Use of remote sensing for estimating global warming potential at permafrost area in East-Siberia

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1. GREEN HOUSE GAS EMISSION IN SIBERIA

Siberian boreal forests cover about 9.0 10^6 km^2 and represent roughly 20% of the World's forested areas (Krankina and Dixon 1992, Gaveau et al. 2003, Sukhinin et al. 2004). It is estimated to hold 21-37% of the world's terrestrial carbon in the forests and soils (Sukhinin et al. 2004, Zhang et al. 2003).

This area is susceptive to fire due to the dry climate with only 150 mm annual precipitation in some region (Soja et al. 2004). These fires can be divided into crown fires, moderate-severity surface fires, and low-severity surface fires. High-intensity crown fires are described as those where 40% of aboveground fuels are consumed as well as 100% of combustible fine fuels, moderate-intensity surface fires are those where 90% of understory vegetation and 50% of the litter is consumed and low intensity surface fires are those where only a small fraction of understory vegetation and litter is consumed (Conard and Ivanova 1997, Conard et al. 2002, Soja et al. 2004). In Siberia, surface fires are most often found (Kajii et al. 2002). Crown fires are estimated to account for 10% of fires during average years and up to 50% of fires in severe years (Conard et al. 2002).

Carbon stored in vegetation are released due to fires as high as 20 Mg C ha^{-1} in case of crown fire, and 10 Mg C ha^{-1} in case of moderate fire (Shulze et al. 1999). During burning of organic soils 1 to 12 Mg C ha^{-1} can be released (Shulze et al. 1999, Conard et al. 2002, Kasischke and Bruhwiler 2003). There are even studies reporting that 80 Mg C ha^{-1} can be released if peatland are severely burned (Kasischke and Bruhwiler 2003). The emitted amount varies according to the amount of aboveground biomass and soil carbon storage. A standard scenario for Siberia given by Soja et al. (2004) divided Siberia into four zones and estimated the carbon consumption for 12 ecosystems for each zone at high, medium and low severity fires. The estimated carbon consumption ranged from 3.4 to 75.4 Mg C ha^{-1}. Based on weighted carbon storage in different biomass components, mean levels of carbon emission for crown fires, moderate-severity surface fires, and low-severity surface fires are estimated to be 22.5, 8.6, and 2.3 Mg C ha^{-1}, respectively (Conard et al. 2002).

During fire, gases such as carbon monoxide (CO), methane (CH_4) and non-methane hydrocarbon (NMHC) are emitted in addition to carbon dioxide (CO_2). For forest, the ratio for

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CO_2, CO, CH_4 and NMHC released due to crown fire and moderate surface fire is 443: 35: 2: 1.1, and for low severity the ratio is 385: 70 : 3.9 :2.5, respectively (Kajii et al. 2002). There area also concern about NOx emission during fires.

Not only is the temporal release of stored carbon of concern, but also the long term disturbance of the ecosystem. Once burned, the disturbance return interval ranges typically from 50–240 years, with an average of approximately 100 years (Gerard et al. 2003). Moreover, partial or complete removal of the soil organic layer drastically alters insulating effects resulting in increased soil temperature of 2-6^{o}C, thereby alters increasing soil respiration for up to 25 -50 years following a fire (Soja et al. 2004). Additionally, higher soil temperatures alter the ecosystem by: increasing decomposition and nutrient mineralization, increasing active layer depth (depth of growing sason permafrost thaw) for up to 50 years, and increasing hydraulic conductivity (Soja et al. 2004).

Apart from the carbon emission during forest fire, green house gasses are also released from ponds, called alas, and the surrounding moist grasslands. While CH_4 are absorbed by dry grasslands or forests, CH_4 emission from grassland near the pond can be 17.3 to 174 kg C ha^{-1}, and that from pond water surface 237 kg C ha^{-1} (Takakai et al. 2005, this issue). The CH_4 emission was highly related to the soil water status.

Carbon fixation by forest can mitigate the effect of GHG emission induced by fires or wetlands. The net primary production (NPP) value, the difference between photosynthesis and tree respiration, is said to range between 1.02 and 1.49 Mg C ha^{-1} in Siberia (Shulze et al. 1999). A study near Yakutsk showed a NPP value of 1.68 Mg C ha^{-1} Chikahisa et al. 2005) and a net ecosystem production (NEP), a value subtracting respiration of microbes in soil from the NPP, of 1.29 Mg C ha^{-1} (Chikahisa et al. 2005).

There is a great uncertainty in the total amount of GHG fluxes in Siberia. Estimates of carbon balance ranges between a source of 0.5 Pg C y^{-1} and a sink of 1.0 Pg C y^{-1} (Bergen et al. 2003). Due to anthropogenic and natural disturbance, Siberia may have changed from sink (average of all Russia: 101 kg C ha$^{-1,}$) to source (average of all Russia: 71 kg C ha$^{-1,}$ Shulze et al. 1999). To prevent environmental damages of global scale, the magnitude of fire and land cover change must be estimated more precisely at regional scale.

2. SCALING UP METHODS

Measurements can only be conducted at a point or plot scale. Thus, to estimate a regional scale those data must be scaled up. Scaling up models can be illustrated in a three dimensional diagram shown in Fig. 1 (modified from Hoosbeek and Bryant 1992, Seyfried 2003). In scaling up, attention should be paid on the magnitude of the parameters influencing

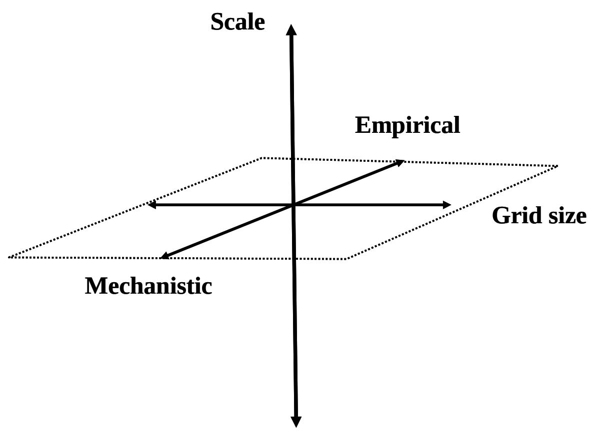

Fig. 1. A three-dimensional diagram describing models in the context of scale, spatial variability and modeling approach. (modified from Hoosbeek and Bryant 1992, Seyfried 2003)

the target phenomenon. The relative influence of an environmental parameters changes with scale. Increasing modeling scale would be straightforward if important processes did not change with scale, if spatial variations of model parameters and inputs were easily described or insignificant, and if model parameters scaled linearly (Seyfried 2003). In fact, processes do change with scale, spatial variations may dictate model results, and model parameters are often nonlinear with respect to scale.

Lark et al. (2004) analyzed the influence of soil-physical parameters on the nitrous oxide (N_2O) emission using a transect of 1024 m in 4 m interval and analyzed it using the wavelet analysis. They showed that there was no correlation of pH, nitrate nitrogen (NO_3^--N) with the amount of N_2O emission at 4 to 32 m distance, while it changed to significantly negative correlation for pH and positive correlation for NO_3^--N above 64 m distance. On the other hand, water and soluble carbon showed significantly positive correlation with the N_2O emission at small scales and turned negative correlation at bigger scales. This study showed that relationship between variables from one part of the landscape to another varies according to the referred scale.

This is not only the case for empirical modeling approaches. In case of mechanistic models, first, there is a substantial mismatch between the scale at which these processes have generally been studied, mostly in laboratory columns and small experimental plots ranging in size from 1 to perhaps 100m, and the application scale, which ranges from 1000m up to continental or even global scales (Seyfried 2003). Secondly, no matter how well the model represents the process of interest, if the required parameters are of reduced accuracy, the resultant simulation must also have reduced accuracy. Thus, a model, which is mechanistic at small scales, becomes empirical at some larger scales (Seyfried 2003).

Mulla et al. (2003) compared four different scales, plot, field, minor watershed and major watershed scales, to estimate the N load in the river of a watershed. The spatial resolution increased from plot to major watershed (e.g. from 1:5000 at field scale to 1:125 000 at minor watershed for soil map). At major watershed scale there was an increased reliance on geological information systems (GIS) and statistical mass balancing techniques, and a reduced reliance on process based simulation. Process-based modeling becomes unwieldy at the scale of major watersheds, and the uncertainties and coarse spatial resolution in input parameters did not justify a modeling approach. (Mulla et al. 2003) The comparison of the results showed that the estimation at the major watershed scale was closest to the measured result. Mechanistic models tend to be more demanding in terms of data requirements than empirical models. It can be concluded, that empirical models are more adapted in using relationships found for monitoring data or land surface properties.

Up-scaled models intended to portray spatial variations require spatially extensive data as data input and for model testing. Lack of availability of such data is one of the major limitations to evaluate a phenomenon in a regional scale. Considering that digital elevation models and land cover maps are essentially remote sensing products (largely derived from aerial photography), remote sensing seems to be the only source of such data at a regional scale (Seyfried 2003). The critical consideration is whether the accuracy and precision of the data derived from remote sensing are sufficient for the needs of the model (Seyfried 2003).

To evaluate the influence of fire in Russia, satellite remote sensing method appears to be the only practical method to create maps of the soil type, land cover, vegetation volume and elevation for its vast and remote nature (Sukhinin et al. 2004, Wagner et al. 2003).

3. EXAMPLE OF GLOBAL WARMING POTENTIAL ANALYSIS IN SIBERIA

This section shows one trial to use remote sensing in scaling up ground monitoring data. The objective of this study was to evaluate the influence of land cover change due to fire on the global warming potential (GWP) at a regional scale. Two scales were investigated (Fig. 2). Scale 1 is about 6909 km^2 and deals around Yakutsk. Scale 2 is about 1 km^2, dealing the

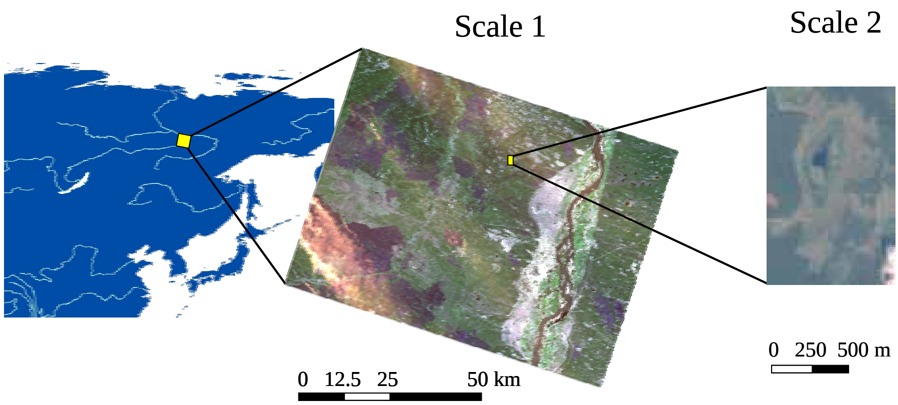

Fig. 2. Study site of this study. Scale 1 around Yakutsk (6909 km^2) and scale 2 around Neleger (1.02 km^2).

surrounding of an alas at Neleger. For scale 1, Landsat ETM data (30m resolution) on 27th Aug. 1999, and 12th Aug. 2002 was analyzed to classify land covers at each date. For 1999, information of Landsat ETM data on 30th Oct 1999 was used to identify forest vegetation types. For scale 2, IKONOS data (1m resolution) on 11th July 2001 was used in addition to the Landsat data used in scale 1. Satellite data was analyzed by unsupervised classification (ISODATA) using ERDAS Imagine 8.7. Land cover was distinguished among water bodies, forest, grassland (dry and wet), burning severity (high, moderate and low) and unidentified area such as town, cloud and smog. The forest type was subdivided into birch, larch, pine and dead trees for 1999 and into dense or thin in 2001 and 2002. The imagine analysis was validated using ground survey data on 1999 and 2002. The numbers of reference ground truth points were 92, 1043 and 56 for Landsat ETM data on 27th Aug. 1999, Landsat ETM data on 12th Aug. 2002 and IKONOS data on 11th July 2001, respectively.

To estimate the GWP of various land covers, monitoring data at Yakutsk was used (Table 1, Hatano et al. 2005, this issue and Takakai et al. 2005, this issue). The GWP was defined as the

Table 1. Global warming potential (GWP) for water bodies, forest dry and wet grassland and high, moderate and low burning severity fire near Yakutsk. (Hatano et al. 2005, Takakai et al. 2005, this issue)

		Water bodies	Forest	Grassland		Burning severity			
				dry	wet	high	moderate	low	average
	CO_2	369	-513	586	-142	7475	2574	688	3912
GWP	CH_4	728	0	0	294	400	250	67	266
(Mg CO_2	N_2O	12	0	44	-1	180	123	33	125
eq km^{-2})	**sum**	1110	-513	630	151	8055	2946	788	4303

sum of CO_2, CH_4 and N_2O emission, expressed in CO_2 equivalent: 1g of CH_4 equals to 23g of CO_2, and 1g of N_2O to 296g of CO_2 with a time span of 100 years (IPCC 2001). The total GWP of water bodies, forest, dry grassland, wet grassland, high, moderate, low and average burning severity were 1110, -513, 630, 151, 8055, 2946, 788 and 4303 Mg CO_2 eq km^{-2}, respectively. The GWP of average burning severity was used to evaluate the influence of fire in 1999, while values of high, moderate and low burning severity was used in 2002.

3.1 Results from scale 1: around Yakutsk

The validation showed that for Landsat ETM of 27th Aug. 1999, the precision for birch was 18 %, that for larch 90 %, that for pine 96 % and for dead trees 75 % (Fig 3). The overall precision for this classification was 82.6 %. Pine was the dominant vegetation at this area, thus the small area of birch was hard to identify. More difficulty was found in the detail classification for the Landsat ETM data on 12th Aug. 2002 (Fig. 4). The precision for water bodies was 27.3 %, that for dense forest 46.8%, that for thin forest 42.0 %, that for dry grassland 34.6 %, that for wet grassland 29.1 %, that for riverbank grassland 14.3 %, that for area with high, moderate and low severity burning, 74.2 %, 2.0 % and 49.7 %, respectively. The total precision for the detail classification

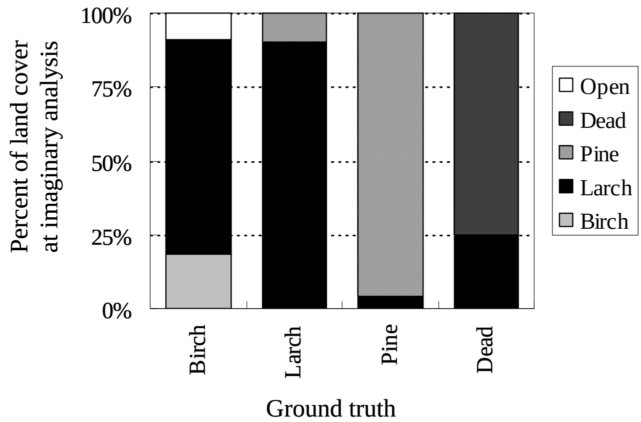

Fig. 3. Precision of imaginary analysis of the land cover from the Landsat ETM picture on 27th Aug. 1999 around Yakutsk.

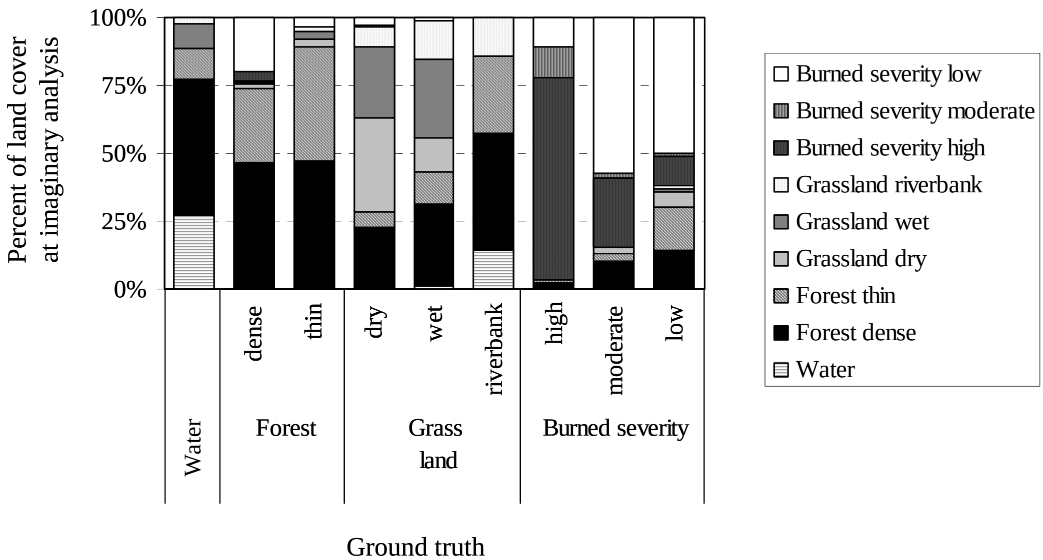

Fig. 4. Precision of imaginary analysis of the land cover from the Landsat ETM picture on 12th Aug. 2002 around Yakutsk.

of the total area was 42.3 %. As the land cover was just roughly distinguished by water bodies, forest, grassland and fire, the precision was 27.3 %, 81.7 %, 46.1 % and 81.0 %, respectively. The low precision for water bodies was due to the small area of a pond, which resulted in a mixed reflection. However, as the result of 1999 and 2002 was overlaid, 91 % of the water bodies in 1999 were found also in 2002 as water bodies. In addition, the ground reference points in 2002 does not include the Lena River. Thus, the low precision of water bodies might be due to the difficulties to distinguish small ponds at a 30 m resolution. Precision of the forest and burning area was drastically improved from detail to rough classification. One pixel of a satellite imagine can be an aggregate of several land cover reflections. The accuracy of the registration of the remote sensing data is usually on the order of one to few pixels. That means that the data collected remotely from a given location may actually represent land surface conditions two or thee pixels away from the true position. There is also concern about the interpretation of the ground truth data (Seyfrield 2003). The same might be true for the identification of grassland as for water bodies. Almost the half of grassland was identified as dense or thin forest. Similar reflectance of the grassland and forest might be the reason.

The comparison of the land cover area of 1999 and 2002 is given in Table 2. Water body area decreased from 381 to 268 km^2, forest area from 4518 to 3342 km^2. There was no increase for grassland. The difference in the forest area was found to have burned. The burning area increased from 226 to 1632 km^2, occupying 24 % of the total area. To evaluate the influence of land cover change on the GWP, the area of land covers were multiplied by the GWP value for each land cover from Table 1. Due to the decline in forest area, the sink capacity reduced from -2319 Gg CO_2 eq in 1999 to -1716 Gg CO_2 eq in 2002. Water bodies, grassland and burning acted as GWP sources. Among them, burning contributed the most with 970 Gg CO_2 in 1999, and 6751 Gg CO_2 eq in 2002. As all GWP of land covers were summed, it was found that this area was a sink of -273 Gg CO_2 in 1999. In 2002, the decline in forest area and increase in burning area changed this sink to a source of 5693 Gg CO_2.

Table 2. Results of land cover area and associated amount of global warming potential (GWP) around Yakutsk in 1999 and 2002.

		Area		GWP	
		1999	**2002**	**1999**	**2002**
		(km^2)		(Gg CO_2 eq)	
Water bodies		381	268	423	298
Forest		4518	3342	-2319	-1716
Grassland	**dry**	908	658	572	414
	wet	541	831	82	125
Burning severity	**high**		642		5172
	moderate	226	287	970	844
	low		704		554
Town & smog		335	177	0	0
Sum		6909	6909	-273	5693

3.2 Results from scale 2: around Neleger

The precision of the imagine analysis of the IKONOS picture for the scale 2 around Neleger on 11th July 2001 was a little improved compared to the analysis of Landsat data, since it had higher resolution of 1 m compared to those of Landsat data with a resolution of 30 m (Fig. 5). The precision of water, dense forest, dry grassland was 100 %, 86 % and 85 %. Wet grassland was difficult to distinguish from dry grassland as well as forest. The small area and the similarity in surface color may have led to the low precision of 42 %. Thin forest could not be distinguished with dense forest. Distinguishing small area and the interpretation of mixed information of a pixel may be the reason. The overall precision for the detail classification was 64.3 %, while that for the rough classification was 87.5 %. Increase in resolution improved the precision, however, the same problem in distinguishing land covers was found also for the higher resolution of IKONOS.

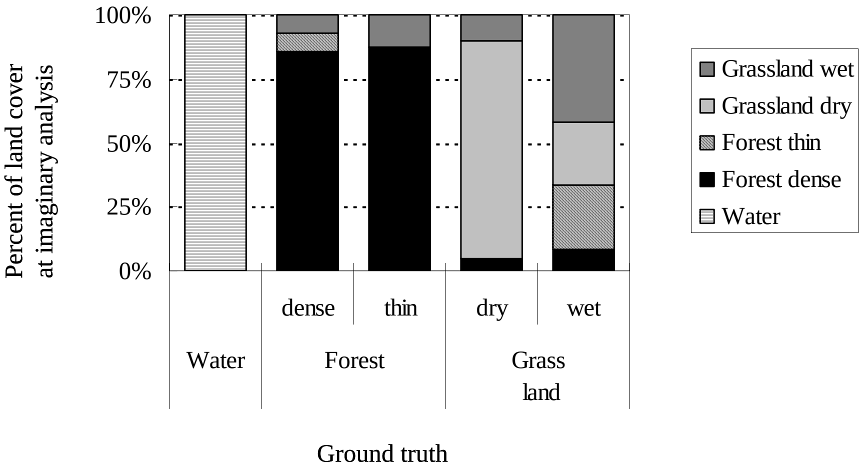

Fig. 5. Precision of imaginary analysis of the land cover from the IKONOS picture on 11th July 2001 around Neleger.

The land cover change for scale 2 is shown in Table 3. There was no big difference in 1999 and 2001. About half of the area was determined as forest in 1999 and 2001. Comparison of the area covered by the cloud in 2001 with the land cover of 1999 and 2002, the area was determined as forest. In 2002, the forest area decreased from 0.523 km^2 in 1999 to 0.479 km^2 to 0.381 km^2. Water bodies seemed to have decreased and area of dry grassland to have increased. A significant part was also found to have burned, occupying 7.4 % of the total area. The impact of water bodies on the global warming decreased from 1999 and 2001 to 2002 according to the land cover change by 10-12 Mg CO_2 eq, that of grassland increased by 40-46 Mg CO_2 eq. The sink capacity of the forest decreased by 42-73 Mg CO_2 eq. In addition to these change, the burned area increased GWP by 326 Mg CO_2 eq. Thus, this area changed from a sink of GWP of -40.3 and -20.7 Mg CO_2, in 1999 and 2001, respectively, to a source of 388 Mg CO_2 eq in 2002.

Table 3. Results of land cover area and associated amount of global warming potential (GWP) around Neleger in 1999, 2001 and 2002.

		Area			GWP		
		1999	**2001**	**2002**	**1999**	**2001**	**2002**
			(km^2)			($Mg\ CO_2$ eq)	
Water bodies		0.014	0.017	0.006	16.0	18.4	6.5
Forest		0.523	0.463	0.381	-268.6	-237.5	-195.8
Grassland	**dry**	0.291	0.264	0.351	183.4	166.2	220.7
	wet	0.191	0.262	0.206	28.8	39.6	31.2
Burned		0.000	0.000	0.076	0.0	0.0	325.5
Cloud		0.000	0.014	0.000	0.0	-7.4	0.0
Sum		1.020	1.020	1.020	-40.3	-20.7	388.1

*: comparison of the area cover by the clod in 2001 with the land cover data from 1999 and 2002, the area was determined as forest.

4. DISCUSSION

The upscaling of monitoring data can be described in three steps. The first step is the parameterization of the monitoring data, where the data are explained by environmental factors. The second step is to get information about the spatial variability. At this step, parameters able to reflect the spatial variation of the target scale must be drawn to a GIS map. The last step is the evaluation at a regional scale, by estimating the GWP at the whole area, for example. The challenge at the parameterization is to cover additional information or relationship with more easily obtained data at a larger scale than the monitoring is conducted (Seyfried 2003). At the second step, the precision is important. If the gained parameters are of reduced accuracy, the estimation result also has reduced accuracy. In most fundamental sense, the loss of precision with upscaling is due to the error caused in reflecting the spatial variability.

For this study, parameterization of monitoring data was not conducted. There is a need to reflect the environmental factors to the monitoring data. In chousing the parameters, attention should be paid on the nature of the satellite data. Satellite pictures are snap shots of one time. They also give only information of above ground. Soil moisture can be obtained to 2-3cm depth, however, it still has high uncertainties and further studies are required.

The precision of this study was 42 to 83 % for the detail classification, while it was 73 to 88 % for the rough classification. The precision was improved from 30 m resolution Landsat data to 1 m IKONOS data. However, the principal problems in the analysis of the pictures were the same for both resolutions. It was difficult to distinguish between dry, wet grassland and dense and thin forest. There is a need to improve the classification method as well as the interpretation of the ground data.

The evaluation result showed that at scale 1, 24 % was burned, and GWP increased from -39 to 824 Mg CO_2 eq km^{-2} from 1999 to 2002. At scale 2, 7.4 % was burned and GWP increased from -40 to 381 Mg CO_2 eq km^{-2}. Both results from scale 1 and 2 showed that the area around Yakutsk changed from a sink to source from 1999 to 2002. The highest contributions to this change were the reduction in forest area, both dense and thin together and the increase in area with high burning severity. The precision of the forest together ranged from 81 to 99 %, and that of the area with high burning severity was 75%. Thus, it can be concluded that the magnitude of the change in GWP might be true.

5. CONCLUSION

There was as significant change in land cover from 1999 to 2002 due to fires around Yakutsk. The area changed from GWP sink to source due to this change. Remote sensing and GIS seemed to be the only tool to scale up monitoring data at a regional scale. The land cover change in Siberia is alarming. Future study must combine remote sensing with monitoring data to evaluate the phenomenon found at point or plot scale to regional scale. Based on this information, scenario analysis can be conducted to analyze how land cover change can or should be handled.

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