsk region: Angarsk, Bratsk, Zima, Irkutsk, Nizhneilimsk, Usol'ye, Ust-Ilim, Cheremkhovo and Shelekhov.

Methods. Photosynthetic activity of common pine (*Pinus sylvestris* L.*)*, Siberian spruce (*Picea obovata* Ledeb.) and Siberian larch (*Larix sibirica* Ledeb.) was studied in the plantation established at the suburb of Irkutsk (52°14'21"N, 104°16'7"E) in 1985. The plantation is located on a gentle slope (2-3°) of eastern exposition. The soil is gray forest neo-podzolized clay loamy, underlain by Jurassic carbonaceous loam clays with sand below. Ground waters are located fairly deeply (11-50 m) and do not produce a considerable impact on soil moisture. The plantation is arranged in rows: the first and fourth rows are planted with pine trees, the second and third rows – with alternating spruce and larch trees. During the growth period the plantation was controlled by cutting to lighten the canopy.

Experimental investigation of conifers photosynthetic activity in 2008-2010 was started from the emergence of first evidence of positive gas exchange of needles in early spring (first days of April) and finished with the completion of photosynthetic process in the first ten days of November. The monitoring was conducted in 24 hours mode for three days every week. The tests involved three trees of each species.

Daily monitoring of the assimilation of carbon dioxide by needled 1-year twigs with infra-red gas analyser "Infralyt-4", automatical registration of environmental conditions (air temperature, overall illumination, soil temperature at 20 cm, relative air humidity) and determination of soil water supply every ten days were performed according to commonly accepted methods (Shcherbatyuk, 1990; Shcherbatyuk *et al*., 1991; Suvorova *et al*., 2009).

Values of net photosynthesis for each hour were calculated for light periods of all the days (Long, Hallgren, 1989) of monitoring. In 2008, 2009 and 2010 duration of photosynthesis monitoring amounted to 81, 70 and 77 days. Daily photosynthetic productivity was calculated as a sum of all hourly values of net photosynthesis. Monthly photosynthetic productivity of needles was calculated as a product of average daily photosynthetic productivity determined by the number of experimental days and the number of days in a month. Annual photosynthetic productivity was determined as a sum of photosynthetic productivity throughout all vegetation months.

The data on distribution of pine, larch and spruce stands within forestries whose territories correspond to municipal districts were provided by the Irktusk Region Forestry Agency (Form 1.9..., 2011). Parameters of tree stands of 4 age groups (young, middle-aged, maturing and combined mature and overmature) were selected in keeping with regional parameters (Vashchuk *et al.*, 1997; Vashchuk, Shvidenko, 2006).

Calculation of GPP (t CO_2) took into account change in net photosynthesis depending on tree age (Suvorova, 1992). Needle mass per hectare was calculated according to N.I. Kazimirov's method considering ratios of fresh foliage and its conversion to dry weight 0.78 and 0.48 for pine, 0.6 and 0.46 for spruce, 0.56 and 0.43 for larch (Groshev *et al.*, 1980).

Specific values of annual photosynthetic productivity of trees within each age group were used to calculate photosynthetic productivity of the tree stand for the territory occupied as per the formula:

$$GPP_R = Ph_V \cdot S_R \cdot M$$

where GPP_R – photosynthetic productivity of the tree stand of the given age group in the territory of the municipal district, t CO_2; Ph_V – annual photosynthetic productivity of needle mass unit, g CO_2 g^{-1} of dry mass of needle; S_R – area of the territory of the given age group tree stand in the district, ha; M – needle dry mass per 1 ha, t.

Total photosynthetic productivity (GPP) was calculated as a sum of GPP of larch, spruce and larch tree stands of the four age groups for each of the 9 municipal districts of the region.

Efficiency index of gas absorbing (CO_2-absorbing) by forests (EIGAF) was introduced to evaluate the ability of coniferous tree stands to assimilate CO_2 of anthropogenic origin in the course of photosynthesis. The index is calculated as proportion of CO_2 emisssion level (t) from HPP and BP of an individual municipal district in respect of photosynthetic productivity of coniferous (pine, larch and spruce combined) tree stands growing in its territory:

$$EIGAF = V_1 / V_2,$$

where V_1 – CO_2 emisssion level (t) per year, V_2 – annual photosynthetic CO_2 assimilation (GPP, t) by coniferous tree stands. EIGAF values below 1 identify domination of photosynthetic absorption of CO_2 over CO_2 emisssion and high gas-absorbing activity of forests; values above 1 exhibit low gas-absorbing activity of forests and high level of technogenic CO_2 in the atmosphere of this municipal district. We accepted that with EIGAF ≤ 1 coniferous forests are able to assimilate all technogenic CO_2 from HPP and BP of

the given district. This concept was justified by the earlier acquired data, according to which within the interval of CO_2 concentration of 300-800 ppm for pine, 300-1100 ppm for larch and 300-1300 ppm for spruce there takes place a significant increase in their photosynthetic assimilation of carbon dioxide (Shcherbatyuk *et al*., 1991).

The information on the amount of technogenic CO_2 emisssion from nine heat power plants (HPP) and two boiler plants (BP) in 2008-2010 was provided by the JSC «Irkutskenergo». The plants are located in the territory of main industrial municipal districts of the Irkutsk region: Angarsk, Bratsk, Zima, Irkutsk, Nizhneilimsk, Usol'ye, Ust-Ilim, Cheremkhovo and Shelekhov.

RESULTS

Overall amount of emisssion from the JSC «Irkutskenergo» plants in 2008 amounted to $23.5 \cdot 10^6$ t of CO_2, which is 22 and 17% higher than in 2009 and 2010 respectively. The largest amount of technogenic CO_2 is released by PP situated in Angarsk, Irkutsk and Bratsk districts, which account for 13 to 41% of regional emisssion. In 2009-2010 the amount of released carbon dioxide was relatively the same, however, in respect 2008 such districts as Angarsk, Usol'ye, Ust-Ilim showed reduction of CO_2 emisssion by 22-36% due to implementation by the JSC «Irkutskenergo» of measures to optimize thermal complexes, fuel balance and improvement of energy supply (Fig.1).

In terms of climatic parameters vegetation periods of 2008-2010 are comparable to average multi-annual data (Irkutsk climate, 1981), and they may be characterized as fairly favorable by the level of moisture and heat for photosynthetic activity of conifers.

Annual photosynthetic productivity (GPP) of coniferous tree stands was calculated for the Irkutsk region districts under study (Tab. 1).

During the years of monitoring (2008-2010) photosynthetic assimilation of carbon dioxide by conifers in the districts ranges between $0.8 \cdot 10^6$ and $31.8 \cdot 10^6$ t CO_2. The largest photosynthetic productivity is typical of coniferous tree stands of Ust-Ilim, Nizhneilimsk and Bratsk districts, as they are among the five most forested districts of the region.

To evaluate efficiency of gas-absorbing (CO_2-absorbing) activity of coniferous forests we introduced a index, which represents a proportion of technogenic CO_2 emisssion and the value of overall photosynthetic productivity (GPP) of coniferous (pine, spruce and larch) stands (Fig. 2).

Judging by the data presented (Fig. 2), in Angarsk, Irkutsk, Usol'ye and Zima districts the values of the index in the period studied vary due to the change in the level of CO_2 emisssion from power plants and boiler plants of the JSC «Irkutskenergo». Other districts do not show any significant fluctuations of the index values. In eight districts (Bratsk, Zima, Irkutsk, Nizhneilimsk, Usol'ye, Ust-Ilim, Cheremkhovo, Shelekhov) the index values vary within the interval of 0.01 to 0.97, which means that in these districts coniferous tree stands are able to assimilate all CO_2 released in the course of fuel burning by the facilities of the JSC «Irkutskenergo».

In Angarsk district the index value exceeded one, which proves inability of the coniferous tree stands to assimilate the whole of technogenic CO_2. This is mostly accounted for by high amounts of CO_2 emission (Fig.1) and low values of photosynthetic productivity of coniferous tree stands due to their low area (Tab. 2). Depending on the year the index in this district varied from 7 to 12.

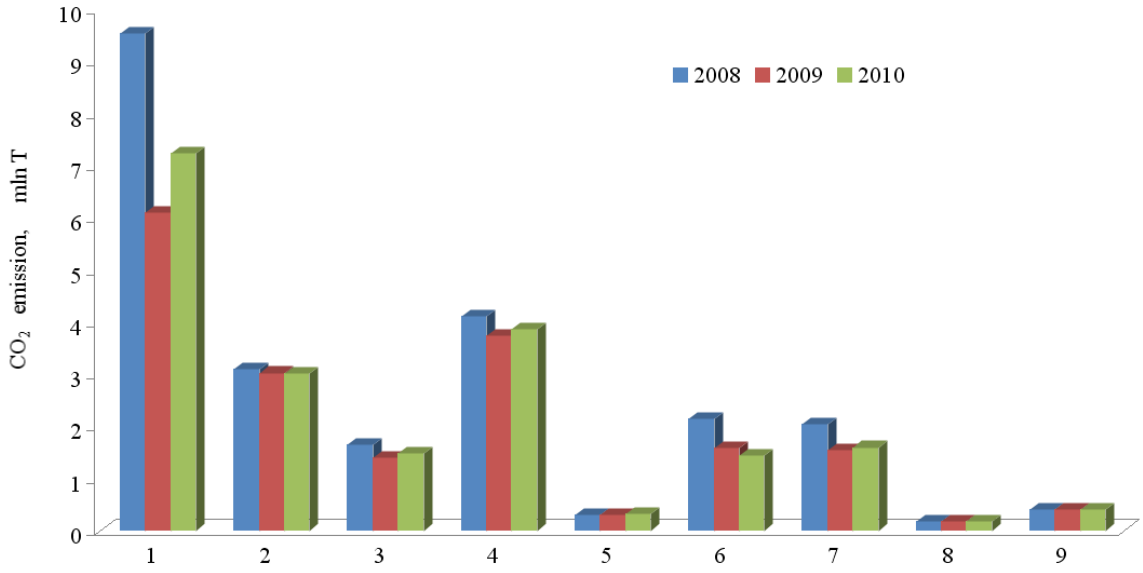

Figure 1. Level of CO_2 emisssion from the JSC «Irkutskenergo» plants: breakdown by administrative districts of the region. Districts: 1 – Angarsk, 2 – Bratsk, 3 – Zima, 4 – Irkutsk, 5 – Nizhneilimsk, 6 – Usol'ye, 7 – Ust-Ilim, 8 – Cheremkhovo, 9 – Shelekhov.

Table 1. Annual photosynthetic productivity of coniferous tree stands in 2008-2009

Administrative district	Photosynthetic productivity (GPP) of coniferous tree stands, t CO_2	
	2008	**2009**
Angarsk	772795	841404
Bratsk	22082763	22959301
Zima	3525325	3757544
Irkutsk	4246109	4547416
Nizhneilimsk	25789247	25497372
Usol'ye	3223602	3493240
Ust-Ilim	31445176	31516844
Cheremkhovo	3210097	3411661
Shelekhov	1214367	1275716

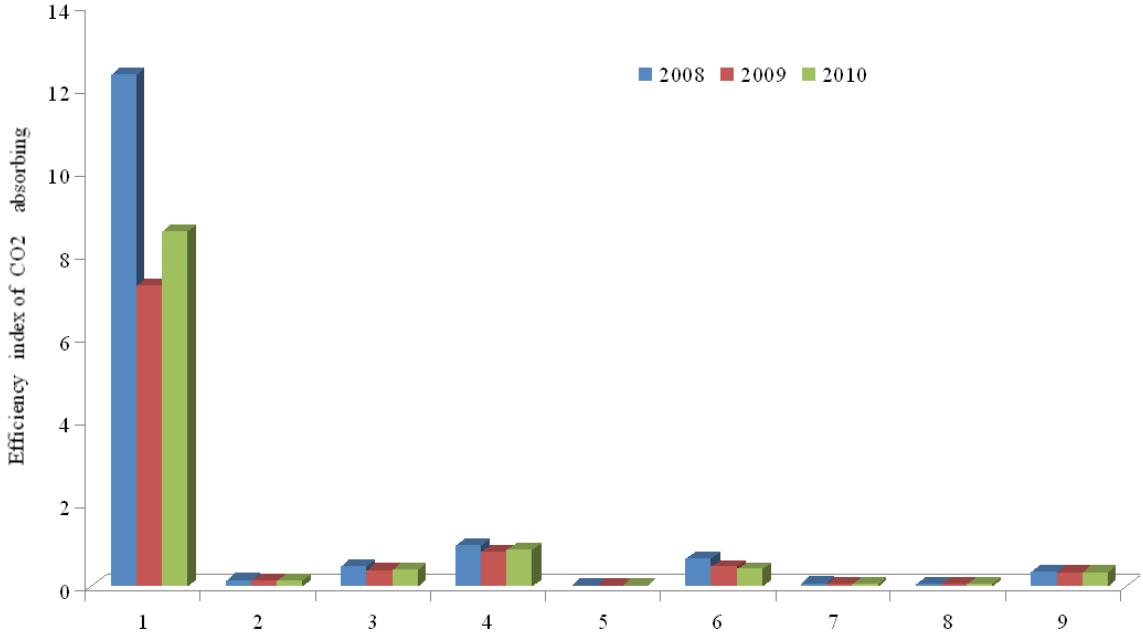

Figure 2. Values of efficiency index of gas absorbing (CO_2-absorbing) forest activity (EIGAF) in the Irkutsk region districts locating HPP and BP of the JSC «Irkutskenergo». Districts: 1 – Angarsk, 2 – Bratsk, 3 – Zima, 4 – Irkutsk, 5 – Nizhneilimsk, 6 – Usol'ye, 7 – Ust-Ilim, 8 – Cheremkhovo, 9 – Shelekhov.

Table 2. Overall areas of coniferous tree stands in the territory of monitored municipal districts of the Irkutsk region

Administrative district	Total area, km^2	Coniferous tree stands area, km^2	Proportion of areas conifers/forests overall	Proportion of areas forests overall/district territory
Angarsk	1149	572.32	0.54	0.93
Bratsk	33024	15423.88	0.61	0.75
Zima	6989	2544.91	0.55	0.67
Irkutsk	11345	1569.16	0.66	0.21
Nizhneilimsk	18900	14798.17	0.63	0.78
Usol'ye	6882	2439.12	0.52	0.69
Ust-Ilim	36596	19985.90	0.65	0.84
Cheremkhovo	9887	2130.31	0.31	0.69
Shelekhov	2020	883.34	0.55	0.80

DISCUSSION

All over the world there are several strategies aimed to reduce CO_2 emisssion from heat power plants. Among them are technological measures designed to decrease the amount of greenhouse gases in plants' emisssion (Raghuvanshi *et al*., 2006; Power..., 2010; Hammond, Spargo, 2014), construction of underground (Zeng *et al*., 2013) and underwater (Environmental..., 2011) storages of technogenic CO_2. In our case technological measures

also contributed to reduction of CO_2 emisssion of the JSC «Irkutskenergo» plants by over 20% (Fig.1). Many researchers prioritize area increase of forests, mostly coniferous, which are able to accumulate technogenic carbon for hundreds of years (Sedjo, 1992; Heath *et al*., 1993; Houghton, 1997; McPherson *et al*., 1999; IPCC, 2000; Goodale *et al*., 2002; Korovin, 2005). For Irkutsk region with immense areas of coniferous stands this concept is very important. In the territory of the district studied coniferous tree stands normally occupy over 50% of the total area of forest lands, except Angarsk and Shelekhov districts, where they take up larger areas – from 2500 to over 15000 km^2 (Tab. 2).

The idea that carbon dioxide concentrations in the atmospheric air increased through technogenic emisssion may be assimilated by coniferous tree stands in the course of photosynthesis was supported by previously acquired results of the study showing that the coniferous species under study within CO_2 concentration range from 300 to 1300 ppm significantly increase their photosynthetic activity (Shcherbatyuk *et al*., 1991).

Despite fairly favorable conditions for photosynthetic activity in 2008-2010, conifers under study possessing species specific peculiarities of photosynthesis response to environmental factors demonstrated relatively diverse photosynthetic productivity. Besides, total gross production (Tab. 1) was determined by peculiarities of distribution of each species tree stands in the territory of the region and their age dynamics. In the central Bratsk, Nizhneilimsk and Ust-Ilim districts that share of spruce and larch tree stands is higher than in southern Angarsk, Irkutsk and Shelekhov districts dominated by pine tree stands.

We have demonstrated that in eight districts of the nine districts studied (Bratsk, Zima, Irkutsk, Nizhneilimsk, Usol'ye, Ust-Ilim, Cheremkhovo, Shelekhov) EIGAF values vary within the range of 0.01 to 0.97, that is in these territories coniferous tree stands are able to assimilate all CO_2 released through burning fuel by the JSC «Irkutskenergo» plants. Only in Angarsk district the ratio values exceeded one, and, depending on the year of study (2008-2010), ranged from 7 to 12, which proves inability of coniferous tree stands to absorb all technogenic CO_2 released by power plants. There are several reasons accounting for this circumstance. The main one is that this is the highest level of CO_2 emisssion in 9 districts. Besides, Angarsk district is the smallest regional municipality with the area of 1149 km^2, which is 10 times smaller than the area of Irkutsk district and 30 smaller than the area of Bratsk district (Tab. 2). Despite the fact that the percentage of forested areas there is comparable to Shelekhov and Ust-Ilim districts (about 90% of the total territory), coniferous tree stands occupy half of the forest area – only 572 km^2 (Tab. 2). These are mostly pine tree stands with specific GPP (t CO_2 ha^{-1} $year^{-1}$) being lower than in other conifers (Suvorova *et al*., 2010). Based on the data acquired we ascertain that Angarsk district tree stands are presently unable to fully assimilate CO_2 emisssion of heat power complex. Nevertheless, EIGAF calculated for all the 9 districts equaled in 2008 – 0.25, in 2009 – 0.19 and in 2010 – 0.20, which means that overall CO_2 emisssion

amounted to 19-25% of photosynthetic productivity of coniferous forests. This confirms high ability of absorption by municipal forests of CO_2 emisssion from HPP and BP. We cannot ignore the fact that though deciduous arboreal species accumulate in their phytomass atmospheric carbon during a shorter period compared to conifers (100-150 years), they play an important role in involvement of anthropogenic carbon in biological cycles. Evaluation of gas-absorbing activity of deciduous plantations of Angarsk municipal district and elaboration of recommendations on changes in the structure of forest territories with the view to enhance their CO_2-absorbing activity may become the object of further research.

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