COAL FIRES IN NORTHERN CHINA AND OPERATIONALIZATION OF '4S' TECHNIQUES

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ABSTRACT

Sustainable development of society, resource exploitation and economic development require a balance between reasonable utilisation of available resources and the environment for human beings. China has the richest coal resources in the world. However, these are seriously endangered by coal fires, which cause deleterious effects on the environment. In recent years, there has been an increasing concern about coal fires, all around the world. Research on the detection of coal fires has been carried out in Xinjiang and Ningxia Autonomous Regions of Northwest China. This has shown the significant possibilities of remote sensing for dynamic monitoring. As a fire-fighting program is put into operation, an operational system for data management and auxiliary decision-making for the fire fighters is urgently required. Remote sensing, global positioning system, geographical information system and expert systems (called the '4S' in Chinese as each of these four technologies start with the same character in Chinese) are the data collection and management techniques those can be used for fire fighting. This paper discusses the present situation of the coal fires and the primary reasons for the fire development in Northwest China. The basic requirements of the end-user for fire fighting are analysed with regards to hazard reduction such as putting out the fires, environmental rehabilitation and the administration in relation to the reduction activities. In order to provide a decision-supported information management system for the fire-fighting program, the professional expertise in relation to 3D monitoring and visualisation, methods of reasonable assessments and effective information management should be well assembled, with GIS support, as an operational support system. Additionally, sufficient administrative support is also needed for the successful operation of fire fighting.

1. INTRODUCTION

With resource exploitation for meeting the ever increasing demand for energy in recent years, the spontaneous combustion of coal seam and induced fire (shortly **coal fire**) represent a severe problem, in many countries such as China, India and Indonesia. Coal fires frequently occur where primitive mining techniques are still being used. These fires not only have caused environmental degradation and pollution locally, but also make a potential contribution to global problems like the emission of 'greenhouse' gases, as they burn away the non-renewable coal resources.

Remote sensing techniques and geophysical methods have been used for the detection of coal fires, e.g. in USA, Germany, Australia, China, India and Indonesia from 1960's. Airborne or space-borne thermal IR methods have been used and reported by several authors, e.g. Moxham and Greene (USA, 1967, 1968), Ellyett (Australia, 1974), Guan and Genderen (1996), Mukherjee et al. (India, 1991) and Prakash et al (1997) for detection of surface and underground coal fire. Another geophysical method (Zhang[1] X.S., 1976 and Zhang J.M., 1998) has been applied to delineate the boundary of coal fires. These results show that coal fire is detectable by RS and geophysical methods. Information about the surface distribution of the coal fire could be used for further assessment of the environmental impacts. Integration of temporal images can demonstrate the dynamic development of coal fires.

Dynamic monitoring and management of coal fires involves, beside detection, risk analysis and prevention before coal fires occur, fire fighting and management when it happens, monitoring and controls after it is distinguished. However, the information provided by RS images are not sufficient to fulfil the practical requirements of fire fighting and continuous monitoring of the fire development. An estimate of the fire parameter and a visualised 3D reconstruction of the underground situation of the coal fire is needed for the fire fighter, no matter what method is used. Because the visualised 3D data is favourable to 3D description and management of coal fire, a reasonable assessments on environmental impacts can be given based on 3D analysis.

Fire-fighting in Xinjiang (Guan and Genderen, 1998) and Ningxia regions have been emphasised under the financial support of the Chinese and Dutch governments and the EEC in recent years, due to the environmental impacts following the enlargements of coal fires. The ongoing study concerned

[1] Geophysical research on the cola fire detection in Xinjiang Region, China, 1976.

the Rujigou coalfields, in Ningxia Regions of China (Zhang J.M., 1998), a typical case of an area with such a problem and favourable to study on 3D detection. An integrated application of '4S' techniques, Remote Sensing (RS), Geographic Information System (GIS), Global Positioning System (GPS) and Expert System (ES) have been used for the information support of the coal fire fighting program.

2. COAL FIRES IN NORTHERN CHINA AND CO_2 CONTRIBUTION TO THE ENVIRONMENT

China is the largest coal producer, consumer and exporter in the world. In 1996, 75% of energy consumption of China was from coal. It has played a very import role in the energy industry. Due to a special natural circumstance and human-induced reasons, spontaneous combustion of coal seam and induced fires have apparently caused an enormous output of un-measurable CO_2 and poisonous gases, contributing to - among others -the 'greenhouse' effects. Statistic result (Guan, 1996) show that up to 10-20 millions tons of coal per year is being destroyed by coal fire. The contribution of $CO_{2\ to}$ the global atmosphere has increased approximately by 2-3% of the total output of the world.

2.1 Distribution of Coal Fire in North China

Coal fires are distributed mainly in the dry and semi-dry regions of northern China (see Fig.1) and stretch 5000 km along the east-west direction and 750 km in the north -south direction, where 90% of coal resource are concentrated. Graphically, it is located between E 74°-135°and N35°-45°. Coal fire occurs in coal-containing rocks formation of the Jurassic and Tertiary systems. They are divided into 23 sub-regions, according to their geographical locations, such as Tabei, Yili, and Tuha area in Xinjiang Region, Rujigou area in Ningxia Region, Yaojie area in Gansu prov., and Daqingshan area in Inner-Mongolia Region, involving more than 80 coalfields in north China. Coal fires include surface fires and underground coal fires, burning downward and upward respectively. The investigations in Xinjiang Region show that coal fires develop between tens to hundreds of meters horizontally and tens of meters in depth from the surface. It was found that the maximum depth is 400 and 330 meters, in ancient and modern coal fire area, respectively.

2.2 Features of Coal Fire

Coal fire is a special phenomenon, which occurs under certain circumstances. Adequate air supply, a heat source and the coal being susceptible to burning are the essential elements. The availability of these factors defines the occurrence of spontaneous combustion of the coal seams and subsequent burning.

In general, coal undergoes self-oxidation at ambient temperature, with a production of heat. If the heat produced is not dissipated, the temperature of the coal mass inside will increase and the rate of oxidation will be accelerated. Under favourable conditions of heat accumulation, this process continues until the coal ignites (known as the ***spontaneous combustion***). The burning starts after those four stages such as the oxidation, self-heating, heat-concentration and temperature increase so as to reach the critical temperature. As the coal burning starts, it develops in the directions where the three basic components (air, heat and coal) are available. Extended fires are frequently referred to as fire areas.

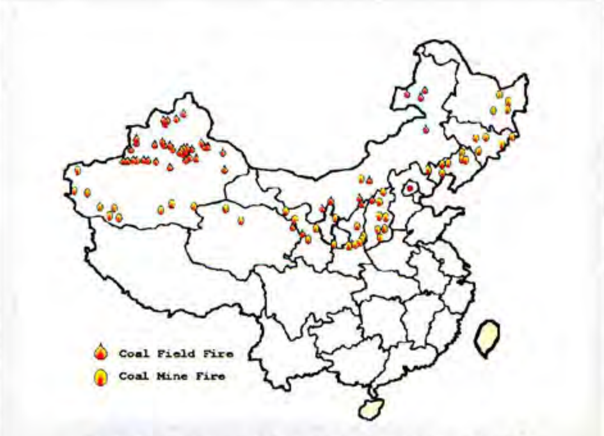

Fig.1. Sketch map of Coal fire in the northern China[2]

Abundant coal resources exits in north China and the natural climatic environment are very favourable for coal fires. The coal, characterised with medium or low metamorphism, has a low ratio of volume to outer surface, has high porosity and high moisture content and contains pyrites. These factors easily lead to spontaneous combustion. Consistent solar radiation and little rainfall lead the great differences of temperature between day and night, which also lead to coal fire. The presence of oil shales, carboniferous shales and pyrites, in the coal-containing strata can transmit from layer to layer and lead the fire being more serious. Weak and disturbed strata, shallow overburden with connected faults and cracks, multi-seams in close proximity, accumulation of fine coal particles, cracks and fissures in coal or adjoining strata provide better ventilation and allow for coal to be exposed and oxidised. In addition, careless mining activity can provide the heat sources and the air supply. With the resource exploitation, in recent years, there has been a great increase in the number of shafts due to the private mining and careless operation. These kinds of mines leave some fire species and form a wind ventilation network favourable to fires, increasing the risk of coal fires. Other risk factors include the losses of coal in a worked-out area, the excessive fissures due to strata movement (stress relief), caving to surface under shallow overburden or near outcrop, mining of thick seams-partial extraction, ventilation anomalies or imbalances, constrictions, large-scale pressure differential. The possibility of fires is high in the mines where most of these sub-factors are present, and it will be extremely difficult to[2] prevention. However, the spontaneous combustion may be reduced or eliminated by following the safety rules to minimise the number and effect of these factors.

[2]Investigation report of coal fires in North China, the National Co-ordination Office for Remote Sensing Application of Geology, 1993.

There are natural and man-induced coal fires, which is characteristic of the dynamic process and the indicators of which are gas releases, landslide, and thermal anomalies et al. The surface and shallow coal fires occur especially where mining activities are out of order The former is general beyond control; the latter can be controlled. However, it would be dangerous to mining activities, when coal fire is found both on the surface and underground.

2. 3 Environmental Impacts Caused by Coal Fire

The coal fires in China are not only an economic threat but also make a significant impact on the environment, leading to continuous influences on the sustainable development of society. There are four levels of impact, including

- Underground layer (water circulation in disorder, damage to the stability of rock structure, unsafe mining, etc)
- Surface (landslide, vegetation degradation, low quality of land resources)
- Regional environment (air pollution, climate, ecological abnormal…)
- Global (acid rains, greenhouse gases etc).

The social and economical consequences of the above listed problems are

- Resource exploitation is affected, unsafe mining and low productivity
- Health problems occur such as the occupational disease, air-pollution related disease, localised disease, etc.
- Requirements occurs for operational policy in environmental & resources protection, mining regulation, safety, health protection
- All the above are connected to a need for extra expenditure

Due to its significant contribution of poisonous gases to the global climate and the side effects on economic development, the coal fire monitoring and fire fighting program has been considered as an important issue in the "21st Century Agenda" announced by the Chinese government.

3. FIRE FIGHTING FOR HAZARD REDUCTION

It is very difficult to stop a coal fire, after it occurs, grows and spreads. Because the Earth is best considered as a single system, the different environmental stresses and changes are linked to each other. A number of analyses of the trends or variation of earth surface show that the global worming due to 'green house' effect seems to be accelerated since the dramatically increased output of CO_2 and other exhaust gases from fuel burning occur. In this sense, the coal fire is also a hazard in relation to the natural environment, resource exploitation and social development. Therefore, the coal fire fighting is actually a program to reduce the impacts on the global warming and to recover the environment, a more complex task than merely putting out the fire and saving the resources.

In order to improve the quality of the global environment and reduce the exhaust gas output of the fires, investigations in north China have been carried out by using remote sensing, from the beginning of the 90's. The results show that the coal fires are detectable and the regional monitoring can be done by using remote sensing. Considering the coal fire as a hazard, the requirement and actions in relation to coal fires, in time sequence, are the following:

❑ *Prevention(before a fire occurs)*

- Monitoring in multi-layers, data analysis, dynamic estimation, estimation potential loss of resource
- Preparation (predicting hazardous areas, preparation of protection program)
- Protection(publication, preparation, …)
- Estimation of potential economic loss & cost of hazard reduction

❑ *Fire fighting (during the fire's lifetime)*

- Continuous monitoring
- Dynamic evaluation on loss, input for reduction
- Fire fighting management (budget input, allocating resources for coal fire reduction)

❑ *Post-fire fighting (after fires is distinguished)*

- Ecological recovery & environmental treatment
- Lands recovery
- Resource exploitation
- Reduction of the societal influences (health and safety requirement)

Therefore, the operational program has to tackle the following issues:

❑ *Natural features & methodology research for the technical support*

- The location of coal fires, the natural boundaries and depth limitation, development speed and fire intensity, as well as released gases
- The conditions favourable to coal fires (coal quality, air supplement, heat sources)
- Influences from surroundings factors (geological background, climate, hydrology, location, human activity)
- Methodology research (monitoring, evaluation, protection & fire fighting)

❑ *Study on social-economical aspects for decision support*

- Fire fighting plan, the systematic standard and rules for the assessment and operation
- Estimation of economic loss & input for reduction(method study, ecological recovery, budget input)
- Management research on operational policy & regulation (environment & resource protection, purchase & order exploitation)
- Influences on local communities (manpower input, treatment related to fire fighting)

4. '4S' OPERATIONALIZATION FOR FIRE FIGHTING

4.1 Fire Fighting Requirements

As we see, fire fighting is a complex operation, in which dynamic monitoring, resource allocation for fighting, planning management, prevention and environmental improvement are involved. The operationalization is the process in which '4S' techniques can be effectively used, in order to provide those supports such as the fire detection, data analysis, decision making and information management. Accordingly, there are the various requirements from '4S' techniques, to support the program. These techniques help to answer questions related to where, when and how the coal fire develops. Question *'where'* need the exact location of the coal fire which can be detected and visualised in a spatial system. Question *'when'* refers to the time aspect of the coal fires and can be answered only by temporal monitoring. Question *'how'* is related to circumstances of the burning and impacts on the environment and society and requires the analytical capabilities of the '4S' technology. Based on all the above answers, the decision could be made and the program will be effectively operated.

In practice, there are three levels of the fire fighting operation. Regional fighting focuses on resource management, management, monitoring of the coal fire and the risk assessment. Local fire fighting involves dynamic monitoring, data management and planning related to fire areas. Spot operation concerns the treatment like digging out a fire and making underground walls to stop a fire.

Fig.2 presents the logical relationship between the coal fires and '4S' techniques. Generally speaking, the research on the detection, monitoring and assessment, planning and management will provide the knowledge base of the expert system. It involves those in relation to all processes of the hazard reduction. In the system, remotely sensed data acquired from different platform form the major data source for the monitoring of the coal fires at different scales. GPS provides the high accuracy spatial attribute. GIS can integrate various data, with various attributes into database, on which various analyses can be carried out.

Fig.2 The relationship diagram between '4S' and the coal fire

4.2 Main Role of '4S' Techniques in Fire Fighting

From the operationalization point, Fig 3 shows the logical layout of the information management system for coal fire management, based on '4S' techniques. The most important elements of the system are discussed in the following.

3D Detection Using Remote Sensing The most important indicators of the coal fires are the thermal anomalies, burnt rocks, heat stress on the vegetation, gases and landslides. Only the thermal anomaly and burnt rocks could be obviously detected through the field measurement. But the temporal changes are so minute that they can not be sensed with the existing devices. Detection of coal fires using remote sensing and some ground detecting methods, can be carried out at different levels (subsurface, surface, airborne and satellite measurements). With increases of the spatial and spectral resolution and shortened temporal circle, remote sensing can provide more and more detailed surface information about the coal fire. Additional information, like geological, geophysical, geochemical, topographical, mining and ancillary data, available for most of the coal fire areas, should have to be used in an integrated manner for the most efficient utilisation.

Localisation Using GPS The most important contribution of GPS to the operationalization is the possibility of high accuracy in positioning. This is very necessary when phenomena (e.g. the development of cracks, abnormal point of coal fire) have to be monitoring with higher accuracy than the resolution of the available remote sensing data. GPS also proves to be useful in positioning if higher temporal frequency of the measurements is needed than is available by using remote sensing data. For instance, the observation can be carried out at fixed positions for control and moving positions for dynamic changes, considering the development speed of the coal fire, since coal fire development is not so obvious to measure it using remote sensing. The high accuracy positioning provide the position information, which is very helpful to the interpretations of ground measurement.

The Case Analysis and Decision Using Expert Knowledge Fire fighting, and hazard reduction need extended knowledge about the coal fires, environmental effects, social response and management. The rule and criteria in the system are then established according to the knowledge and experiences. It provides the methodology and procedures in relation to hazard reduction. Some cases of interpretation can be stored for the guidance of system operation. Therefore, a special knowledge base has to be logically organised in the system. The expert knowledge base is partly comprises of physical models (e.g. heat transport) and partly comprises of decision rules set up on the basis of the experience of local experts.

Knowledge set, therefore, contains the following:

- Methodology of data capture using remote sensing, ground measurement and observation (geophysics, geology, mining, etc.)
- Methodology for compilation of maps and sections, statistical and geostatistical analysis
- Data standardisation and management
- 3D digital imaging for constructing image of underground coal fire
- Methodology of risk assessment and prediction
- Assessment of the environmental recovery
- Engineering design for the fire fighting
- Program suggestions for the most efficient prevention methods based on analysis

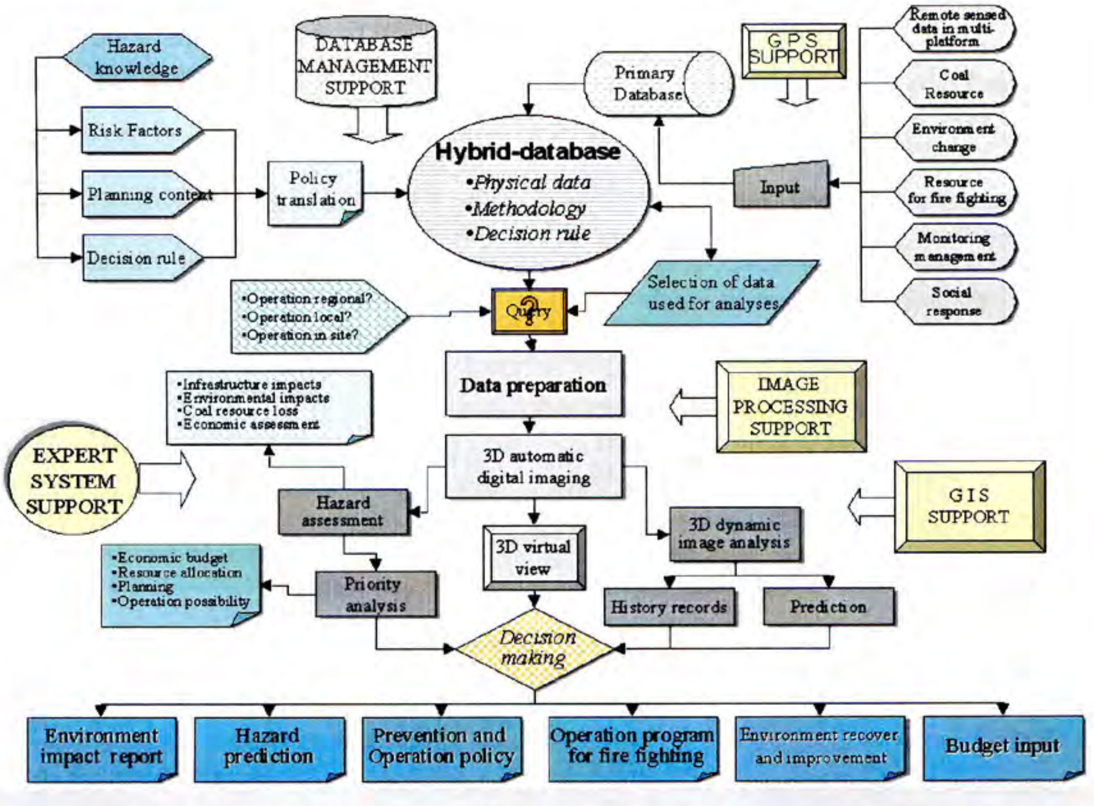

Fig. 3. Information management system for assessment & decision, supported by '4S' techniques

- Budget estimation for the fire fighting and hazard reduction
- Monitoring of the reduction and resources management

Data Management and Analysis Using GIS GIS has been proved as a powerful tool for the effective data management and analysis. The most important characteristics is the capability for handling the spatial aspects of the data. The following functions and operations are included,

- Data management
- Visualisation for easy understanding
- Geostatistical analysis and modelling
- Temporal analysis
- The comprehensive interpretation
- Spatial analysis, e.g. risk assessment and prediction
- Ancillary design for fire fighting

Obviously, the operationalization using '4S' technology includes the methodology study, data management and representation, and integrated information system for decision support. CoalMan, being presently developed by Chinese and Dutch partners for the project: 'Development and implementation of a coal fire monitoring and fighting system in China', is a supportable system for data management and analysis. Based on up-to-date GIS and DBMS technology, the system contains some coal fire. Remote sensing data, assisted with ground data serve as the main data source to identify and map fire areas. A GIS software (ILWIS) provides the framework in which the data are integrated. GPS serves as a tool to increase the accuracy of mapping and data caption in the field. ES contains the professional knowledge gained by research, fire fighting and fire management. It provides a tool for data analysis and management.

However, the degree of the operationalization depends apparently on several factors. One key issue is the accuracy of the data and the analysis methods, but another, not negligible issue is the way how the system is integrated into the daily activity of the fire fighters.

4.3 Management Support To '4S' Operationalisation

Fire fighting is the complex project, in which technology, resources, administration, economy and population are involved. Therefore, effective management is very important for the successful operationalization of '4S' techniques. In order to create a favourable environment for fire fighting, there are some aspects which should be considered, such as

- The setting up of a dynamic monitoring system for repeated information
- Assessment system for risk analysis, including infrastructure, resources, mining and environment impacts
- Ecological and lands recovery program and resource exploitation
- Budget planning for hazard reduction
- Prevention program in operation
- Systematic policy and regulation favourable to hazard reduction.

In conclusion, coal fire is a serious hazard, posing impact on the sustainable development of the society, the economy and the environment in north China. With the help of the '4S' techniques, proper information acquisition and management system can be set up, locally and regionally. It can provide various decision supports for the effective operation. The necessary administrative and budget input are also important factors to success. Therefore, '4S' operationalization will helpful to fire fighting and hazard reduction, in order create a harmonious environment for human beings and to promote social development.

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REFERENCE

Cassells C.J.S. and Genderen J.L. van, 1995. Thermal modelling of underground coal fires in northern China. In: Remote Sensing in Action, *Proceedings of the 21st Annual Conference of the Remote Sensing Society*, pp.544-551.

Genderen J.L. van and Guan H.Y., 1997. Environmental monitoring of spontaneous combustion in the north China coal fields, Final report to European Commission under Contract No. CI1*-CT93-0008 (DG-HSMV), Printed by ITC and ARSC, ISBN: 90 6164 1527

Guan, H., Genderen, J.L.van, and Schalke, H.J.W.G., 1996. Study and survey on the geological hazards of coal fire in northern China. *30th International Geological Congress* Abstracts, Beijing, China, pp: 4-14

Prakash A., Gupta R.P. and Saraf A.K., 1997. A Landsat TM based comparative study of surface and subsurface fires in the Jharia coalfield, India. *International Journal of Remote Sensing*, 18, pp 2463-2469.

Prakash A., Sastry R.G.S., Gupta R.P. and Saraf A.K., 1995. Estimating the depth of burried hot feature from thermal I.R. Remote sensing data, a conceptual approach. *International Journal of Remote Sensing*, 16, pp 2503-2510.

Prakash A., Gupta, R.P. and Saraf, A.K., 1997, A Landsat TM based comparative study of surface and subsurface fires in the Jharia coalfield, India, *International Journal of Remote Sensing*, Vol. 18, pp. 2463–2469

Rosema A., Genderen, J.L. van, and Schalke, H.J.W.G., 1993. Environmental monitoring of coal fires in north China. *Project Identification Mission Report*, BCRS 93-29, ISBN 90 5411 1054, 24 p.

Slavecki, R. J., 1964, Detection and location of subsurface coal fires, *Proceedings of the 3rd Symposium on Remote Sensing of Environment*, 14–16 Oct. 1964 (Ann Arbor, Michigan: University of Michigan), pp.537-547

Vekerdy, Z. and Genderen, J.L. van, 1999, CoalMan – information system for the monitoring of subsurface coal fires and the management of fire fighting in coal mining areas, *Proceedings of the Geoinformatics: Beyond 2000*, 9-11 March, 1999, IIRS, India, pp: 179-184

Wan Y.Q and Zhang X.M, 1996. Using a DTM to reduce the effect of solar radiance on Landsat TM thermal IR images and detection coal fires, *Asian-pacific Remote Sensing and GIS Journal*, 8(2) pp 65-72.

Zhang J.M., 1998. Study on 3D dynamic monitoring of spontaneous combustion of coal seam. *Ph.D. Thesis*, China University of Mining & Technology (Beijing), China P.R.

Zhang J.M., He Bin, Wang Mei and Lin Yizong, 1998. Dynamic electro-magnetic imaging for coal fire monitoring, *Journal of Coal*, pp

Zhang J.M. and H.Y. Guan, 1999. Study on 3D imaging method for detection of underground coal fires and application to Rujigou coal field of Ningxia, China, *Proceedings of the 13th international Conference on applied Remote Sensing*, pp: II-142-149

Zhang J.M., S.N. Ning and Y. Cao, 1998. Study on coal fire impacts in northern China and management policy, *Hazard Reduction of China*, 8(1), pp 55-66

Zhang X.M., Genderen J.L. van and Kroonenberg S.B., 1997. A method to evaluate the capability of landsat-5 TM band 6 data for sub-pixel coal fire detection. *International Journal of Remote Sensing*, 18, pp 3279-3288.