SYNERGISTIC USE OF ERS-1/SAR AND OTHER SATELLITE DATA FOR THE POLLUTED AREAS IDENTIFICATION FOR BOREAL FORESTS OF ST. PETERSBURG REGION

Donchenko V.V., Goltsova N.I., Bobylev L.P.

Nansen International Environmental and Remote Sensing Centre

Korpusnaya Str. 18, 197110 St. Petersburg, Russia

phone: +7 812 235 74 93, fax: +7 812 230 79 94

E-mail: nansen sovam.com

O. M. Johannessen

Nansen Environmental and Remote Sensing Center (NERSC), Edvard Griegs vei 3a, N-5037 Solheimsviken, Bergen Norway and Geophysical institute, University of Bergen

phone:+47 55 29 72 88, fax: +47 55 20 00 50

e-mail: Ola.M.Johannessen nrsc.no

WWW: http://www.nrsc.no:8001/

Kritsuk S.G., Pitulko V.M.

Scientific Research Centre for Ecological Safety, Russian Academy of Sciences

Korpusnaya Str. 18, 197110 St. Petersburg, Russia

phone: +7 812 235 74 93, fax: +7 812 235 43 61

ABSTRACT

This study is dedicated to development of the interpretation basis for analysis of satellite remote sensing data in terms of indicators characterizing the ecological situation and the degree of the anthropogenic pollution of ground ecosystems. For this purpose ERS/SAR images were used together with Landsat/MSS and NOAA/AVHRR data as well as the data of ground measurements of the spectral brightness of the components of pine biocenoses and the results of studies of the moss chemistry and bioindicators. The ERS/SAR images enabled one to assess the distribution of the forested areas, to classify the forests, a combination of the ERS/SAR, Landsat/MSS and NOAA/AVHRR images obtained in different time has made it possible to trace the dynamics of changes in the forested ecosystems. The statistical structure of the samples has been studied, major factors of the variability of the complex variables such as NDVI and night temperatures have been revealed, which are most significant connected with the indicators reflecting the state of the forests. The interpretation algorithms allowed establishing correlation between the spectral features of images and the data of reference ground observances for a region with a stressed ecological situation.

1. INTRODUCTION

The most important element of the monitoring programs is the complex monitoring of forests which combines both the bioindicative and instrumental investigation techniques and has a well developed methodical basis in the form of international programs. The requirements of promptitude, field of vision, and objectivity are best met through combining the multispectral satellite survey and a network of fixed ground stations. At present an experience has been gained in interpreting the materials of satellite survey to assess the propagation of pathological changes in the conifers. There are reliable reference data for the south-western areas of the Leningrad province (Slantsy - Kingisepp - Luga Bay).

The Remote sensing derived Landuse information enables one to characterize the landscape basis of an ecological maps on which the proper ecological information will be imposed either in the form of initial spectral data or in the form of their transformations (e.g. NDVI), or as a complex parameter of load. The satellite imagery of a high resolution makes it possible to reliably identify the non-forested areas [Ref. 3]. In case of the forested areas one can differentiate the forest fund territory between homogeneous forest-tax formations by prevailing types, age and thickness. The reliability of decoding of the prevailing types reaches 65-80%, the error of age of trees determination - 1 class, thickness of planting - 10-15%.

Pollution of the ground biota (forested territories) of the Leningrad province has been monitored for five years by the Scientific Research Centre for Ecological Safety and Nansen Centres in St.-Petersburg and Bergen (within the ICP-Forests program) over the 32×32-km grid For the territory of the Kingisepp and Slantsy districts a grid of 16×16 km was formed and two sites of intensive monitoring were organized. Methods of sampling, defoliation assessment, lichenoindication as well as methods of chemical analysis have been intercalibrated with the countries of Europe. The coordinates of each site are in the UN EEC data base.

2. OBJECTIVES OF THE STUDY

Overall objective is the development of approaches to synergistic use of satellite remote sensing data in different spectral ranges for the assessment of ecological situation in the study area.

Besides, one can mark out some specific objectives:

Creation of the landscape basis of the ecological map making use of the Landuse classification of the complex of satellite data (ERS, Landsat, NOAA) with the allocation of the reliable boundaries of the proper forested territories, including the areas of the pine trees propagation.

Study of the spectral characteristics of the pine biocenoses.

Identification of the factors of aerotechnogenic oppression.

Study of the dynamics of the anthropogenic change in the forest ecosystems. Assessment of the state of forests in the region.

3. TEST AREA AND DATA DESCRIPTION

3.1. Test area characteristics

This study has been accomplished for the area with the hard ecological situation (Fig 1) which is located at the

Russia - Estonia boundary. Here the main sources of pollution are the energetic enterprizes of Estonia, the mining enterprizes of Narva, Slantsy, Kingisepp, and others. This zone is characterized by very high emissions of sulphur which cause serious damages to the forest ecosystems. The content of sulphur and calcium in pine-needles is much higher than anywhere

***Figure 1**. Territory under the study.(- sampling points; - sources of pollution)*

in toxicants is apparent not only due to huge amounts of emissions but also due to the meteo-synoptic situation.

3.2. Data used in the study

Results of field observations interpret well the area's territory by the grid of test sites. Nevertheless, there is no complete spatial picture of the region on the whole, the biotic condition of its difficult-to-access sites and territories not included in the plans of previous field sudies. To obtain a complete picture, an attempt has been undertaken to use satellite data.

A. In-situ (field measurements) data

Observations at the test sites are made using the ICP-Forests international techniques with the help of the intercalibration methods of data collection and analysis. The study has been focused on the indicators which can affect the spectral characteristic of pine trees - defoliation, discolouration, the longevity of pine-needles, the amount of indicative types of lichen-epiphytes, the content of heavy metals and other toxicants in soil humus and in forest mosses, a number of forest-tax parameters determining the density of forest canopy (diameters of the trunk and crown, valuation parameters, plant thickness, etc.).Changes in the pine trees' defoliation in 1995 over the investigated territory are shown in Fig. 2.

In addition to above mentioned ground measurements have been taken of the spectral brightness of the prevailing plants of the pine biocenoses.

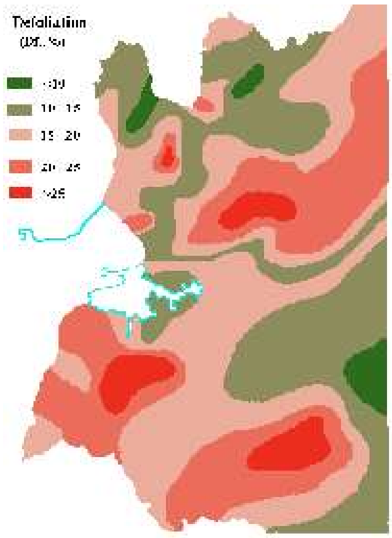


***Figure 2**. Changes in the pine trees' defoliation in 1995 over the territory of the Kingisepp area of the Leningrad province, from the data by N.I. Goltsova.*

B. Remote - sensing data

The following satellite remote sensing data have been used in the study:

ERS-1/SAR as of 13 March, 1993; 18 March, 1994; 20 August, 1994; 13 and 29 September, 1994; 16 and 25 March, 1995; 15 and 31 August, 1995;

- NOAA/AVHRR as of 8 March, 1991; 2 and 3 June, 1992, and 15 August, 1994;

- Landsat/MSS as of 29 April, 1989 and 12 September, 1993.

4. TECHNIQUES DESCRIPTION

4.1. Initial processing of digital satellite data

To provide a comparability of the in-situ data with remote sensing data the geometric correction of the latter is carried out. To take into account the conditions of SAR scanning, the corresponding data were reduced to one level of the reflected signal by extracting the second-order trend drawn from the image lines (by the X-coordinate).

Retrieval of the surface temperature was carried out from the NOAA/AVHRR data of thermal channels 4 and 5 making use of the technique described in [Ref. 1]. The atmospheric correction was made using the standard model of the atmosphere.

The vegetation index was calculated making use of the band-difference technique described in [Ref. 2], for the NOAA/AVHRR from data of channels 1 (visible range) and 2 (near-IR range), and for Landsat/MSS from data of channels 2 and 4.

Upon correlating the coordinate system of ground observations and the geometric correction of satellite data for the area of observation points (~300 m in diameter), mean values of the following parameters were estimated:

- daytime thermodynamical surface temperature (near 03:00 p.m.) - Day T;

- nighttime thermodynamical surface temperature (near 04:00 a.m.) - Night T;

- vegetation index - NDVI;

- surface albedo - ALB;

- image brightness from the data of NOAA/AVHRR, ERS-1/SAR and Landsat/MSS.

These parameters supplemented the initial data matrix of ground survey (78 sites).Besides, over a greater area of observation points (~500 m in diameter), variations of these parameters were assessed.

After the water mask had been imposed, the factor analysis of images was made for several groups of images, which showed that the "forest-field" factor is the main factor of variability (not less than 50%).The correlation with the data of ground observations was studied for two sets:

- for the whole totality of the data available;

- for the sampled points located deep in the forests (the sampling was based both on the topographic material and on the Landsat/MSS and ERS-1/SAR data).

4.2. Elimination of non-forest areas

Despite the difficulties mentioned above, an analysis of space images makes it possible to identify the forests damaged by air pollution. However, the accuracy of pollution estimates and determination of the type of prevailing pollutants depends much on the accuracy of the contouring of the forested areas, since changes in the spectral characteristics of the surface caused by natural and anthropogenic stresses to vegetation, depend directly not only on the intensity of stresses but also on the type of the surface assessed. Therefore the targets should be thoroughly selected, especially within the areas with decreased spectral indices. It is these areas that include the sites of forests aerotechnogenically oppressed, which are, finally, an object of monitoring.

The algorithm to contour the forest areas includes the folowing two procedures:

contouring of the urbanized territories, mountain workings, agricultural fields and meadows;

contouring of the area of marches in the remaining territories (mainly the forested ones) with differently weakened trees under the influence of natural factors.

The first procedure is accomplished most efficiently making use of the remote sensing data (Landsat, ERS-1/SAR, NOAA). The result of the forested areas allocation making use of the Landsat (Band 4) and ERS-1/SAR composite is shown in Fig. 3. One can easily identify the urbanized territories, the coniferous and broad-leaved forests.

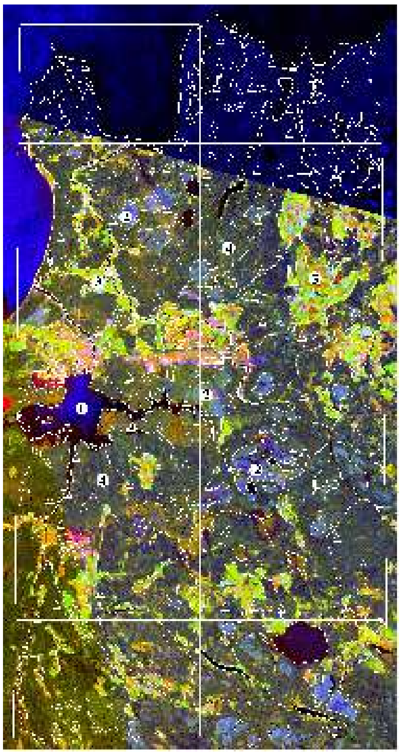


Figure 3. *Allocation of the forested areas making use of the Landsat (Band 4) and ERS-1/SAR composite. 1 - water surfaces, 2 - marshes, 3 - agriculture fields, 4 - forested areas.*

The second procedure is accomplished for any season from the data of SAR images as well as for spring - from the distribution of nocturnal surface temperatures, clearly reduced over he marshed areas from NOAA/AVHRR data. The example of allocation of the marshed areas from the distribution of nocturnal surface temperatures is given in Fig. 4. In this case the territories largely covered with marshes are still cold and contrast with a warmer background of the remaining lands.

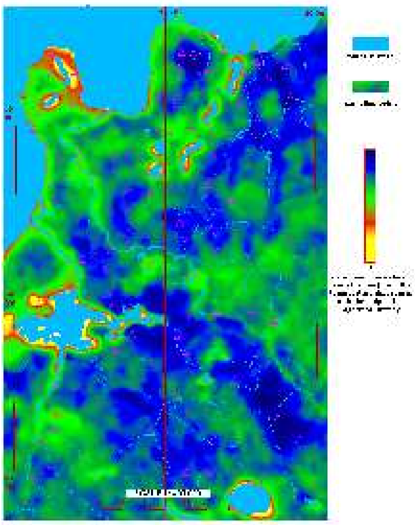


Figure 4. *Allocation of the marshed areas from the distribution of nocturnal surface temperatures.*

4.3. Statistical techniques

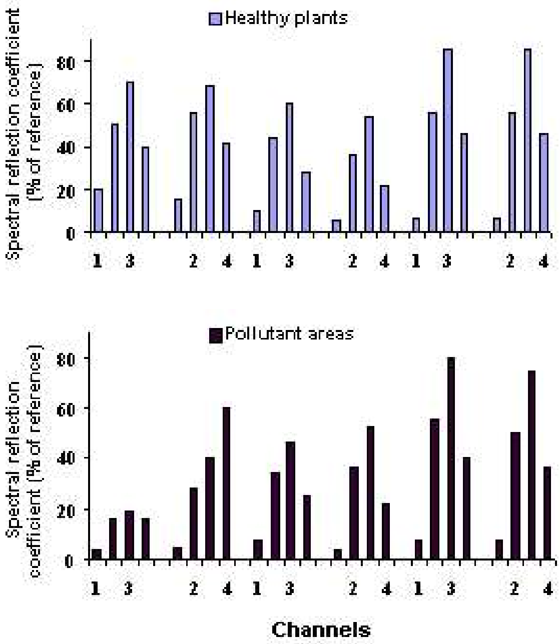
The factor analysis of the distribution of the spectral channels' intensity and the values of the spectral indices as a function of natural manifestations, which cause an oppression of the forest ecosystems, has shown that the main contribution to the variability of the studied sample is made by 3-4 parameters whose variations describe up to 95% of total dispersion. The variability of the data of all the scanners used is determined by the combination of the forested and non-forested lands (52-56%), the seasonal phases of vegetation (16-19%), and the marshed areas (8-9%). Hence, in this case the Landuse classification of the forests, agricultural and urbanized lands, and the marshes for each phase of vegetation separately is the necessary and sufficient basis of the ecological maps.

With the use of the STATGRAPHICS-3.0 software the statistic structure of the sets has been studied as well as the main factors of the variability of the complex variables (such as NDVI and Night T) have been determined which are most significantly connected with the indicators reflecting the condition of the forests (in particular, with the content of Ca in mosses, pine defoliation, etc.)

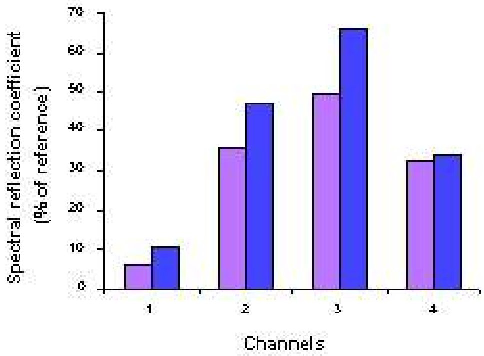
5. RESULTS

5.1. Correlation between spectral features of space images of forests and reference ground observation.

Defoliation and discolouration of pine trees lead to a decrease of reflection coefficient in all spectral ranges, and with an intensive anthropogenic forcing - mainly in the near-IR range.The reflection coefficients in spectra channels 0.3-0.63 mkm (No 1), 0.63-0.8 mkm (No 2), 0.8-1.0 mkm (No 3), 1.0-1.75 mkm (No 4) for the prevailing plants of pine biocenoses at a different stage of the aerotechnogenic oppression have been used as a learning material for the interpretation of the space data (Fig. 5). For that purpose the Field Impulse Photometer (1993, Vavilov State Optical Institute, St.Petersburg, Russia) was used. The mean spectral characteristic of the pine trees has been calculated with the use of the weight coefficients of the contribution of each plant community to the reflectivity of the entire canopy of the trees.



(a)



(b)

Figure 5*. (a) Reflection coefficients for the prevailing plants of pine biocenoses: A - moss, B - pine (bark), C - pine (needles), D - spruce (needles), E - deciduous undergrowth, F - soil cover; (b) average reflection spectra for canopy with account of the contribution of each plant. Channels: 0.3-0.63 mkm (1); 0.63-0.8 mkm (2); 0.8-1.0 mkm (3);1.0-1.75 mkm (4)*

From average reflection spectra it is seen that differences between oppressed and healthy trees exist in every spectral range studied. There is a general decrease of spectral brightness: in channel 1 - by 30%, in channel 2 - by 25%, in channel 3 - by 26%, and in channel 4 - by 5%, which can be explained by a sharp decrease of pigmentation as a result of irreversible physiological changes with the dust-gas pollution of the vegetation cover. These dependences substantiate the information content of simple spectral indices (in particular, signal difference, simple ratios of signals from different channels, etc.).

Results of assessment of the state of forests in the investigated territory from the data of multispectral space survey (NOAA/AVHRR, 2 June 1992, NDVI change) are given in Fig. 6. In the Kingisepp district about 1050 km^2 of forests have a vegetation index below the norm, in the Slantsy district - about 600 km^2

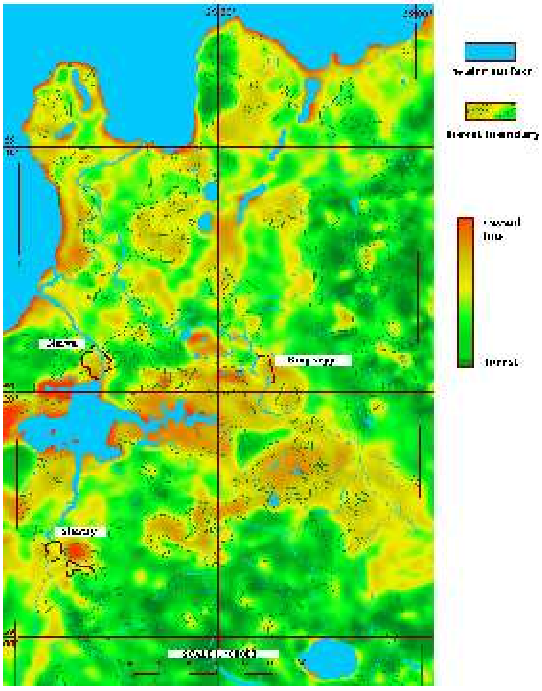


Figure 6. *The vegetation index scale.*

5.2. Algorithm for identification of air pollution of the forests

For the reliably identified forests a comparison was made of healthy trees (high NDVI) and the trees weakened by air pollution. The study was completed by establishing connections and relationships between the parameters obtained by the multispectral space systems and the factors inducing the stress to the plants. The rank correlation between the propagation of some toxicants in the investigated domains and the bioindicators can be seen in Table 1.

Analysis of the covariance matrix distribution shows that the discription of anomalies of heavy metals in soils, defoliation of pine trees as well as the vegetation index more closely correlate in spring, whereas changes in the values of spectral brightness for Landsat channels 2, 3 and 4 agree well with those of defoliation in the fall, there being observed an inverse dependence of spectral brightness on the pine-needles' lifetime. The impact of seasonal conditions on the statistical stability of correlations between the ground and remotely obtained data testifies to the fact that the monitoring of pine-trees of the boreal zone is more efficient in the early vegetation period.

Domain toxicant,	Defoliation of the whole crown	Discolouration of the whole crown	Longevity of needles	Licheno-indication	NDVI
Mosses:					
Pb	+	+	-	+	(+)
Zn	+	-	+	+	(+)
S	+	+	+	+	+
Ca	+	-	(+)	+	++
Fe	+	-	+	(+)	-
Humus:					
Pb	+	-	-	+	(+)
Zn	+	+	+	-	-
S	+	+	++	+	(+)
Soils:					
Ca	++	++	++	++	++
S	++	+++	++	+	(+)
Fe	+	+	+	+	-
Pb	+	+	-	+	(+)
Zn	+	+	+	+	(+)
Defoliation	xxx	-	+	+	++
Discolouration	-	xxx	+	++	+
Longevity of needles	+	++	xxx	+	+
Licheno-indication	+	++	+	xxx	++
NDVI	++	+	+	++	xxx

+ consistent changes; - lack of consistent changes; ++ close consistency ; (+) unstable consistency.

***Table 1**. The rank correlation between the distribution of some toxicants and the bioindicators.*

The statistical structure of total set (78 stations, 16 parameters of soil, 16 parameters of mosses 1 indicator of the density of total deposits, 4 bioindicators, 6 forest-tax characteristics, 18 remote indicators) can be informatively interpreted with the use of the correlation analysis, but without its sorting by the types of soils the meaningful correlations are established only at a 96% confidence level, and the value of partial coefficients of correlation, as a rule, exceed negligibly 0.25-0.3, which suggests nevertheless the existence of a number of basic dependences between the remotely sensed and ground data showed in Table 2.

The statistical structure of the sorted set of the points characterizing the proper forest masses differs much from total set. First of all, the correlation sharply grows between the variables (the correlation coefficients exceed 0.60 at a 99% confidence level), which makes it possible to retrieve the fields of distribution of the pollutants. For example, in Fig. 7 one can see the dependence between some parameters determined from remote sensing data on the one hand and S and Ca concentration in soil as well as the range of discolouration of pine needles on the other hand.

In-situ data	Remote sensing
characrteristic of tree masses:	
crown density	SAR signal, all the channels of Landsat and NOAA/AVHRR, Day T
height and diameter of trees	Landsat channels 2, 3, 4; Day T
age of trees	Night T, all the channels of Landsat
defoliation and discoloura tion	Day T, NDVI (NOAA and Landsat)
pollution of mosses:	
total density of deposits	Day T, NDVI (Landsat)
pollution of the humus horizon:	
Al, Ca, Fe, K, Mg, V	NDVI (Landsat)
Ca, Cu, Fe, Pb, V	Day T

***Table 2**. Main suggested dependencies between in-situ and remote sensing data (total sampling)*

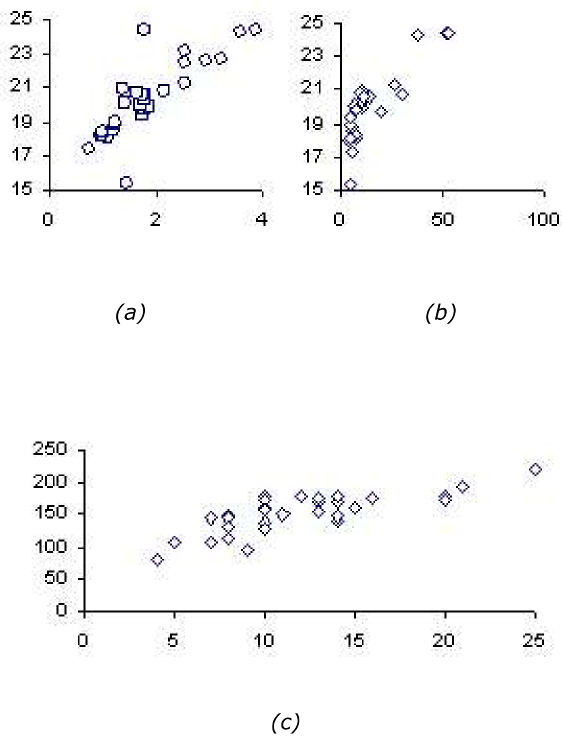


***Figure 7**. Dependence of: (a) - daytime temperatures on the content of sulphur in soils, (b) daytime temperatures on the content of calcium in mosses, (c) vegetation index on the degree of pine-needles' discolouration.*

An interpretation of the statistical structure of the "forest" set can be realized more reliably, moreover, with a markedly broadened possibility of identification of the indicators of the state of pine biocenoses. The corresponding dependences between in-situ and remote sensing data are shown in Table 3.

Thus, the principal possibility has been shown to identify the density and composition of air deposits from the remotely senseddata. It should be noted that it is based on the fact that the presence of high concentrations of heavy metals and other toxicants either in soils or in deposits is manifested through the physiological and morphological changes in plants. The stress of biocenoses is expressed through cutting the biomass increase, pigmentation weakening and increase of the vegetation cover roughness.

In-situ data	Remote sensing data
characteristic of tree masses:	
crown density	SAR signal (r = - 0.67), all the channels of Landsat and NOAA/AVHRR,Day T
height and diameter of trees	Landsat channels 2, 3 4, Day T
age of trees	NDVI Landsat, SAR (r = + 0.76)
defoliation and disco louration	Day T, NDVI (NOAA and Landsat)
lichen-epiophytes	NDVI (NOAA and Landsat)
pollution of mosses:	
total density of deposits	Landsat (channels 3 and 4, r = 0.45)
Ba, Cd, Ca, Mg, S	AVHRR (channel 1, r = 0.5)
Zn	Albedo (r = 0.51)
Ba, Ca, Cu, Mg, S, Zn	NDVI (NOAA); Ba, Mg, S and Zn being meaningfully connected with NDVI at a 99% level, r = 0.5-0.6
Al, Cr, Fe, Pb	Landsat (channels 3 and 4, r = 0.45)
pollution of the humus horizon (weaker but as before statistically meaningful correlations r = 0.3)	
K, Mg	NDVI (Landsat and NOAA)
Ca, Cu, Fe, Pb	Day T, Night T, all the channels of Landsat and NOAA

Table 3*. Main suggested dependencies between in-situ and remote sensing data (sorted "forest" sampling)(r - correlation coefficient).*

5.3. Demonstration of dependence between vegetation index and Hg concentration in forest moss

As a first attempt to visualize the general distribution of healthy trees and the forests subject to the aerotechnogenic oppression of different intensity, a comparison was made of the maps of vegetation index (NOAA/AVHRR) and Hg in forest mosses. The distribution of Hg in forest mosses over the investigated territory is shown in Fig.8. Imposing of the scheme of the distribution of Hg in mosses and propagation of weakened trees (Figs. 3, 7) shows that the forests with a decreased VI are located within the zone of the Hg-marked emissions.

A comparison of data by the composition of indicative types of lichen on the pine trunks and by the pine-needles' lifetime reveals the similar-to-space-image regularity of the distribution of the areas with the weakened forests (in these zones the pine-needles' longevity is shorter and the composition of lichen is reduced from five species resistant to oxides to their total disappearance).

Similar fields of distribution have concentrations of total Zn, Pb, Fe, S and exchange forms of Zn, Mn, Cd, S in the humus horizon of soils, as well as gross amounts of Fe, Ca, Zn and S in forest mosses. The high atmospheric loading with dust and sulphur oxides, the high content of toxic heavy metals (zink, cadmium) both as exchange forms in soils and deposited on forest moss has led during several decades to thinning of the forested ares, which is seen on the space image (see Fig.6).

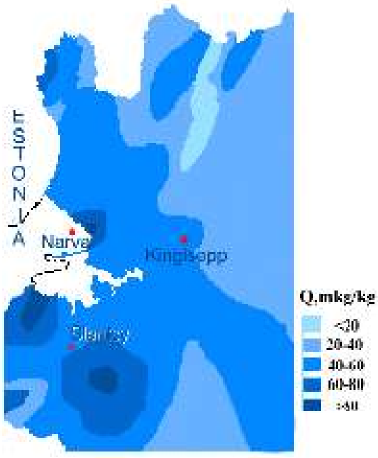


Figure 8. *The distribution of Hg in HNO_3 - extracts of forest mosses over the territory of the Kingisepp area of the Leningrad region*

6. CONCLUSION

"Ecological anomalies" in boreal forests which appear under the influence of aerotechnogenic pollution can be effectively revealed, identified and investigated making synergistic use of complex of remotely sensed observation data obtained from the space systems NOAA, Landsat and ERS with one bearing in mind both monitoring and forest inventory making issues.

The main conclusions of the study are the following:

1 Potential possibilities as well as the main approaches towards the synergistic use of different remote sensing data for the polluted areas of forest study are shown.

2. The suggested approach allows, taking standard areas as an example, to establish statistically important connections between parameters obtained from multi spectral space systems and factors that cause plant stresses. The study shows the principal possibility of identification of density and composition of air deposits from the complex of remotely sensed data. Statistical stability of links between ground-based and remotely sensed data subject to seasonal conditions. Monitoring of pine trees of boreal zone is more effective in the beginning of vegetation period.

3.. Stressed and healthy trees over the studied area are different in all investigated spectral diapasons owing to physiological changes of plants with dust and gas pollution of local biocenoses. The obtained dependencies ground the informativeness of simple spectral indices (in particular