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The research of air pollution based on spectral features in leaf surface of *Ficus microcarpa* in Guangzhou, China

Jie Wang · Ruisong Xu · Yueliang Ma · Li Miao · Rui Cai · Yu Chen

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Abstract Nowadays development of industry and traffic are the main contributor to city air pollution in the city of GuangZhou, China. Conventional methods for investigating atmosphere potentially harmful element pollution based on sampling and chemical analysis are time and labor consuming and relatively expensive. Reflectance spectroscopy within the visible-near-infrared region of vegetation in city has been widely used to predict atmosphere constituents due to its rapidity, convenience and accuracy. The objective of this study was to examine the possibility of using leaves reflectance spectra of vegetation as a rapid method to simultaneously assess pollutant (S, Cd, Cu, Hg, Pb, XCl, XF) in the atmosphere of the Guangzhou area. This article has studied the spectral features of polluted leaf surface of *Ficus microcarpa* in 1985 and 1998. According to the analysis, comprehensive assessment for the change of atmospheric condition and degrees of pollution were given. This conclusion was confirmed by the monitored data got from chemical analysis. Future study with real remote sensing data and field measurements were strongly recommended.

Keywords *Ficus microcarpa* · Spectral feature · Remote sensing · Air pollution · Guangzhou

J. Wang (✉) · R. Xu (✉) · Y. Ma · L. Miao · R. Cai · Y. Chen
Guangzhou Institute of Geochemistry,
Chinese Academy of Sciences,
P. O. Box 1131, Guangzhou GD 510640,
People's Republic of China
e-mail: wangjie1022@163.com
e-mail: xurs@gig.ac.cn

R. Xu · Y. Ma · R. Cai
CAS Key Laboratory of Marginal Sea Geology,
Chinese Academy of Sciences,
Guangzhou 510640, People's Republic of China

Y. Ma
Institute of South China Sea,
Chinese Academy of Sciences,
Guangzhou 510640, People's Republic of China

J. Wang · L. Miao · Y. Chen
Graduate School of Chinese Academy of Sciences,
Beijing 100039, People's Republic of China

Introduction

In the last three decades, remote sensing techniques have been extensively applied in the field of environment monitoring. Detection of particulate air pollution by remote sensing has well developed methodology, many applications and extensive literature (Sifakis and Deschamps 1992). From 1978 to 2000, a group of scientists like Andres, Collins, Goetz, Rock and so on successfully established a biogeochemical remote sensing model for environment and natural resources research. Collins' study showed that the red edge slop is related with the mount of chlorophyll in some kinds of leaves (Collins 1983). Goetz and Rock (1983) pointed out that the spectral feature in the visible band is good for detecting the chlorophyll content in vegetation, while the spectral feature in the near infrared band is good for detecting the texture of leaves, and the spectral feature in the infrared band is suitable for detecting water, nitrogen, lignin, phosphorous, protein, amino acids, sugar, starch, and cellulose in some species of leaves. Rock (1986a) and Rock et al. 1988 studied rapid forest decline due to various forms of air pollution based on analysis the spectral responses in high-damage sites and low-damage sites, he found that both current year and older foliage from high-damage sites showed an approximately 5 nm shift away from the normal inflection point of the red edge reflectance feature toward shorter wavelengths (a blue shift). The study of Susan and Brian (1990) indicated that the reflectance spectra of three conifer species showed clear changes in response to simulated ambient ozone exposures in open top chambers after one growing season. Pablo et al. (2000a, b), Gomez et al. (2001), Hasager and Nielsen (2001) and Raymond (2001) detected photosynthetic algal pigments in the natural populations by using high-resolution spectroradiometer, and studied the chlorophyll fluorescence effect on the apparent reflectance of vegetation, and investigated the physical basis for the spectroscopic estimates of the nitrogen concentration in leaves. Mutanga et al. (2003) pointed out that analysis of the shape, depth and slopes of the major absorption feature in the visible band can estimate nitrogen and ultimately map rangeland quality at canopy scale. Leaf Area Index (LAI) was proposed by Kalacsk et al. (2004) for investigating a tropical moist forest. Xu (2002) and Xu and Ma (2004) proposed a biogeochemical remote sensing model for exploration of environment and natural resources. Current techniques for the determination of pollutants in the atmosphere generally involve collecting samples at a particular site and analyzing the collected samples either in real time or more frequently at a later time in the laboratory. Remote sensing holds the potential of carrying out continuous analyses at a wide range of locations.

Findings from previous work have shown that the visible and near-infrared bands are very suitable for the applications considered vegetations polluted (Price et al. 1992). The study in a previous project based on Landsat TM data and field work showed a total environmental deterioration, caused by air pollution (Tommervik et al. 1992). This article presents the results from a project focusing on studying and analyzing the spectral reflectance features in the leaf surface of *Ficus microcarpa* which exposed to the air pollutants, and using Landsat TM data of 1985 and 1998 in the study of air pollution in GuangZhou city. The objectives of this study were to detect the polluted vegetation changes from some spectral feature. Similar studies using some indices of TM data in the detection of air pollution have been carried out in the study area. The further objective was to assess the feasibility of using remote sensing technology to detect the air pollution by comparing the analysis of remote sensing data with field chemical analysis.

Study area and data processing

Study area

The study was conducted in the city of GuangZhou, China. The intensive development of industry and road traffic and the increasing number of automobiles in the city lead to a notable increase of air pollution. Government statistics (from Environmental Quality Report of Guangzhou City) showed, in 1985, the average total suspension particle was amount to 0.275 mg/m^3 per day and the average dust laying was 12.79 $tons/km^2$ per month in the city. In 1998, the average total suspension particle was amount to 0.311 mg/m^3 per day and the average dust laying was 13.313 $tons/km^2$ per month. It is suggested that the air pollution is an important problem which should be resolved. First of all, effective technology of monitoring air pollution is needed.

Data collection and biochemical assay

Field investigations were carried out and systematic samplings were completed from the adult tree leaves of *Ficus microcarpa* which grew everywhere aiming for a botanical and environmental ecological study in Guangzhou city in 1985 and 1998. The study area, together with the sample locations and numbers were given in Fig. 1. Experimental analyses of the composition and pigments in the leaves as well as measurements of spectral reflectance on the leaf surfaces were performed for the samples.

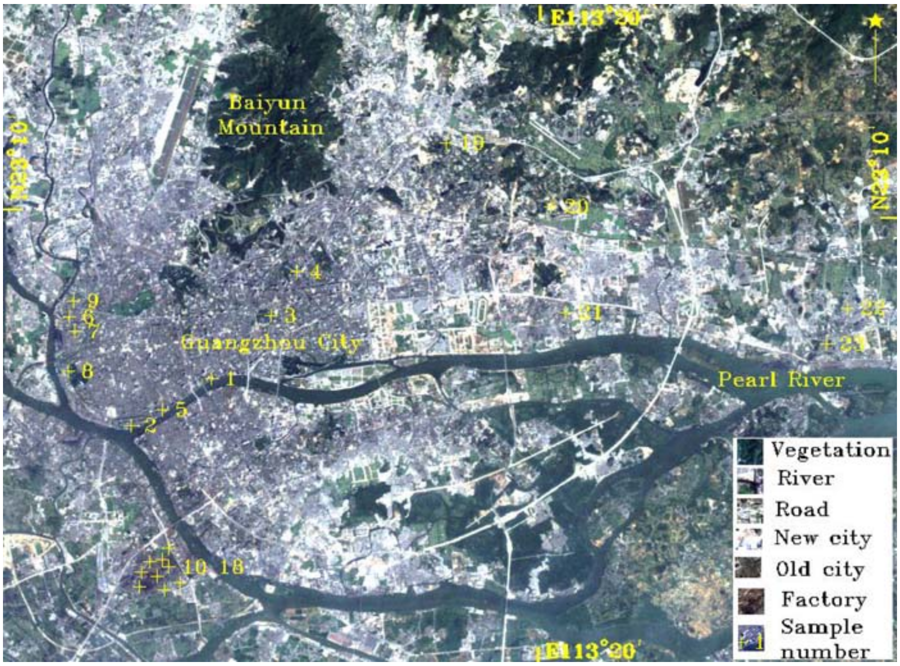

Fig. 1 The study area, sample point and number. Nature color image of LandsatTM of Guangzhou city, China, in Jan. 1998

The fresh leaves were firstly cleaned with clear water, and then pigments of the leaves were analyzed by ultraviolet spectrophotometer (Jeffrey and Humphrey 1975). Part of the fresh leaf samples were dried, grinded and melted with acid for other conventional analysis. The contents of Cu, Pb, Zn, Cd, Cr, etc. in the leaves were analyzed by atomic absorption spectrophotometry (Cornejo et al. 1995) with the detection limit of 10^{-11} g (Hitachi, 170-70 model, Japan), the Hg content was analyzed by cold atomic fluorescence spectrometry (Ebdon et al. 1981) with the detection limit of 10^{-12} g, the S content was analyzed by combustion and coulometric titration (Kevin and Edward 1990) method with the detection limit of 10^{-9} g, the XF (fluorine compound) content was measured by ion selective electrode (Chang-Yi 1982) method with the detection limit of 10^{-10} g, the XCl (chlorine compound) content were measured by argentometric titration (John 1969) with the detection limit of 10^{-9} g. Some of the results are listed in Tables 1 and 2.

Spectral reflectance measurement

Leaf samples in the same location and same time as above were collected from the adult tree species of *Ficus microcarpa* for spectral reflectance measurements in January 1985 and 1998. In this research spectral reflectance measurements were performed in laboratory. The leaf reflectance was measured by using a spectrometer GER 2600 (Geophysical Environmental Research, USA). The GER 2600 has a nominal spectral range from 350 to 2,500 with approximately 1.5 nm nominal band width from 350 to 1,050 nm and 11.5 nm nominal band width from 1,050 to 2,500 nm. A white panel (Spectralon, Labsphere, North Sutton, NH, USA) was used as a 100% reflectance standard for all measurements. A linear interpolation routine was used to estimate values at 1 nm intervals prior to calculation of indices from both instruments. Spectral reflectance was firstly measured on fresh leaves surfaces which were polluted by suspension particles in air, then, the polluted leaves were lightly scraped with dry cotton, and spectral reflectance was again measured on leaves cleaned in this way. In addition, some spectral reflectance of leaves were also measured which were in non-polluted areas for contrasting analysis to make the anomaly features of polluted leaves outstand. Measurements were made on three intact leaves which were laid horizontally, parallel to each other and slightly overlapping. The reflectance of five leaves for each leaf type were acquired and then

Table 1 Chemical composition and chlorophyll content of *Ficus Microcarpa* leaves in Guangzhou city, China (1985.1)

Sample no	Cu (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Zn (mg/kg)	Hg (mg/kg)	S (mg/kg)	XCl (mg/kg)	XF (mg/kg)	Chlorophyll a (%)	Chlorophyll b (%)
1	13.88		0.021	1.210	21.60	0.140	3.900	2.210	69.50	0.066	0.035
2	4.990	0.096	0.013	0.870	14.73	0.070	3.400	1.280	73.50	0.089	0.072
3	2.520		0.010	0.610	17.01	0.030	2.000	0.990	27.00	0.081	0.062
4	5.950	0.048	0.013	0.810	17.22	0.160	2.400	0.071	45.00	0.078	0.063
5	4.560		0.022	2.410	24.13	0.010	3.500	0.460	102.5	0.081	0.064
6	5.140	0.190	0.011	0.970	19.69	0.130	2.800	2.020	145.0	0.078	0.028
7	3.560	0.160	0.013	2.360	21.22	0.310	10.60	0.880	207.5		
8	3.840	0.030	0.008	2.430	17.84	0.020	6.600	0.430	112.0		
9	4.620	0.140	0.004	1.540	14.85	0.110	2.100	0.106	57.50		
10	2.530	0.300	0.012	0.720	16.35	0.070	3.800	0.520	103.0	0.088	0.069
11	2.990	0.530	0.031	1.650	21.17	0.070	4.500	1.770	120.0	0.069	0.053
12	3.200	0.290	0.017	49.73	22.01	0.020	3.700	0.710	80.00	0.098	0.076
13	5.820	0.012	0.009	66.60	21.58	0.100	4.500	2.090	208.0	0.072	0.057
14	4.420	0.230	0.010	1.170	19.46	0.120	3.900	0.028	117.5	0.111	0.087
15	3.320	0.110	0.016	0.880	18.68	0.240	4.300	0.140	72.00	0.082	0.065
16	2.750		0.014	0.810	21.15	0.40	2.900	0.710	268.0	0.079	0.065
17	3.250		0.028	1.140	17.27	0.020	4.700	0.180	85.70	0.072	0.057
18	2.880	0.150	0.021	1.200	43.92	0.050	3.400	0.106	81.50	0.044	0.039
Abundance	14.00	27.00	0.050	0.230	100.0	0.010	3.400				
BCF											
min	0.180	0.001	0.800	2.650	0.150	1.000	0.590				
max	0.990	0.020	6.200	290.0	0.440	40.00	3.110				

All sample location is in Fig. 1.
XCl Chlorine compound; *XF* fluorine compound; *abundance* element abundance value of vegetation; from Brooks (1983); *BCF* bioaccumulation factors

Table 2 Chemical composition and chlorophyll content of *Ficus Microcarpa* leaves in Guangzhou city, China (1998.1)

Sample no.	Cu (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Chlorophyll a (%)	Chlorophyll b (%)
1	10.00	33.10	0.080	5.300	0.053	0.017
2	8.900	11.90	0.080	2.300	0.098	0.036
4	8.100	17.00	0.170	5.600	0.085	0.031
5	8.400	18.20	0.070	2.900	0.075	0.027
6	9.700	10.60	0.080	5.700	0.078	0.027
13	11.70	39.70	0.850	66.80	0.059	0.021
14	11.50	43.40	0.770	8.000	0.073	0.027
19	8.100	10.60	0.050	1.600	0.062	0.225
20	10.10	1.400	0.080	1.900	0.014	0.049
21	9.300	19.30	0.120	3.600	0.072	0.252
22	12.70	31.10	0.290	4.400	0.070	0.026
23	7.800	13.40	0.120	1.500	0.070	0.025
Abundance	14.00	27.00	0.050	0.230		
BCF						
Min	0.560	0.050	1.000	6.520		
Max	0.910	1.610	17.00	290.0		

All sample location is in Fig. 1.
XCl Chlorine compound; *XF* fluorine compound; *abundance* element abundance value of vegetation; from Brooks (1983); *BCF* bioaccumulation factors

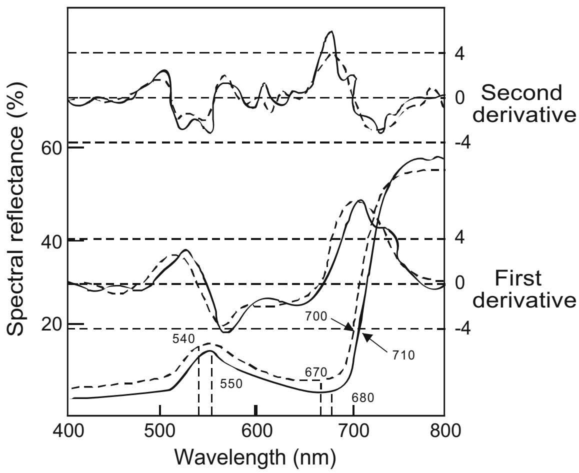

Fig. 2 The curves of spectral reflectance, first and second derivative of polluted area (*dashed line*) and non-polluted area (*solid line*) on the clean leaf surface of *Ficus Microcarpa* in Guangzhou city, China (1985.1)

averaged with calibration. Some of the results are shown in Figs. 2, 3, 4 and 5.

Analysis of spectral features

Analysis of spectral reflectance

Leaf reflectance at visible wavelengths increased and leaf reflectance at infrared wavelengths decreased as concentrations of the heavy metals Cd, Cu, Pb, or Zn increased in plants (Horler et al. 1980). So in order to detect the polluted plants, the minimum and maximum reflectance and other feature of leaf reflectance at visible and infrared bands should be paid more attention. In this research, the minimum spectral

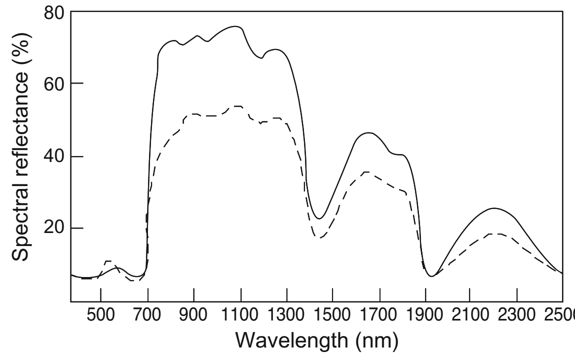

Fig. 4 The curves of spectral reflectance of dirty leaf surface (*dashed line*) and the clean leaf surface (*solid line*) in polluted area of *Ficus Microcarpa* in Guangzhou city, China (1998.1)

reflectance in the blue (expressed as "B") and red (expressed as "R") bands, the maximum spectral reflectance in the green (expressed as "G") band for the leaf surface of *Ficus microcarpa* from the study area were extracted. Subsequently, the average spectral reflectance (expressed as "V") from the band 400 nm to 700 nm were calculated, as well as the average spectral reflectance in the band of 700–1,100 nm (expressed as "IR") and the average values of the steep slop from band 690 to 750 nm.

Most of the studies to detect plant stress used one or two ratio-based vegetation indices (VI), such as the simple ratio SR($SR=R_{TM4}/R_{TM3}$, Pearson and Miller 1972) or the normalized difference vegetation index NDVI ($NDVI=(R_{TM4}-R_{TM3})/(R_{TM4}+R_{TM3})$, Rouse et al. 1974), computed from broadband remote sensing data like Landsat TM (Curran et al. 1992; Herwitz et al. 1990; Peterson et al. 1987; Spanner et al. 1990a, b). In order to fulfill this task, Landsat TM data collected in January 1985 and 1998 were selected in accord with

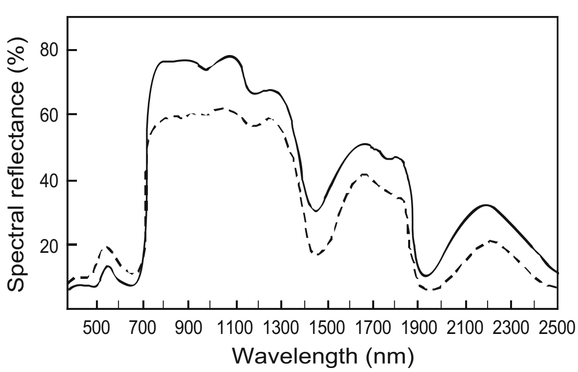

Fig. 3 The curves of spectral reflectance of polluted area (*dashed line*) and non-polluted area(*solid line*) on the clean leaf surface of *Ficus Microcarpa* in Guangzhou city, China (1998.1)

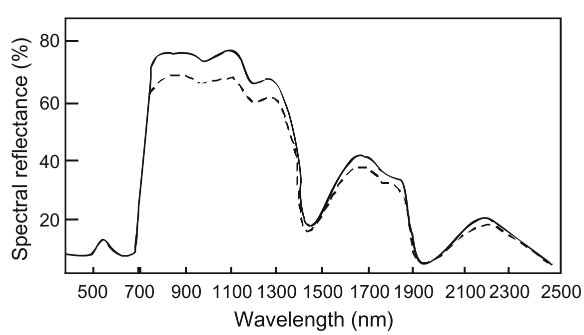

Fig. 5 The curves of spectral reflectance of dirty leaf surface (*dashed line*) and the clean leaf surface (*solid line*) in non-polluted area of *Ficus Microcarpa* in Guangzhou city, China (1998.1)

Table 3 Spectral reflectance feature on the leaves surface of *Ficus Microcarpa* in Guangzhou city, China (clean leaf, 1985.1)

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
B (%)	6.40	7.40	7.60	6.90	7.00	8.00	8.80	7.40	7.10	7.40	7.30	7.50	7.50	7.40	7.20	7.30	7.60	7.40
G (%)	15.1	14.4	12.5	14.1	12.8	14.8	15.9	15.9	11.4	13.1	11.7	13.4	13.1	11.3	14.2	13.2	12.0	16.0
R (%)	6.20	7.10	7.30	6.60	6.80	8.40	8.40	7.30	6.80	7.20	7.20	7.30	7.20	7.00	7.20	7.10	7.00	7.20
S	7.25	7.24	7.29	7.65	6.96	4.68	6.33	6.09	6.41	6.15	5.59	6.56	6.10	5.91	5.51	6.68	7.11	6.65
V (%)	8.76	9.27	8.56	8.73	8.50	10.2	10.6	9.85	8.12	8.85	8.37	8.98	8.91	8.27	7.94	8.92	8.53	9.53
NDVI	1.13	1.12	1.12	1.13	1.12	1.07	1.10	1.11	1.12	1.11	1.10	1.14	1.11	1.11	1.10	1.12	1.13	1.11

All sample location is in Fig. 1,
B minimum reflectance in the blue band; *G* maximum reflectance in the green band; *R* minimum reflectance in the red band; *S* the value of red-edge slop of spectral reflectance in the band of 690–750 nm; *V* average value of the spectral reflectance from 400 to 700 nm; *NDVI* the normalized difference vegetation index.

the date of spectral reflectance measurement. The spectral reflectance was then integrated over the Landsat TM band (TM1, TM2, TM3, TM4, TM5, TM7), and the NDVI and SR values were calculated to determine the plant stress (Tables 3 and 4). The TM_4 band is sensible to the poison extent of polluted vegetables in near infrared band. So the difference($\Delta TM_4 = TM_{4c} - TM_{4d}$) of the spectral reflectance integral values over the TM_4 band of leaf surfaces between non-polluted area (TM_{4c}) and polluted area (TM_{4d}) was derived (Fig. 6).

Analysis of spectral wave shapes

Remote sensing has previously been used to detect stress in plants before visible symptoms have been

Table 4 Spectral reflectance feature on the leaves surface of *Ficus Microcarpa* in Guangzhou city, China (the clean and dirty leaves, 1998.1)

Sample no.		1	2	4	5	6	13	14	19	20	21	22	23
B (%)	Clean	9.00	6.10	6.20	7.30	6.50	6.10	6.10	6.00	6.10	6.00	6.40	5.90
	Dirty	6.60	8.10	5.90	7.90	7.00	6.40	6.00	6.50	6.90	6.60	7.70	6.30
G (%)	Clean	18.7	9.20	11.9	14.2	14.8	11.9	13.0	12.3	8.90	11.9	13.5	12.2
	Dirty	13.7	1.23	10.4	12.6	13.3	11.6	11.5	12.1	9.40	9.40	13.0	12.1
R (%)	Clean	8.40	5.40	5.60	6.60	5.70	5.50	5.50	5.30	5.60	5.30	5.90	5.40
	Dirty	6.60	8.20	5.40	8.80	6.40	6.70	6.10	5.80	6.80	6.70	7.50	5.80
V (%)	Clean	11.4	6.54	7.26	8.72	8.31	7.21	7.44	7.23	6.56	7.07	7.89	7.19
	Dirty	8.80	9.25	6.90	9.43	8.56	7.87	7.48	7.75	7.50	7.37	9.09	7.74
IR(%)	Clean	59.0	73.7	65.7	66.5	68.5	63.8	67.2	74.4	56.4	70.7	68.7	70.6
	Dirty	38.4	50.0	50.0	45.9	52.8	47.3	51.5	64.1	47.3	46.3	51.5	56.2
TM1	Clean	9.86	6.19	6.50	7.65	6.97	6.42	6.42	6.42	6.23	6.24	6.91	6.36
TM2	Clean	16.5	7.90	9.80	12.0	12.4	9.86	10.7	10.0	7.85	9.81	11.1	10.0
TM3	Clean	9.83	5.56	5.85	7.11	6.49	5.80	5.87	5.62	5.78	5.56	6.28	5.65
TM4	Clean	58.7	76.1	67.4	66.0	69.6	64.9	67.8	76.6	57.2	71.1	70.0	72.3
TM5	Clean	38.7	70.0	39.8	48.0	38.6	36.3	38.0	38.2	35.3	42.8	39.1	37.1
TM7	Clean	19.7	15.3	19.5	27.5	17.9	16.0	17.9	17.4	16.2	21.6	18.4	17.2
NDVI	Clean	1.10	1.17	1.16	1.14	1.15	1.16	1.16	1.17	1.15	1.16	1.16	1.16
SR	Clean	5.97	13.7	11.5	9.29	10.7	11.2	11.6	13.6	9.90	12.8	11.1	12.8

All sample location is in Fig. 1.
Dirty Spectral reflectance was measured on fresh leaves surfaces which were polluted by suspension particles; *clean* spectral reflectance was measured on leaves surfaces which were lightly scraped with dry cotton; *B* minimum reflectance in the blue band; *G* maximum reflectance in the green band; *R* minimum reflectance in the red band; *V* average value of the spectral reflectance from 400 to 700 nm; *NDVI* the normalized difference vegetation index; *IR* average reflectance value at 700–1,100 nm; *TM1–7* integral value of the spectral reflectance of Landsat TM1–7; *NDVI* the normalized difference vegetation index; SR- simple ratio of vegetation indices (TM4/TM3).

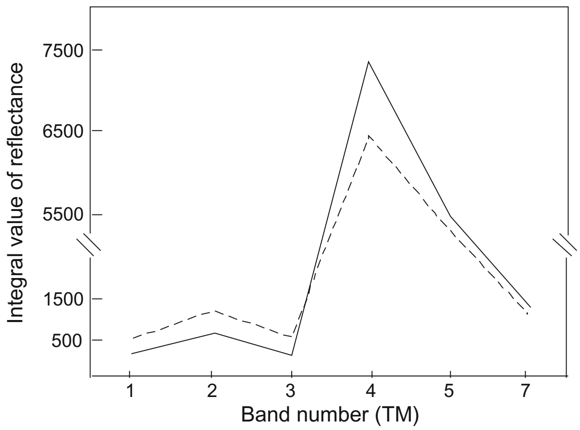

Fig. 6 The integral value of the spectral reflectance with the TM4 band of polluted area (*dashed line*) and non-polluted area (*solid line*) on the leaf surface of *Ficus Microcarpa* in Guangzhou city, China (1998.1)

observed. The region of the red-edge has also been used as a means of identifying stress. This is the area where there is a sharp change in reflectance between wavelengths 690 and 750 nm. Derivative analysis of this region shows a peak that can be used to describe changes due to stress. This peak which makes the inflection point of the reflectance spectrum in the red-edge region is defined as the absolute maximum of the first derivative in the range 690–750 nm (Horler et al. 1983; Miller et al. 1990). Rock et al. (1988) detected a shift in red edge, towards the blue, of approximately 5 nm when measuring severe foliage stress on spruce trees due to air pollution.

In this paper, both first and second derivative of the reflectance spectrum were performed for the leaf surfaces of *Ficus microcarpa* collected from the study area. Here the first derivative analysis is been used as means to estimate changes of the spectral red-edge slop and the value of red-edge slope of spectral reflectance in the band of 690–750 nm (expressed as "S" in Table 3) will be thus derived for correlation analysis. The second derivative analysis was intended for locating the wavelength positions of both the maximum and the minimum spectral reflectance values in every band (Josep et al. 1993) (Tables 3 and 4, Figs. 2 and 7).

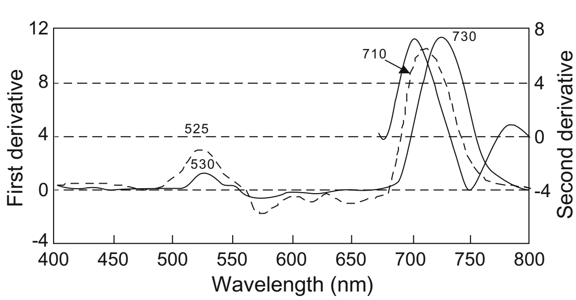

Fig. 7 The first and the second derivative of the spectral reflectance of polluted area (*dashed line*) and non-polluted area (*solid line*) on the clean leaf surface of *Ficus Microcarpa* in Guangzhou city, China (calculated data is from Fig. 3, 1998.1)

Correlation and stepwise regression analysis

Correlation analysis was carried out among the SR and NDVI values, the Cu, Pb, Zn, Cd, Hg, S, XCl, XF contents, the chlorophyll contents (as listed in Tables 1, 2, 3 and 4) in the same sample, and the results were shown in Tables 5 and 6. Furthermore, Stepwise regression analysis was performed between the difference (ΔTM_4) in TM_4 band reflectance integral values and the atmospheric dust laying in the study area.

Fuzzy cluster analysis

In order to practically apply the spectral features of leaf surfaces to monitor and detect the atmospheric pollution in city areas, Q-type fuzzy cluster analysis based on the spectral data as listed in Tables 3 and 4 was performed. The results yielded from our study reveal that the degree of air pollution in the study area could be roughly divided into five categories, i.e., non-pollution, slight pollution, moderate pollution, heavy pollution and very heavy pollution, and the rate of reliability of these analytical results was found to be above 85% when compared to the data derived from field investigation in the study area.

Conclusions

Reflectance features

As shown from Figs. 2, 3, 4 and 5, Tables 3 and 4, the spectral reflectance for the polluted leaf surface is 3–5.5% higher than that for the non-polluted leaf surface in the visible band, while it is 10–15% lower than the latter in the near infrared band. Both of the SR and NDVI values for the polluted leaf surface are 5–10% lower than that for the non-polluted leaf surface of *Ficus microcarpa*. In the polluted area, the spectral reflectance after visible bands on a

Table 5 Correlation coefficient of the spectral reflectance feature with biochemical components on the clean leaf of *Ficus Microcarpa* in Guangzhou city, China (1985.1)

Coefficient	Cu	Pb	Cd	Cr	Zn	Hg	S	XCl	XF	Chlorophyll a	Chlorophyll b
B (%)	−0.524	0.043	−0.176	0.081	0.009	0.207	0.617	0.036	0.439	0.169	0.030
G (%)	0.235	−0.471	−0.083	−0.082	0.393	0.194	0.436	0.149	0.104	−0.528	−0.591
R (%)	−0.462	0.094	−0.201	0.046	0.044	0.221	0.492	0.182	0.436	0.082	−0.218
S	0.244	−0.340	0.125	−0.079	−0.009	−0.136	−0.186	−0.222	−0.355	−0.119	0.197
V (%)	−0.025	−0.220	−0.190	0.011	0.237	0.157	0.562	0.273	0.407	−0.286	−0.552
NDVI	0.408	−0.526	0.147	0.200	−0.079	−0.218	−0.736	−0.297	−0.346	0.109	0.418

Analysis data is from Tables 1 and 3; each symbol is as same as Tables 1 and 3.

polluted leaf surface is 15–25% lower than that on the same leaf surface cleaned with dry cotton. However in the non-polluted area, such kind of difference turns out to be remarkably reduced, about 1–10%, (Table 4 and Figs. 4 and 5). The minimum reflectance values in both blue and red bands for the leaf surface in polluted area are lower than those in non-polluted area, while the maximum spectral reflectance in the green band in polluted area is higher than that in non-polluted area (Tables 3 and 4).

Spectral wave shape features

An analysis about the spectral wave shapes (Table 3, Figs. 2 and 7) demonstrates that the position of the red edge for the polluted leaf shifts about 5–20 nm to shorter wavelengths when compared to that for the non-polluted leaf, and the red edge steep slope for the polluted leaf is 10–20% higher than that for non-polluted leaf.

Mechanism of the spectral features

Air pollution in study area is mainly due to transportation, industry and other human activity. The air pollutants include large amounts of toxic elements such as Cu, Pb, Zn, Cd, Cr, Hg, S and their compounds. These pollutants will take part in the physiological circulation of plants through their respiration or enter into the biogeochemical circulation of plants through the absorbing effects via their root systems in soils and underground waters. Among the pollutants, the toxicity of Cu, Pb, Cd, and Hg are strong for plants, while the toxicity of Zn, Cr, and XF are weaker. When the contents of the toxic elements, including their compounds, are higher than their abundances in the vegetation (Tables 1 and 2), these elements will restraint the absorption of nutrient substance and consequently affect the physiological functions of the plants, which will definitely result in the difference of spectral features between polluted vegetation and non-polluted vegetation.

The spectral feature of leaf surface of *Ficus microcarpa* in study area was mainly determined by the difference in the plant's biogeochemical feature, which was predominantly effected by toxic elements and compounds. For example, the spectral reflectance of leaves in the visible band was highly correlated with the contents of toxic elements Cu, S and chlorophyll. The correlations between the NDVI

Table 6 Correlation coefficient of the spectral reflectance feature with biochemical components on the clean leaf of *Ficus Microcarpa* in Guangzhou city, China (1998.1)

Coefficient	B	G	R	V	IR	TM1	TM2	TM3	TM4	TM5	TM7	NDVI	SR
Cu	0.044	0.126	0.080	0.089	−0.321	0.061	0.123	0.090	−0.324	−0.257	−0.257	−0.063	−0.246
Pb	0.269	0.449	0.290	0.355	−0.138	0.300	0.416	0.296	−0.178	−0.211	0.045	−0.516	−0.271
Cd	−0.232	−0.049	−0.206	−0.163	−0.131	−0.214	−0.089	−0.200	−0.129	−0.267	−0.263	0.207	0.060
Cr	0.193	0.421	0.184	0.300	−0.256	0.212	0.393	0.234	−0.280	−0.208	−0.252	0.084	−0.033
Chlorophyll a	−0.327	−0.683	−0.305	−0.502	−0.332	−0.407	−0.610	−0.352	−0.276	−0.261	−0.238	0.329	0.429
Chlorophyll b	−0.391	−0.728	−0.367	−0.560	−0.262	−0.467	−0.662	−0.417	−0.203	−0.263	−0.251	0.317	0.459

Analysis data is from Tables 2 and 4; each symbol is as same as Tables 2 and 4.

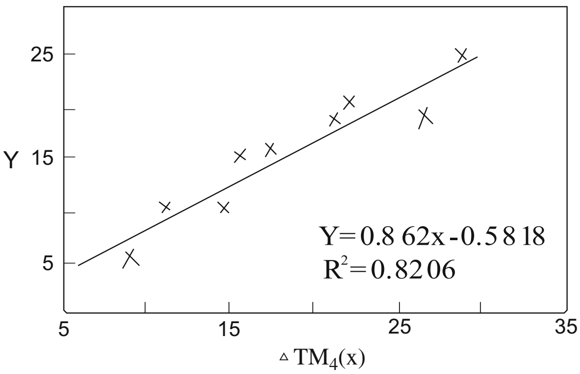

Fig. 8 The correlation analysis figure of difference value [$\Delta TM_4(x)$] with the dust laying amount (Y) in Guangzhou city, China (1998.1)

values and contents of Pb, S are strong, the NDVI and SR values are positively correlated with the chlorophyll content of the leaves collected from study area (Tables 5 and 6). In addition, there is a strong negative correlation between the integration value of TM2 band and the chlorophyll content in the leaves.

The bioaccumulation factors (BCF) were calculated, which was defined as the ratio between the element content of the leaf and the element abundance value of this vegetation (Brooks 1983). The BCF for Cu, Pb, Zn in the *Ficus microcarpa* leaves were less than 1, but those for Cr, Hg, Cd and S were greater than 1, and could be as high as 290 times (Table 1), which demonstrated that the spectral effects of Cd, Cr, Hg, and S were more remarkable than those of Cu, Pb, and Zn in the polluted *Ficus microcarpa* leaves in study area.

Indicating air pollution degree of city using spectral feature of leaf

As shown in Tables 3 and 4, it was unreasonable to determine the air pollution degree in a city area simply by a single spectral feature of a leaf surface. Nevertheless, a systematic analysis based on all significant spectral features for a leaf surface was feasible in this aspect. In order to detect the degree of air pollution in Guangzhou city, the authors performed a fuzzy cluster analysis about the data listed in Tables 3 and 4, and the results demonstrated that the degree of air pollution in Guangzhou city could be classified into five categories, namely, no-pollution (sample number 22 and 23), slight pollution (sample number 6, 16 and 17), moderate pollution (sample number 1, 7, 8, 9, 13 and 19), heavy pollution (sample number 3, 4, 5, 10, 20 and 21), and very heavy pollution (sample number 2, 11, 12, 14, 15 and 18), and the rate of reliability was proved to be above 85% when the analysis results were compared to the field-measured values for air pollution in study area (Table 6).

Model for prediction of air dust laying with ΔTM_4

Our research also indicated that the integral values for the spectral features in the TM_1, TM_2 and TM_3 bands

Table 7 Division of polluted degree based on ΔTM4 feature and dust laying value in Guangzhou city, China

Symbol		Very heavy pollution area	Heavy pollution area	Moderate pollution area	Slight pollution area	Non-pollution area
Dust laying (T/km^2 per month)	Mean value of 1985	25.00	16.80	14.90	10.60	7.000
	Mean value of 1998	25.38	19.10	15.21	11.51	8.230
	Winter of 1985 (mean value)	0.340	0.240	0.240	0.180	0.040
Total suspension particle, amount (mg/m3)	over standard value(%)	75.00	25.00	12.50	0.000	0.000
	day mean value of 1985	0.330	0.250	0.280	0.190	0.070
	over standard value (%)	56.30	31.30	31.30	6.300	0.000
ΔTM4	1985.1	2,199	1,842	1,637	1,404	79.00
	1998.1	2,593	2,503	1,694	1,487	104.6
Sample No.		2,11,12,14,15,18	3,4,5,10,20,21	1,7,8,9,13,19	6,16,17	22,23
Reliable rate (%)		100.0	100.0	100.0	85.00	86.00

ΔTM4 Difference value with TM4 of the clean leaf minus TM4 of natural dirty leaf; the data of dust laying and total suspension particle amount is from Environmental Quality Report in Guangzhou city(1985,1998), Environment Monitor Center of Guangzhou city, China, 1985,1998.; the sample no. is as same as Table 1.

respectively for the polluted vegetation are higher than those for the non-polluted vegetation, while a reverse situation occurs for the TM_4, TM_5 and TM_7 bands. Furthermore, the difference of the integral values for the spectral features in the TM_4 band between the polluted and the non-polluted vegetation was greater than in any other bands. A model describing the relationship between the spectral integral difference for the TM_4 band [ΔTM_4 (x)] and the amount of air dust laying in study area (Y, tons/km^2.m) was given as follows:

$$Y = 0.8620 * x - 0.5818, \quad R^2 = 0.8206$$

And the equation clearly showed that ΔTM_4 is positively correlated with the mount of atmospheric dust laying in study area (Table 7, Fig. 8).

Difference in biogeochemical effect of *Ficus microcarpa* between 1985 and 1998

Our study results also demonstrated that the spectral features of polluted leaf surface of *Ficus microcarpa* in study area in 1998 were more remarkable than in 1985. As shown in Tables 1, 2 and 7, the contents of Cu, Pb, Cd, Cr, Hg, etc. in the leaves of *Ficus microcarpa* in study area in 1998 were higher than in 1985, and the ΔTM_4 values in 1998 were higher than that in 1985. However, the chlorophyll content of leaves in 1998 was lower than in 1985, while the amount of air dust laying in 1998 was more than in 1985 (Table 7). Consequently, not only the analytical results of the spectral features, but also the field test data for air pollution in Guangzhou city, suggested that the air pollution is getting more and more severe in Guangzhou city, China.

Discussion

Vegetation is of very distinct spectral reflection feature, which is associated with physiological characteristic of itself. Physiological and ecologic characteristics of vegetation will be changed when polluted by air pollution, while the changes directly influence the spectral reflectance feature. Subsequently, the spectral feature such as maximal reflectance, absorption peak, red edge position and so on changes as well. All the variation of spectral features is very useful to study the abnormal reaction of plants and extract available environmental information. In this paper, the spectral features based on the plant *Ficus microcarpa* are analyzed and relative models are established by means of correlation and stepwise regression analysis and fuzzy cluster analysis. On the basis of the analysis, comprehensive assessments of the atmospheric condition change and pollution degree are given which are identical with monitored data in field. It represents that it is practicable that remote sensing technique is applied to extract the atmospheric pollution information, the thinking and method is of guiding significance for further atmospheric environment assessment. Further more, traditional method for monitoring air pollution represents point observations they do not capture the pollution over large areas and satellite data can now be used in areas where ground measurements are not available. If there is transport of pollutant from one region to another region, then surface measurements cannot capture the synoptic nature of these events and it is difficult to identify the source of pollutants. Since satellite measurements are routinely available on a global basis, the transportation of pollutants can be examined.

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