colonized the reproductive parts and caused sooty mould of flowers after 18 days of spraying (Figure 1f and h). Due to infection premature dropping of flower buds was also noticed. In the natural environment, pathogen colonized the reproductive parts and caused sooty mould of flowers after 18 days of spraying. During infection process A. pullulans produced blastospores, conidia and chlamydospores. The secondary spread of disease was through wind-borne conidia/blastospores.

Further, impact of A. pullulans infection on seed viability was studied by seed germination test. Infection resulted in production of sterile and malformed seeds (Table 4; Figure 1f-h). Thus A. pullulans as a floral pathogen inhibited floral development, embryo development, seed filling and rendered the seeds sterile. It was noticed that all its morphological stages were infective. As the pathogen produces chlamydospores, it may be an added advantage to carry over the pathogen to the next season and to formulate it at commercial scale. Spraying of A. pullulans has no deleterious effects on other plant species which share the common ecological niche, as was confirmed by host safety test. However, a detailed study on its ecology needs further attention. In view of copious seed production, wind dispersal nature and invasive capacity of eupatorium weed even in hilly areas and plains, exploitation of A. pullulans as a floral pathogen appears to be a hopeful potential mycoherbicide of eupatorium, as it causes sterile and malformed seeds, and thereby checks the weed seed production and its spread to virgin lands. Research is in progress to develop formulation of A. pullulans as a mycoherbicide for large-scale field application.

7. Tute, J., Plant Pathological Methods, Fungi and Bacteria, Minneapolis, USA, 1961, p. 239.

Received 2 January 2004; revised accepted 27 August 2004

S. K. PRAHSHANTI*
SRIKANT KULKARNI

Department of Plant Pathology,
University of Agricultural Sciences,
Dharwad 580 005, India
*For correspondence,
e-mail: prasamhi@rediffmail.com

Coal-fire detection and monitoring in Raniganj coalfield, India – A remote sensing approach

Raniganj coalfield, West Bengal is the largest coalfield in India, belonging to the Gondwana Super Group1. Asansol, situated about 210 km NW of Kolkata (Figure 1), is the main town in this coalfield. Mining in this region dates back to the British period. Initially coal mining was confined to open cast mines only, but gradually it was extended to the underground also. Coal-fire in Raniganj coalfield is either because of fire infection from adjacent fire-affected coal seams or anthropogenic activities or spontaneous combustion of coal. Oxidation of coal is an exothermic process and if the heat generated is allowed to accumulate, then the accumulated temperature ignites the coal. This natural process is called spontaneous combustion and is one of the major causes of coal fire in Raniganj coalfield. Thus India is losing good quality coal prior to its exploitation. Hence, there is need for detection and monitoring of coal fires in coalfields in order to control them effectively.

Remote sensing technique in thermal band offers a cost-effective and time-saving technology for mapping various geoenvironmental features like coal fires, forest fires, oil-well fires, volcanic eruptions, etc.2. These features are identified in band-6 (10.4–12.5 µm) as high-temperature anomalous areas3 because hot bodies on the surface of the earth mostly emit radiation in this band. Landsat-5 Thematic Mapper (TM) daytime digital data were used for this study. Night-time data were not considered for this study because ground control points, which are required for registration of the satellite image to the base map, are difficult to identify. The limitation of daytime data is that thermal anomalies represent partial underground coal fires with partial solar heating of non-burning coal seams and black shale with higher emissivity4. Winter-season data were selected for this study as the anomaly between fire and non-fire zones will be conspicuous. Topographic factors like aspect, slope angle and morphology of the area have a strong relation with reflectance and radiant temperature of an object5. Raniganj coalfield has a subdued topo-
Figure 2. Coal-fire map of Raniganj coalfield.

The information content of an area in band-6 of the satellite data is in the form of DN's. Conversion of these DN's to at-satellite temperatures is important for coal-fire mapping. This is done using Planck's radiation equation for black body for the bandwidth 10.4–12.5 μm.

\[
L_\lambda = \frac{12.5}{10.4} \left( \frac{2\pi h c^2}{\lambda^5} \right) \left( \frac{1}{e^{hc\lambda T} - 1} \right) d\lambda
\]

where \( L_\lambda \) is the total spectral radiance in band-6 (W/m²/μm/Sr), \( \lambda \) the wavelength (μm), \( T \) the temperature (K), \( h \) the Planck constant (6.63 × 10⁻³⁴ J s), \( c \) the speed of light (3.0 × 10⁸ m/s), and \( k \) the Boltzmann constant (1.38 × 10⁻²³ J/K).

The inverse Planck equation will be:

\[
T = \left( \frac{C_2}{C_1 \ln((1/e 1)^{1/(\pi L_\lambda \lambda^5)})+1} \right)
\]

where \( C_1 = 3.742 \times 10^{-16} \) Wm²/μm², \( C_2 = 0.0144 \) mK, and \( \varepsilon \) is the spectral emissivity.

Equation (2) to calculate the temperature can be simplified as:

\[
T = \frac{14400}{\lambda \ln \left( \frac{3.742 \times 10^7}{8 \pi k \lambda^5 L_6} + 1 \right)}
\]

where \( T \) is the radiant temperature in K (at-satellite), \( \lambda \) the average wavelength of band-6 (11.45 μm), \( L_6 \) the spectral radiance in band-6 (mW/cm²/μm/Sr).

\[
L_6 = 0.005632 \times DN + 0.1238
\]

where DN is the digital number of the pixel for which calculation is being made. Using the above equations, radiant temperature was calculated for the terrain.

The temperature calculated from the satellite data depicts the radiant temperature of surface bodies. The heat generated by the underground coal fire is transmitted to the surface through the joints, fractures, faults and rock pores of the strata of Raniganj coalfield and is finally emitted to the atmosphere. Hence there exists a direct correlation between the underground coal fire and its surface manifestations.

The ambient temperature on 19 January 2001 was around 18°C. The land cover is mostly sandy soil and barren sandstone having high thermal capacity. The temperature was estimated using eq. (3) and then divided into four classes (Table 1) for preparation of coal-fire map using pseudo-colour encoding technique (also known as density slicing). Using trial and error technique during density slicing, DN values corresponding to background temperature of 30°C were considered as cut-off between fire and non-fire areas. The coal-fire map (Figure 2) gives an overview of
Ground-truth survey was carried out to verify the thermal anomalies, measure the temperature of fire and distinguish the anomaly between coal fire and domestic/industrial fire. A handheld infrared thermometer was used for the purpose.

The disparity between temperature observed on the surface and that measured from the satellite is because of the dimension of the fire zone and atmospheric absorptions.

In band-6, the highest DN value is 182 and the lowest is 115. Taking a contour interval of 10 DN, an isothermal map was prepared for the Ramnagar open cast colliery (Figure 4).

The present study demonstrates the application of remote sensing for coal-fire detection and monitoring, and also gives the status of the fire-affected areas in the Raniganj coalfield. Both coal-fire map

### Table 2. Major thermally anomalous zones in Raniganj coalfield

<table>
<thead>
<tr>
<th>Location</th>
<th>Longitude/latitude</th>
<th>Temperature (°C)</th>
<th>Fire zone dimension (in m × m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramnagar</td>
<td>86°50′40.6″E, 23°45′26.6″N</td>
<td>42.7</td>
<td>300 × 300</td>
<td>Anomaly due to coal fire in the open cast coal mine</td>
</tr>
<tr>
<td></td>
<td>86°50′22.8″E, 23°45′21.5″N</td>
<td>34.1</td>
<td>80 × 80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>86°50′44.1″E, 23°45′18.3″N</td>
<td>34.1</td>
<td>110 × 110</td>
<td></td>
</tr>
<tr>
<td>Khayerbandh</td>
<td>86°55′23.1″E, 23°47′08.9″N</td>
<td>31.2</td>
<td>20 × 20</td>
<td>Anomaly due to coal fire in open cast mine</td>
</tr>
<tr>
<td></td>
<td>86°55′56.0″E, 23°47′15.0″N</td>
<td>31.2</td>
<td>40 × 40</td>
<td></td>
</tr>
<tr>
<td>Bumpur</td>
<td>86°56′23.0″E, 23°40′25.0″N</td>
<td>38.1</td>
<td>–</td>
<td>Anomaly due to chimney of IISCO steel plant</td>
</tr>
<tr>
<td></td>
<td>86°56′30.0″E, 23°40′36.0″N</td>
<td>31.2</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>86°56′28.8″E, 23°41′01.3″N</td>
<td>31.2</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Jaykaynagar</td>
<td>87°04′06.3″E, 23°39′17.4″N</td>
<td>31.2</td>
<td>–</td>
<td>Anomaly due to BALCO plant and adjacent mine boiler and chimney</td>
</tr>
<tr>
<td>Jamuria</td>
<td>87°11′10.0″E, 23°59′54.0″N</td>
<td>31.0</td>
<td>5 × 5</td>
<td>Anomaly due to coal fire in open cast mine</td>
</tr>
<tr>
<td></td>
<td>87°11′26.0″E, 23°58′02.0″N</td>
<td>31.0</td>
<td>10 × 10</td>
<td></td>
</tr>
<tr>
<td>Pandaveswar</td>
<td>87°04′27.0″E, 23°42′40.0″N</td>
<td>31.0</td>
<td>–</td>
<td>Not checked</td>
</tr>
<tr>
<td>Dhadka</td>
<td>86°59′40.1″E, 23°42′01.4″E</td>
<td>25.7</td>
<td>3 × 4</td>
<td>Anomaly due to methane gas burning</td>
</tr>
<tr>
<td>Dakshinkhanda</td>
<td>87°14′01.6″E, 23°37′22.7″N</td>
<td>25.7</td>
<td>3 × 4</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Coal-fire map of Ramnagar open cast colliery and its surroundings.

The fire-affected areas in Raniganj coalfield, some of the major coal-fire affected/high thermal anomalous regions of Raniganj coalfield are mentioned in Table 2. Figure 3 gives in detail the coal-fire status of Ramnagar open cast colliery.

The present study demonstrates the application of remote sensing for coal-fire detection and monitoring, and also gives the status of the fire-affected areas in the Raniganj coalfield. Both coal-fire map
and isothermal map give an overview of the fire-affected areas in Raniganj coalfield. Surface thermal anomalies are linked to the subsurface fire during field survey (Table 2). At-satellite temperature calculated may not match or correspond to the surface temperature, as conditions in the field vary from place to place and sometimes the fire zone dimensions are very small. However, this can be effectively and reliably used to demarcate the thermal anomalies and take precaution to prevent the fire from spreading further to adjacent areas. With the availability of Landsat-7 ETM+ data with a spatial resolution of 60 m in band-6, detection and monitoring of coal fires can be carried out more precisely. At present, Raniganj coalfield is not severely affected by fire unlike other coalfields, but we will gradually be losing larger amount of coal if precautions are not taken now.


ACKNOWLEDGEMENTS. We thank the Director, NRSA, Hyderabad for infrastructural facility and the Indian Oil Corporation Ltd, Mourigram, for funding the project.

Received 27 October 2003; revised accepted 21 October 2004

TAPAS RANJAN MARTHA*  
A. BHATTACHARYYA  
K. VINOD KUMAR

Geosciences Group,  
National Remote Sensing Agency,  
Hyderabad 500 037, India  
*For correspondence.  
e-mail: tapas_martha@nrsa.gov.in