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REMOTE SENSING MEASUREMENTS OF LEAD CONCENTRATIONS IN PLANTS

INTRODUCTION

The problem of pollution of the environment with heavy metals is getting an increasing attention in the research work. The University of Warsaw, together with the Centre for Space Research of the Polish Academy of Sciences, and the University of Farming Economy in Warsaw, carry out the studies devoted to elaboration of the remote sensing method of inquiry into the environmental pollution caused by heavy metals.

The data contained in the literature suggest that studies have been conducted in which remote sensing was undertaken of the areas polluted by heavy metals. Such attempts were made (see Coulson and Bridges, 1984) using aerial photography taken with the scanner MSS 82 (having field resolution capacity of 2–5 m), channels 4, 5, 7 of the Landsat TM satellite, as well as field studies. On the basis of the thus acquired information the authors mentioned elaborated the map of pollution on the scale of 1:3500.

The object of interest of R.A. Jago and P.J. Curran (1995) was constituted by the dependence between the environmental pollution, the chlorophyll content, and the spectral response from plants. The authors quoted took for the starting point the concentration of chlorophyll in a plant, which is a sensitive indicator of the plant condition, and the spectral responses from the range of 400–1100 nm, while the images of the terrain were obtained using CASI (Compact Airborne Spectrographic Imager) camera, and the radiation was measured with the spectral radiometer SE-590. An intermediate information, measured in the environment, was constituted by LAI (Leaf Area Index), chlorophyll content, and heavy metal content. In the opinion of the authors quoted the regularities linking all the measurements mentioned have been successfully identified.

The examples outlined above may bear the witness to the fact that remote sensing of heavy metals is possible, although it should be emphasised that in the first of the examples quoted pollution of the soil with lead ranged between 262 and 11390 ppm, and the average pollution of the surface layer of the soil amounted to approximately 3000 ppm (for comparison — the average lead content in soils in Poland is at about 20 ppm).

Among other interesting publications one should yet mention *Optical Remote Sensing of the Earth*, by A.F.H. Goetz, J.B. Wellman and W.L. Barnes (1985), where the influence of individual elements originating from the plant processes upon the spectral response obtained is presented. We can cite, for instance, that the changes in functioning of pigments can be analysed in the range between 400 and 700 nm, the structural changes in a cell are seen in the interval 700–1250 nm, and the disturbances in water economy are best visible in the range of 1250–2500 nm.

The above considerations entitle us to state that the remote sensing techniques are being used in the attempts of remote detection of heavy metals. Yet, we miss a complete description of the algorithm of proceeding, allowing for making a transition from taking the photographs or images up to drawing of a map. Thus, undertaking of own experimental studies in this domain was fully justified.

THE METHOD OF STUDY

The basis for all kind of remote sensing research is constituted by the necessity of conducting a precise analysis of the course of the spectral response curve (spectral reflection coefficient as a function of the wavelength) for the object in question, since in the particular intervals of the electromagnetic spectrum the characteristic features of the object analysed are reflected.

The analysis of the available literature did not allow for finding of the reliable information on this subject. Yet, in order to acquire the answer to the question whether remote sensing makes it possible to detect pollution of the environment with heavy metals one must demonstrate that there is a corresponding significant difference in the course of spectral reflection curves.

Two cycles of experiments were conducted for this purpose. In the first case spectral reflection of solar radiation was analysed, coming from the plants (grasses), subject to the action of lead (in total applied amount equivalent to 123 ppm), and compared with the spectral reflection from the reference plants (grown in identical conditions, but without lead).

In the second case comparison was carried out of the reflected signals of electromagnetic radiation coming from the artificial irradiation of the plants (pea) with electric bulbs. The plants had their roots removed, in order to get rid of the mechanisms protecting against the penetration of the lead ions into the leaves and stems (organs responsible for photosynthesis).

STUDY MATERIAL

The study material was constituted by the mix of grasses of the following composition: *Festuca rubra pernille*, 40%, *Festuca rubra tamara*, 20%, *Lolium perenne taya*, 10%, *Festuca ovina ridu*, 20%, *Poa pratensis balin / conni*, 10%.

In the second experiment the seeds of pea (*Pisum sativum*) were used, being an example of a dicotyledonous plant with the well known physiological reactions to heavy metals.

THE SCHEDULE OF STUDY

The first stage of the experimental work was to prepare the containers, in which soils was placed and the grass mixture sown. After the plants have grown, the initial spectrometric measurements started, meant to identify the quantitative and qualitative influence of the intensity, direction and angle of solar radiation on the spectral response obtained. The subsequent stage was to determine the optimum humidity for the plants and the soil. This is a very important problem, since humidity changes the signal registered. A big difference between the vapour contents in the air and in the soil causes intensification of water transpiration by the plants, which, in turn, entails a quicker migration of the dissolved ions of lead in the soil solution and in the plant. After having established all the above mentioned factors the solution of $\text{Pb}(\text{NO}_3)_2$ was applied and the proper spectrometric measurements started along with the taking of samples for the biometric studies and chemical analyses.

After having acquired the initial results on behaviour of grasses with regard to lead, the subsequent stage started, having the goal of gaining the spectrometric responses from the dicotyledonous plants deprived of roots and irradiated with artificial light. This consisted in growing plants, removing roots, applying lead, carrying out spectrometric measurements, taking of plant samples for the analyses, and elaboration of results.

SPECTROMETRIC MEASUREMENTS

The 24-channel spectrometer SPZ5 was used in spectrometric measurements. This device uses 23 intervals of the spectrum with narrow half-widths of the filters, amounting to $\Delta\lambda = 8\text{--}17 \mu\text{m}$, so that the maxima of the energy passing through are, respectively, at 400, 415, 418, 440, 455, 478, 499, 525, 549, 554, 568, 582, 598, 615, 638, 670, 703, 746, 784, 800, 860, 945, and 1025 nm. The analysis of these intervals indicates that the measurement is being carried out in the range visible for man (400–670 nm), and in close infrared, not registered by human eye (703–1025 nm). The optical system of the SPZ5 spectrometer is identical to the one of the spectrometer SPZ2, presented in Rataj et al. (1988).

With reference to the primary procedure of the spectrometric measurements it must be stated that when an object is irradiated with a known amount of energy ($E_{n\lambda}$) of a precisely defined wavelength, it is then possible to measure the amount of energy ($E_{0\lambda}$) reflected from the same object, in

conditions identical to the ones in which it had been irradiated. Having the two values we can calculate for the given wavelength (λ) the spectral coefficient of reflection ($W_{0\lambda}$):

$$W_{0\lambda} = E_{0\lambda} / E_{n\lambda}$$

After all data have been acquired, they are placed in the orthogonal system of coordinates "x,y", where the calculated values of $W_{0\lambda}$, the reflection coefficient, correspond to the "y" values, while the consecutive intervals of the spectrum are placed along the axis "x". By linking the points obtained we get the spectral reflection curve.

In case of vegetation there is a regularity consisting in that the maximum of reflection exists in the range of radiation corresponding to the green colour, the minimum of reflection exists in the range of radiation corresponding to the red colour, while in the infrared the plants do not absorb almost at all, and so the reflection coefficient attains the highest values out of the whole electromagnetic spectrum.

MEASUREMENTS OF PHOTOSYNTHETIC PIGMENT AND LEAD CONTENTS

In order to determine the quantities of the assimilation dyes the methodology of Lichtenthaler and Wellburn (1983) was applied. The weighted samples of grasses and pea were ground in a mortar and filtered under lowered pressure to the measurement bulb. Then, in the quantitatively probed extract of the dyes the measurement of extinction was carried out for chlorophyll and for carotenoids. All the measurements were made with reference to a blind sample (80% aqueous acetone solution).

To obtain the actual quantity of lead in the samples analysed the measurements were made with the use of chemical analysis. The samples of plants, taken for spectrometric measurements, were dried, ground and incinerated, and then dissolved in HCl, so as to have the lead washed out. After heating, the solution obtained was filtered, mixed and left for the quantitative measurement of lead. The measurement was carried out with the atomic absorptive spectrometry (ASA).

THE RESULTS OF EXPERIMENTAL STUDIES

Statistical methods were used in the analysis of the results obtained (see Guilford, 1964), with reference to the arithmetic mean (x), standard deviation (σ), coefficient of variation (V), and its modified form, denoted D . With respect to the latter — when there is no difference between the objects considered, the value of variation coefficient D is 100(%), while when there is a difference, the value of D will show the percentage to which it exists.

THE SPECTROMETRIC MEASUREMENTS OF GRASSES
BEFORE APPLICATION OF LEAD

As shown by the spectrometric measurements both samples of grasses before application of lead do not display essential differences. The values of the reflection coefficients are similar, and the coefficients of variation D fluctuate in the range of a couple of per cent. The precise results are shown in Table 1. The column denoted Grass 1 concerns the reference plants, while the results shown in the column Grass 2 regard the data obtained from the container to which lead will be added. The course of the spectral reflection curve is presented in Fig. 1.

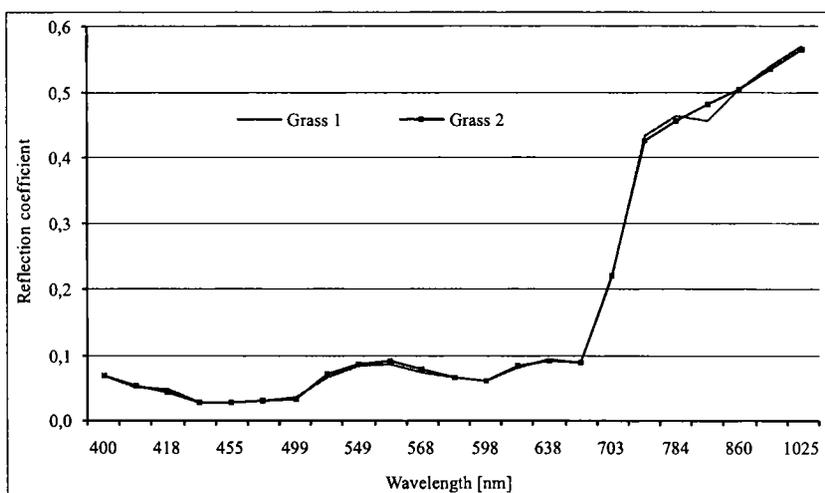


Fig. 1. Curves of spectral reflection for grasses before application of lead.

SPECTROMETRIC MEASUREMENTS OF GRASSES
AFTER APPLICATION OF LEAD

We will now present the measurement series for grasses eleven weeks after application of lead (see Table 2). The previous column of Grass 1 is now continued with the column of Grass without Pb, while the column denoted Grass with Pb contains the results of spectrometric measurements of plants polluted with lead from the container with Grass 2 of Table 1. Having analysed Tables 1 and 2 one can notice that the reference grass does not undergo any significant change during the whole experiment, the coefficients of variability oscillate around a similar level of a couple of per cent. In case, though, of the grass polluted with lead, the results indicate the changes, which are taking place in the cell structure. The graphical illustration of variability of the reflection coefficient as a function of the wavelength for the measurements considered is provided in Fig. 2.

Table 1.
Results from spectrometric measurements of grasses before application of lead

Wavelength (mm)	Grass 1 (T.1.)			Grass 2 (T.2.)			Calibrating screen		Reflection coefficient		Coefficient of variation D
	\bar{x}	σ	V [%]	\bar{x}	σ	V [%]	\bar{x}	V [%]	T.1.	T.2.	
400	6.54	4.67	71.41	6.45	4.54	70.39	94.51	17.06	0.069	0.068	101.32
415	10.18	4.25	41.77	10.26	4.20	40.91	196.36	9.00	0.052	0.052	99.18
418	8.87	4.32	48.73	8.23	4.08	49.49	187.24	5.56	0.047	0.044	107.73
440	14.81	3.88	26.22	14.90	3.83	25.73	521.67	4.80	0.028	0.029	99.35
455	17.75	3.75	21.10	17.87	4.20	23.50	617.71	4.95	0.029	0.029	99.32
478	40.85	5.25	12.86	38.99	4.17	10.68	1300.29	5.12	0.031	0.030	104.78
499	92.72	8.93	9.64	84.50	4.72	5.58	2561.24	5.26	0.036	0.033	109.72
525	254.61	23.37	9.18	280.42	17.12	6.10	3933.39	5.37	0.065	0.071	90.79
549	234.62	22.46	9.57	240.86	16.06	6.67	2790.69	5.47	0.084	0.086	97.41
554	219.01	21.99	10.04	231.83	16.09	6.94	2539.31	5.52	0.086	0.091	94.47
568	217.93	20.59	9.45	230.45	17.30	7.51	2980.83	5.55	0.073	0.077	94.57
582	193.19	18.24	9.44	193.19	14.52	7.52	2928.31	5.62	0.066	0.066	100.00
598	163.44	15.76	9.64	163.44	15.39	9.42	2692.64	5.69	0.061	0.061	100.00
615	750.82	73.22	9.75	769.42	21.75	2.83	9298.64	5.76	0.081	0.083	97.58
638	648.87	65.47	10.09	633.22	20.62	3.26	6888.81	5.81	0.094	0.092	102.47
670	440.63	44.27	10.05	437.37	17.29	3.95	4978.85	5.86	0.089	0.088	100.75
703	415.14	43.50	10.48	416.28	15.15	3.64	1895.94	5.81	0.219	0.220	99.73
746	3600.94	363.72	10.10	3547.18	57.10	1.61	8318.86	5.68	0.433	0.426	101.52
784	4772.60	489.01	10.25	4689.78	77.12	1.64	10310.99	5.72	0.463	0.455	101.77
800	9077.89	925.79	10.20	9566.61	194.77	2.04	19866.35	5.78	0.457	0.482	94.89
860	4773.68	495.05	10.37	4776.73	70.05	1.47	9477.39	5.78	0.504	0.504	99.94
945	807.97	85.34	10.56	801.37	22.98	2.87	1501.11	6.02	0.538	0.534	100.82
1025	3206.66	339.53	10.59	3168.68	161.10	5.08	5622.43	5.95	0.570	0.564	101.20

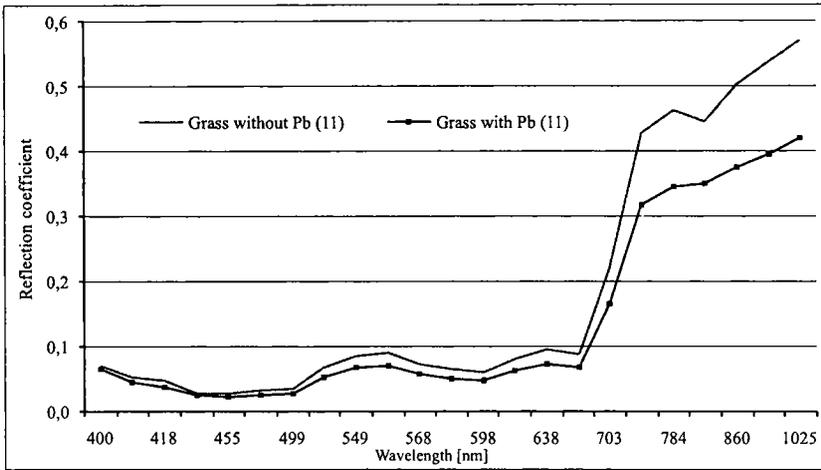


Fig. 2. Curves of spectral reflection for grasses after lead application.

SPECTROMETRIC MEASUREMENTS OF PEA BEFORE APPLICATION OF LEAD

The results obtained from the spectrometric measurements of grasses provided just an outline for the possibility of using remote sensing in the study of plant pollution caused by heavy metals. That is why it became purposeful to present the results obtained from the research conducted on the dicotyledonous plants (pea), with their roots removed, the latter being the organs protecting against the heavy metals. The experiment was carried out in the laboratory, with artificial light, differing from the solar light in terms of both quality and quantity, since the signal reaching the detector is in this case weak. The electric bulbs applied irradiated the plants with the intensity of about 20 W/m^2 , while the surface of the Earth is irradiated with tens of times more of energy.

When analysing Table 3, showing the data concerning the spectrometric measurements of pea before application of lead, we see that the differences between the coefficients (of variability — V and D , and reflection) are well pronounced, though without distinct change trends. The shape of the curves of the spectral reflection for pea before application of lead are shown in Fig. 3. The shape of these curves is quite surprising for plants, since in normal conditions high peaks in the bands of 415 and 455 nm are not registered, and the maximum should be noted within the 550 nm band, while the minimum — for the red light — at about 670 nm. In spite of these "irregularities" one can expect reliable assessment of the influence exerted by lead on plants, because in the studies, considered here, comparison is made of the results for the healthy plants and the polluted ones, obtained in the same conditions.

Table 2.

Results of spectrometric measurements for grasses eleven weeks after application of lead

Wavelength [nm]	Grass without Pb (11) (T. k.)			Grass with Pb (11) (T. z Pb.)			Calibrating screen		Reflection coefficient		Coefficient of variation <i>D</i>
	\bar{x}	σ	V [%]	\bar{x}	σ	V [%]	\bar{x}	V [%]	T. k.	T. z Pb.	
400	6.57	3.67	55.83	6.21	4.18	67.36	94.51	17.06	0.069	0.066	105.29
415	10.16	3.25	31.99	9.08	4.53	49.89	196.36	9.00	0.052	0.046	112.05
418	8.89	3.32	37.39	6.96	3.68	52.87	187.24	5.56	0.047	0.037	127.43
440	15.06	2.88	19.14	12.92	4.32	33.45	521.67	4.80	0.028	0.025	114.61
455	17.35	2.75	15.83	14.36	4.31	30.03	617.71	4.95	0.029	0.023	123.58
478	41.85	4.25	10.16	33.63	4.78	14.22	1300.29	5.12	0.031	0.026	121.46
499	86.93	7.93	9.13	68.58	5.19	7.57	2561.24	5.26	0.034	0.027	127.72
525	258.95	22.37	8.64	203.87	11.69	5.73	3933.39	5.37	0.067	0.052	128.74
549	238.20	21.46	9.01	186.19	10.86	5.83	2790.69	5.47	0.086	0.067	129.01
554	232.09	20.99	9.04	176.20	10.97	6.23	2539.31	5.52	0.090	0.069	129.45
568	221.59	19.59	8.84	168.42	10.22	6.07	2980.83	5.55	0.073	0.057	129.39
582	191.85	17.24	8.98	148.26	9.02	6.08	2928.31	5.62	0.066	0.051	130.30
598	163.52	14.76	9.02	125.72	8.11	6.45	2692.64	5.69	0.061	0.047	130.00
615	748.24	72.22	9.65	570.74	32.70	5.73	9298.64	5.76	0.081	0.061	131.55
638	651.70	64.47	9.89	494.63	29.96	6.06	6888.81	5.81	0.094	0.072	131.18
670	441.30	43.27	9.81	335.16	20.29	6.05	4978.85	5.86	0.089	0.067	131.47
703	411.91	42.50	10.32	312.12	19.68	6.31	1895.94	5.81	0.219	0.165	133.01
746	3498.92	362.72	10.37	2641.26	161.84	6.13	8318.86	5.68	0.426	0.318	134.30
784	4777.78	488.01	10.21	3563.79	220.94	6.20	10310.99	5.72	0.463	0.346	133.92
800	8839.98	924.79	10.46	6930.19	433.78	6.26	19866.35	5.78	0.445	0.349	127.52
860	4774.07	494.05	10.35	3561.69	224.80	6.31	9477.39	5.78	0.504	0.376	134.03
945	806.02	84.34	10.46	594.20	39.99	6.73	1501.11	6.02	0.538	0.396	135.98
1025	3199.97	338.53	10.58	2360.83	153.30	6.49	5622.43	5.95	0.570	0.420	135.83

Table 3. Results of spectrometric measurements for pea before application of lead

Wavelength [μ]	Reference pea (G.k.)			Pea before Pb (G.p.Pb.)			Calibrating screen			Reflection coefficient		Coefficient of variation D
	\bar{x}	σ	V [%]	\bar{x}	σ	V [%]	\bar{x}	σ	V [%]	G.k.	G.p.Pb	
400	2.46	2.92	118.73	2.50	5.04	134.28	10.65	2.85	26.78	0.231	0.235	98.14
415	3.85	3.39	88.22	3.80	2.67	89.09	8.00	2.42	30.20	0.481	0.475	101.18
418	2.70	2.05	75.95	2.64	5.62	136.18	7.45	2.72	36.55	0.363	0.354	102.89
440	2.54	2.69	105.69	3.75	6.39	170.30	42.30	3.13	7.39	0.060	0.089	67.78
455	2.80	2.72	96.93	3.03	5.47	168.33	8.00	2.73	34.06	0.350	0.379	92.44
478	2.67	2.78	104.13	2.35	3.23	172.08	33.80	3.90	11.54	0.079	0.070	113.44
499	2.79	3.24	116.40	2.39	3.09	164.85	71.10	4.06	5.71	0.039	0.034	116.52
525	6.92	4.32	62.50	7.25	5.85	80.68	86.35	4.10	4.75	0.080	0.084	95.40
549	59.83	5.45	9.11	56.79	8.03	15.47	716.70	11.37	1.59	0.083	0.079	105.36
554	21.11	3.78	17.91	18.75	5.80	30.93	270.10	4.87	1.80	0.078	0.069	112.59
568	9.20	4.88	53.10	7.00	5.04	72.04	161.70	4.08	2.52	0.057	0.043	131.39
582	20.29	4.15	20.47	18.08	6.12	39.78	367.65	8.10	2.20	0.055	0.049	112.22
598	16.50	5.33	32.32	15.93	7.79	59.36	319.40	7.35	2.30	0.052	0.050	103.59
615	163.08	5.41	3.32	166.04	8.86	6.14	3391.65	78.24	2.31	0.048	0.049	98.22
638	58.63	5.85	9.98	65.11	7.93	14.58	516.50	9.73	1.88	0.114	0.126	90.05
670	28.33	3.81	13.44	27.25	5.28	19.39	187.60	4.88	2.60	0.151	0.145	103.98
703	27.25	5.13	18.81	24.63	8.80	35.73	142.25	4.44	3.12	0.192	0.173	110.66
746	100.21	3.97	3.96	98.25	9.79	9.97	239.30	5.66	2.37	0.419	0.411	101.99
784	138.54	7.06	5.10	138.00	9.17	6.64	332.15	6.85	2.06	0.417	0.415	100.39
800	439.08	10.67	2.43	453.75	16.32	3.60	1158.20	18.46	1.59	0.379	0.392	96.77
860	193.96	8.27	4.26	192.38	8.99	4.67	460.55	7.01	1.52	0.421	0.418	100.82
945	145.42	4.17	2.87	143.88	7.62	5.30	365.75	5.74	1.57	0.398	0.393	101.07
1025	236.67	9.77	4.13	224.13	15.34	6.84	591.35	9.43	1.59	0.400	0.379	105.60

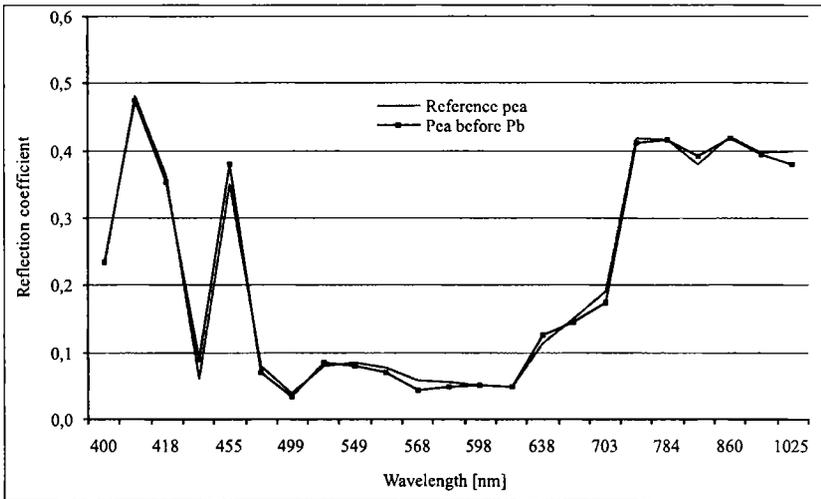


Fig. 3. Curves of spectral reflection for pea before application of lead

SPECTROMETRIC MEASUREMENTS OF PEA AFTER APPLICATION OF LEAD

Observation of the results obtained allows to confirm the very high diversity of the data gathered, and yet all the values of reflection coefficients for pea subject to the action of lead are lower than the reflection coefficients of the reference plants. The differences amount to between a couple and a dozen per cent (see the last column of Table 4, and Fig. 4). Similarly as in the previous measurements, short wavelength bands are characterised by a larger dispersion of results. Still, the coefficient of variation D allows to differentiate between the healthy plants (Reference pea) and the ones polluted with lead (Pea after application of Pb). The spectral responses from the channels above 600 nm indicate quite a good possibility of discriminating between the two samples analysed (the average square error from the coefficients of variation is lower than the coefficient of variation D).

In case of spectrometric measurements of pea an interesting shape of the curves of spectral reflection was obtained (Fig. 4), insofar as the curves in question are in the majority of instances almost parallel, which constitutes a confirmation of the trends observed in the spectrometric measurements of grasses.

MEASUREMENTS OF CONTENTS OF PHOTOSYNTHETIC PIGMENTS AND LEAD

As mentioned before, in parallel with the spectral measurements the samples were taken for determination of contents of the photosynthetic dyes and lead in the leaf tissues. Table 5 presents the contents of pigments,

Table 4.
Results of spectrometric measurements for pea after application of lead

Wavelength [nm]	Reference pea (G.k.)			Pea after application of Pb (G.pp Pb)			Reflection coefficient		Coefficient of variation <i>D</i> G.k./G.pp.Pb [%]
	\bar{x}	σ	<i>V</i> [%]	\bar{x}	σ	<i>V</i> [%]	G.k.	G.pp.Pb	
400	2.93	2.22	75.86	3.07	1.50	48.88	0.275	0.288	95.54
415	4.13	3.00	72.68	3.32	1.15	34.51	0.516	0.415	124.40
418	2.85	2.01	70.66	2.53	1.54	61.05	0.382	0.339	112.85
440	3.60	2.08	57.78	2.58	3.23	124.99	0.085	0.061	139.41
455	3.58	3.50	97.77	3.05	2.63	86.42	0.448	0.381	117.57
478	3.61	1.71	47.27	3.26	1.54	47.27	0.107	0.096	110.79
499	5.99	1.41	23.63	4.83	2.69	55.67	0.084	0.068	124.06
525	12.06	5.56	46.09	10.90	2.00	18.35	0.140	0.126	110.67
549	95.57	4.16	4.36	83.25	4.86	5.84	0.133	0.116	114.80
554	38.90	2.94	7.57	33.10	4.86	14.68	0.144	0.123	117.53
568	18.64	2.83	15.17	15.58	6.39	41.04	0.115	0.096	119.69
582	34.38	1.41	4.11	27.20	1.89	6.94	0.094	0.074	126.38
598	27.92	1.89	6.78	22.53	2.61	11.56	0.087	0.071	123.92
615	274.72	10.11	3.68	222.78	10.02	4.50	0.081	0.066	123.32
638	104.07	4.57	4.39	89.35	8.80	9.85	0.201	0.173	116.47
670	49.25	6.14	12.46	43.65	2.21	5.07	0.263	0.233	112.83
703	46.22	4.20	9.09	40.75	4.29	10.53	0.325	0.286	113.43
746	187.99	6.40	3.40	167.80	5.66	3.37	0.786	0.701	112.03
784	261.25	6.29	2.41	233.20	8.29	3.56	0.787	0.702	112.03
800	815.88	24.39	2.99	723.18	19.55	2.70	0.704	0.624	112.82
860	348.71	11.12	3.19	312.10	9.54	3.06	0.757	0.678	111.73
945	252.81	6.58	2.60	227.50	2.79	1.22	0.691	0.622	111.12
1025	421.64	11.30	2.68	380.63	13.64	3.58	0.713	0.644	110.78

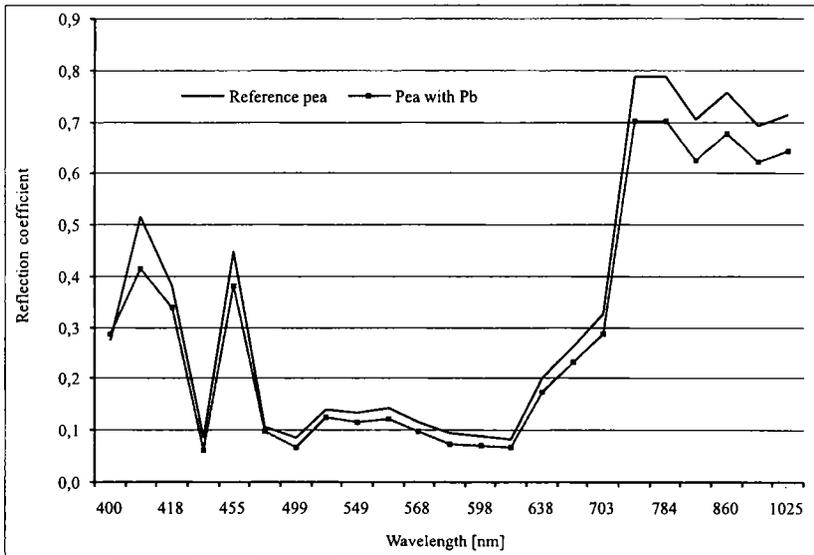


Fig. 4. Curves of spectral reflection for pea after application of lead.

expressed in units of green mass (g.m.) and dry mass (d.m.), for chlorophyll a and b, and carotenoids, along with the indicators for chlorophyll a+b, chlorophyll a/b, and the sum of chlorophylls/carotenoids. The last row is devoted to the contents of lead, measured by ASA. The regularity, which is confirmed in the analyses conducted, is that the action of lead appears first of all through the decreased amount of the chlorophyll a. A similar situation is observed for the pea samples considered.

In Table 5 there is an interesting last row, in which the results concerning lead content in the tissues of plants analysed are presented. In case of reference plants the content of the metal is low, amounting 3.25 ppm, while in the sample of grasses subject to the action of lead the contents of this element was at 48.37 ppm in d.m. The pea roots removed absorbed 484.12 ppm of Pb in d.m.

CONCLUSIONS

Both the survey of existing literature and own studies (Zagajewski, 1998) confirmed the possibility of using remote sensing in the analysis of pollution of plants with heavy metals. Yet, actual application will require conducting further research, leading to identification of definite spectral bands, whose combination will allow to adequately represent pollution. The analyses carried out in infrared, and the literature available, indicate that the longer wave ranges (beyond 700 nm) are in particular promising. The remote sensing (spectrometric) measurements, which play a superior role in the re-

Table 5.

Contents of photosynthetic pigments and lead in the samples analysed

	Grass without Pb		Grass with Pb		Pea without Pb		Pea with Pb	
	mg/g g.m.	mg/g d.m.	mg/g g.m.	mg/g d.m.	mg/g g.m.	mg/g d.m.	mg/g g.m.	mg/g d.m.
Chlorophyll a	2.05	0.47	1.57	0.51	0.99	0.11	0.84	0.13
Chlorophyll b	0.79	0.20	0.68	0.19	0.44	0.05	0.43	0.07
Chlorophyll a+b	2.84	0.67	2.25	0.70	1.43	0.16	1.27	0.20
Chlorophyll a/b	2.59	2.35	2.31	2.68	2.25	2.20	1.95	1.86
Carotenoids	0.38	0.09	0.35	0.10	0.20	0.02	0.20	0.03
Chlorophyll a+b/Carotenoids	7.47	7.44	6.43	7.00	7.15	8.00	6.35	6.67
Pb content [ppm] in d.m.	3.25		48.37		3.25		484.12	

search, without connection to the problems related to plant physiology, would not provide an adequately broad perspective on the observations resulting from the spectrometric data themselves.

At the end of this concrete stage of research work one should state that:

- the remote sensing technique allowed to differentiate between the polluted and unpolluted plants,
- the differences mentioned ranged between a couple and a dozen per cent,
- the results obtained for all the objects considered (including the screen) feature quite an important dispersion in the bands of shorter waves (below 500 nm),
- the longer wave ranges (above 500 nm) differentiated better the plants analysed,
- the biggest differences between the healthy and the polluted plants were observed in the wavelength interval of 700–1025 nm,
- the accompanying analyses (measurements of lead and photosynthetically active pigment content) confirmed the results obtained with the spectrometer SPZ5,
- further studies should yet be carried out for the still narrower spectral bands, corresponding to the processes of photosynthesis.

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