ASSESSMENT OF HYPERSPECTRAL AND SAR REMOTE SENSING FOR SOLID WASTE LANDFILL MANAGEMENT

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ABSTRACT

Globally, waste management is one of the most critical environmental concerns that modern society is facing. Controlled disposal to land (landfill) is currently important, and due to the potentially harmful effects of gas emissions and leachate land contamination, the monitoring of a landfill is inherent in all phases of the site's life cycle. Data from satellite platforms can provide key support to a number of landfill management and monitoring practices, potentially reducing operational costs and hazards, and meeting the challenges of the future waste management agenda.

The few previous studies performed show the value of EO data for mapping landcover around landfills and monitoring vegetation health. However, these were largely qualitative studies limited to single sensor types. The review of these studies highlights three key aspects. Firstly, with regard to leachate and gas monitoring, space-borne remote sensing has not proved to be a valid tool for an accurate quantitative analysis, it can only support ground remediation efforts based on the expertise of the visual interpreter and the knowledge of the landfill operator. Secondly, the additional research that focuses on landfill detection concentrates only on the images' data dimension (spatial and spectral), paying less attention to the sensor-independent bio- and geo-physical variables and the modelling of remote sensing physical principles for both active and restored landfill sites. These studies show some ambiguity in their results and additional aerial images or ground truth visits are always required to support the results. Thirdly, none of the studies explores the potential of Synthetic Aperture Radar (SAR) remote sensing and SAR interferometric processing to achieve a more robust automatic detection algorithm and extract additional information and knowledge for landfill management.

Based on our previous work with ERS radar images and SAR interferometry, expertise in the waste management sector, and practical knowledge of landfill management practices, we propose to evaluate the use of hyperspectral and radar images for landfill monitoring and management. CHRIS offers hyperspectral data of commensurate spatial resolution with Envisat radar images and thus appears ideally suited for studies using multi-sensor data fusion.

The goal of the research is to identify practical ways in which EO data can support landfill management and monitoring, providing quantitative data where possible. Our objectives (based on fieldwork in UK landfills) are (1) to develop robust methods of detecting and mapping landfill sites, (2) to correlate EO data with on-site operational procedures, and (3) to investigate data fusion techniques based on our findings with the separate sensors. Dissemination of the findings will be through scientific journals, professional waste management publications and workshops. It is expected that the research will help the development of techniques which could be applied to monitor waste disposal to land beyond the UK scope of this study, including global monitoring.

1. WASTE MANAGEMENT

Waste is considered as an important sustainable development indicator that is closely intertwined with many interdependent and trans-boundary issues. Waste management is linked to industrial policies, international and national economic strategies, environmental protection agreements and local community development planning. Rigorous international and national regulations also try to establish sustainable systems that prevent or reduce the adverse effects of waste processing and disposal on the environment [1] [2] [3].

Emerging from this complex framework, modern Integrated Solid Waste Management (ISWM) practices concurrently tackle strategic issues related to resource efficiency, waste logistics, economic benefits and resource mass balance [4]. As described by McDougal [5], the goal of ISWM is to implement systems that will result in minimum energy use, minimum environmental impact, and minimum landfill space at a cost affordable to the community.

This strategy aims at reducing the amount of waste sent to landfill by encouraging waste reduction, incineration, re-use and recycling. Nonetheless, the controlled

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disposal of waste into land is still an important and necessary means of effective waste management and, as stated in the Waste Strategy 2000 for England and Wales [6], it remains the Best Practicable Environmental Option for certain types of waste in the foreseeable future. The broad current policy on landfill is to optimise the design and to promote operational practices that will achieve site stabilisation within one generation, achieving the overall objectives of environmental protection and beneficial after-use compatible with the aims of sustainable development.

Fig. 1 shows that, in England and Wales, over half a tonne of household waste was generated per person in 2001-2, 88% of which was disposed into landfills [7]. It also corroborates the fact that even if non-recycled waste represents a decreasing relative proportion, its overall level raised by about 4% between 1998-9 and 2001-2. Furthermore, current figures [8] also confirm that in recent years the amount of municipal waste has been increasing at some 3 - 4% per annum, slightly above Gross Domestic Product, and if it continues to increase at this rate it will have doubled from the 1995 level by 2020.

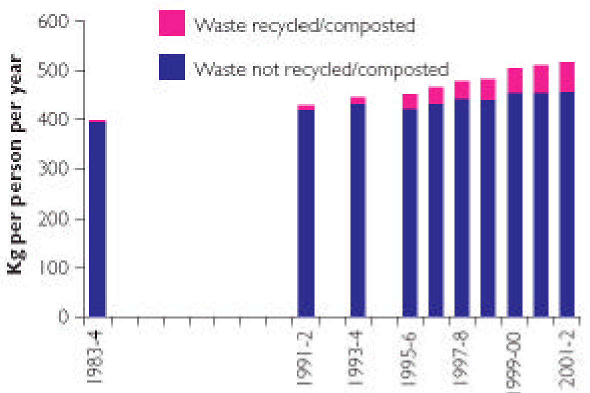

Fig. 1. Household waste and recycling in England and Wales: 1983-4 to 2001-2 [7].

Evidently, as the currently operational sites reach their capacity, new ones will have to be approved by planners, permitted by the regulator and consequently monitored. In England and Wales, there are over 1800 open active landfills, and in the last five years more than 110 licences were issued for new municipal waste sites [9]. Under the PPC regulatory regime [10], landfills are now permitted by the Environment Agency and periodic inspections are required to ensure that all site activities are compliant with permit conditions. Due to the potentially harmful effects associated with methane and carbon dioxide emissions and leachate land contamination, the monitoring of a landfill is an activity which is inherent in all phases of the site life cycle, from the initial appraisal to the operational and post-closure phases. Whilst modern landfills are highly engineered risk assessed facilities, there is considerable uncertainty regarding their long-term efficacy and post-closure monitoring requirements until the permit surrender can be accepted by the regulator [11]. Insufficient monitoring points, poor sampling methods, inappropriately positioned monitoring facilities, insensitive analytical methods and monitoring timescales, all increase the likelihood of inadequate site characterisation and management.

If this is the current state of affairs of controlled and highly regulated disposal sites, the situation in developing countries is much more critical. Recent surveys [12] [13] and a World Bank study [14] are evidence that in low- and middle-income countries, where urban expansion often has high development rates, the open dump approach remains the predominant waste disposal option, and there is limited legislation, regulation and guidance. Future establishment of uncontrolled and illegal landfilling activities of both hazardous (e.g., clinical and chemical wastes) and non-hazardous wastes is therefore an urgent problem. International organisations are fully aware of this critical issue and after the 1992 Earth Summit report, known as Agenda 21 [15], even the United Nations is has been implementing programmes on waste control in developing countries.

In this context, the repetitive and consistent data acquisitions from the broad array of satellite platforms can provide key support to a number of landfill management and monitoring practices, potentially reducing operational costs and hazards, and meeting the challenges of the future waste management agenda.

2. AIR AND SPACE-BORNE REMOTE SENSING FOR LANDFILL MONITORING

The first analysis on the application of remote sensing for waste management was published by Garofalo in 1974 [16]. This study discusses the utilisation of aerial photographs to support estimation techniques of solid waste distribution and production. The methodology is based on the visual interpretation of land use (i.e. low and high residential areas, commercial and industrial areas, agricultural fields and open public areas) and the incorporation of these data into solid waste production models. This preliminary study also suggests that small-scale aerial remote sensing records could support the location selection of new waste disposal sites, the implementation of new waste collection and transportation systems, and a preliminary assessment of potential environmental impacts. However, due to increasing concerns for the environment in the late 1970s and the full awareness of the harmful effects caused by both hazardous and municipal landfills, most of the research that followed focused primarily on landfill detection and the monitoring of gas and leachate migration, without exploring or developing further any of the additional applications proposed by Garofalo. The only exception is a general review published by Breton and Chorowicz [17].

At the simplest level, a number of studies [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] demonstrate the value of visual interpretation techniques of airborne data (e.g. historical black and white, colour and infrared photographs and photogrammetry data) to identify land cover changes on and around the sites and describe the structure of the sites themselves. The principal aim of these projects is to carry out a basic environmental examination by studying the soil textural and hydrological characteristics, and using this information as a guide for subsequent remediation efforts. Visual interpretation is also used by Philipson et al. [28] to test the suitability of satellite images (i.e. panchromatic and multispectral SPOT images acquired in 1986) for regional scale monitoring of land cover changes. The main aspect emphasized by Philipson [28] is the interpretation ambiguity between landfills and areas undergoing some type of development or simply not reclaimed disturbed areas. This level of uncertainty, intrinsic in a visual interpretation approach, has been more recently tackled by Brivio, Doria and Zilioni [29]. They investigate aspects of spatial autocorrelation of Landsat TM data, nonetheless the research method is limited by the fact that they assume an a priori knowledge of the landfill size and location.

On the next level of examination, other studies investigate spectral characteristics and band mathematical procedures using air and space-borne multispectral data. Again, the main aims are to detect landfills based on their spectral signatures [30] [31] and to observe signs of gas emissions or leachate release by detecting vegetation stress on closed reclaimed sites [32] [33] [34] [35] [36]. Jones and Elgy [33] conclude that the relationship between landfill gas dynamics, plant health and soil characteristics is extremely difficult to establish and demonstrate, and poor vegetation growth is also strongly dependant to soil reinstatement during site restoration, waste settlement and waterlogging in certain areas. They also stress that remote sensing is not envisaged in this respect as a substitute for *in situ* borehole sampling methods. Rather, the approach to adopt is to integrate both techniques to optimise their individual advantages. More recent studies by Jago and Curran [37], and Folkard and Cummins [38] demonstrated that the use of airborne hyperspectral data can improve the contaminant-monitoring capabilities of remote sensing over that provided by multispectral data.

With regards to direct gas detection, and without taking into consideration the available ground based sensors described by Bryce et al. [39], on-board aircraft sensors have the technological edge over proposed satellite systems. As Long [40] explains, the shorter atmospheric columns that airborne sensors have to see through allows them to experience less deleterious effects on the detector performance. Due to the better spectral resolution and signal-to-noise ratio, it is argued that methane remote detection technology designed for airborne platforms will always provide better quality information than satellite systems.

Another critical argument presented in many of the above publications is that the 30m ground resolution of many satellite images is insufficient for studying the often small scale variations in contamination that may occur in a landfill site. Indeed, recent work based on space-borne data [41] [42] [43] has only highlighted that the clear advantage of satellite remote sensing is its capability of providing a synoptic and holistic view of vast areas for change detection at relative low costs.

The review of these studies highlights three key aspects. Firstly, with regard to leachate and gas monitoring, space-borne remote sensing has not proved to be a valid tool for an accurate quantitative analysis, it can only support ground remediation efforts based on the expertise of the visual interpreter and the knowledge of the landfill operator.

Secondly, the additional research that focuses on landfill detection concentrates only on the images' data dimension (spatial and spectral), paying less attention to the sensor-independent bio- and geo-physical variables and the modelling of remote sensing physical principles for both active and restored landfill sites. These studies show some ambiguity in their results and additional aerial images or ground truth visits are always required to support the results.

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3. RESEARCH OBJECTIVES

The Cranfield University Space Research Centre (SRC) and the Integrated Waste Management Centre (IWMC) have valuable expertise in the fields of SAR remote sensing and landfill engineering and operations. The SRC has also extensively worked in collaboration with the Cranfield Centre for Geographical Information Management on optical data, biophysical modelling and field observations across a broad range of interdisciplinary research. This synergetic approach allows the research to combine the diverse know-how and to enhance its innovative aspects.

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4. AREA OF INTEREST

The Brogborough and Stewartby landfills are the two test sites selected for this research. Both of them were originally worked as clay pits extracting Oxford clay and are now operated by Waste Recycling Group Ltd. They are located roughly midway between Milton Keynes and Bedford, UK. Filling activities at Brogborough commenced in 1982. The site has an area of circa 195 hectares and it currently receives approximately 2 million tonnes of wastes per annum. Receiving circa 400 vehicles per day from London and other regions of the UK, the planned closure date is estimated to be in 2008. The Stewartby site's area is circa 50 hectares. It has been accepting waste since 1976 and landfilling is now ongoing by removal of the cap and surcharging of various areas. According to the recent new permit released in January 2005, the site will continue receive 1,275,000 tonnes of waste per annum [44]. These sites offer the possibility of assessing operational cells, recently capped areas, and older restored phases.

5. METHODOLOGY

The initial step is to practically go on the site and observe the phenomena occurring due to the physics and operations of waste landfilling. The outcome of these remarks allows the research to identify the analysis techniques to apply on the data for the different objectives.

For the first objective, the investigation of the interferometric coherence supports identification of areas undergoing changes in their properties and geometrical characteristics. Already available historical SAR scenes from the ERS 1/2 tandem mission are used.

The analysis of the backscatter signal is instead used to correlate the SAR images with on-site conditions and operational procedures. A model for the radar wave interaction with solid waste covered areas has to be developed in order to correctly interpret the SAR data. As there is no ground reference information related to the available SAR scenes, it is required to acquire new SAR data and take ground measurements on the same dates of acquisition to confirm the conditions of the sites, and validate the backscatter models. This is done with a ground based SAR system.

The new SAR scenes will also be used to test the detection algorithm based on coherence models developed for the first objective. Discrepancies between the models and the new space-borne data will be subsequently used to modify and enhance the models.
On a parallel side, close dialogue with the various user groups (i.e. waste industry managers, landfill operators, landfill regulators, environment protection institutions, private individuals, property land owners and real estate companies) is useful to carry out an investigation of how SAR data and processing techniques could support other needs linked to business issues, scientific aspects and private safety concerns.

For the implementation phase, the research focuses on the detailed study of landfill design, operational practices and waste properties. It is critical to develop a SAR backscatter and coherence model based on the spatial, temporal and biophysical characteristics of operational and restored sites. This is achieved by the collection of measurements and field observations about objects, areas or phenomena that can influence the data values detected by SAR and optical instruments.

The interferometric coherence analysis is carried out on the already available ESA Earth Remote Sensing (ERS) 1 and 2 SAR data, from the 1996 tandem mission. For the backscatter modelling, a portable ground based SAR, available at the Cranfield University Shrivenham campus, is used to investigate the backscattered signal of different areas of the landfill and its variability in time. Concurrent recorded parameters and observations are: statistical data on surface roughness and its variability in space and time, obtained with the used of a pin profilometer provided by Silsoe Campus and visual analysis; soil moisture and temperature values and their variability in space and time, obtained with a Theta probe provided by Silsoe Campus; weather and atmospheric conditions; GPS values for the calculation of a high-accuracy absolute elevation model; operational waste distribution procedures. Additional discussion with experts also provides valuable information.

There is no need to develop absolute reflectance models for the CHRIS Proba data with respect to the different landfill areas. Analysis of the hyperspectral signatures should improve the detection capabilities of this technique with respect to multispectral data. A number of additional historical optical images (*e.g.*, SPOT, Landsat 4 and 7 multispectral and panchromatic data) obtainable from existing archives are used to support a preliminary analysis. Band and spectral algorithm should be then developed specifically for the hyperspectral data. After geo-referencing these data to the SAR scenes, the fusion of the results at a feature level can be carried out. Application of soft computing algorithms is also explored.

Ultimately, the last step of the research involves the validation of the developed procedures by applying them in an operational context on new remote sensing scenes acquisitions.

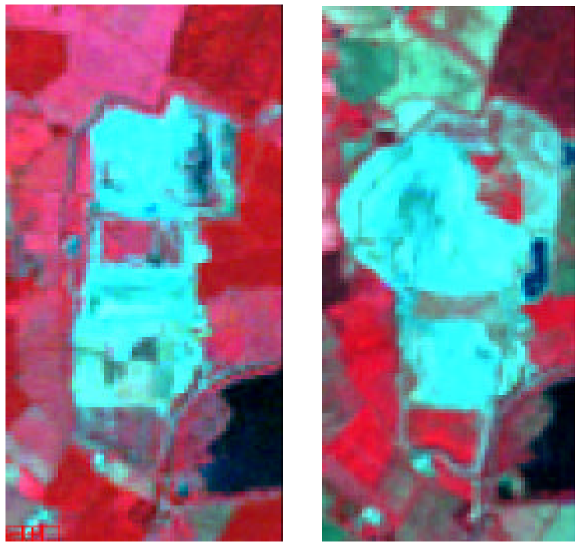
6. FUTURE SATELLITE IMAGES ACQUISITION

The validation phase involves the acquisition of up-to-date SAR remote sensing scenes in order to corroborate the developed procedures by applying them in an operational context. This shall also demonstrate to the end-users the accuracy and significance of the final results

Satellite images are therefore subsequently acquired. The research has been accepted by ESA as a Category-1 project and up-to-date data will be provided from both the ENVISAT ASAR (Advanced SAR) instrument and the hyperspectral PROBA CHRIS (Compact High Resolution Imaging Spectrometer) one. Scenes from these two satellites will be acquired between March and August 2005. The exact Envisat ASAR dates are: 9th May, 13th June, 18th July, 25th July, 22nd August, 29th August. All of them are desceding apart from the 25th July and 29th August acquisitions.

Six ENVISAT ASAR scenes are taken from the two tracks to allow interferometric calculations of coherence. This plan allows the research to investigate ascending (2 scenes) and descending tracks (4 scenes) obtained respectively in the evening and in the morning. The SAR incidence angle ranges between 19.2° - 26.7° (i.e. ESA Image Swath 2). PROBA CHIRS data is acquired accordingly as close as possible in time to the selected ENVISAT dates, in order to minimise the changes between the two scenes. The ENVISAT ASAR mode to be used is SLC ASA_IMS_1P with VV polarisation. The PROBA CHRIS mode to be used is Mode 3 at full spatial resolution, full swath, and using 18 bands for land/aerosols. The use of the multi-source data is required due to the complementary characteristics of the SAR and optical imaging techniques.

An example of multispectral images is shown below in Fig. 2.



Landsat 4 - 1992 Landsat 7 - 2001

Fig. 2 Zoom on Brogborough landfill site. Copyright University of Manchester/University College London Year 2001. Original Landsat 7 distributed by Infoterra International.

7. REFERENCES

1. European Union (1999). *Landfill Directive*. Available at: http://europa.eu.int/eur-lex/pri/en/oj/dat/1999/l_182/l_18219990716en00010019.pdf (last accessed 3rd February 2005).

2. UK Legislation (2000). *The Pollution Prevention and Control (England and Wales) Regulations 2000*. Available at: http://www.legislation.hmso.gov.uk/si/si2000/20001973.htm (last accessed 15th November 2004).

3. UK Legislation (2002). *The Landfill (England and Wales) Regulations 2002*. Available at: http://www.legislation.hmso.gov.uk/si/si2002/20021559.htm (last accessed 15 th November 2004).

4. Bagchi, A. (2004). *Design of Landfills and Integrated Solid Waste Management*. 3rd ed. John Wiley and Sons, Hoboken, New Jersey.

5. McDougall, F., White, P., Franke, M., and Hindle, P. (2001). *Integrates Solid Waste Management: A Life Cycle Inventory*. Blackwell Science, Oxford.

6. DEFRA (2000). *Waste Strategy 2000 for England and Wales*. Available at: http://www.defra.gov.uk/environment/waste/strategy/cm4693/index.htm (last accessed 20th January 2005).

7. DEFRA (2004a). *Sustainable Development Indicators in Your Pocket 2004*. Defra Publications, London.

8. DEFRA (2004b). *Recycling and Waste*. Available at: http://www.defra.gov.uk/environment/waste/intro.htm (last accessed 28th January 2005).

9. Butcher, K. (Environment Agency) (2005). *List of Landfill Sites*. (unpublished Excel spreadsheet provided on 29th November 2004).

10. DEFRA (2005). *Pollution Prevention and Control*. Available at: http://www.defra.gov.uk/environment/ppc/ (last accessed 7th February 2005).

11. Environment Agency (1996). *Guidance on Good Practice for Landfill Engineering*. R&D Technical Report CWM-106/94(C). DoE, London. Available from Environment Agency, Bristol.

12. Ogawa, H. (1996). Sustainable Solid Waste Management in Developing Countries. In: *7th International Solid Waste Association International Congress and Exhibition*. Yokohama, October 27 - November 1, 1996, Vol. Parallel Session 7, "International Perspective". International Solid Waste Association, Denmark.

13. Nair, C., Environmental Resources Management. (1993). *Solid Waste Management in Emerging Industrialised Countries*. Available at: http://www.eco-web.com/cgi-local/sfc?a=/editorial/index.html&b=/editorial/01060.html (last accessed 8th November 2004).

14. Johannessen, L. M. and Boyer, G. (1999). *Observations of Solid Waste Landfills in Developing Countries: Africa, Asia, and Latin America*. The World Bank, Washington.

15. United Nations (1992). *Agenda 21. Chapter 21: Environmentally Sound Management of Solid Wastes and Sewage-Related Issues*. United Nations, Washington.

16. Garofalo, D. and Wobber, F. (1974). Solid Waste and Remote Sensing. *Photogrammetric Engineering*. Vol. 40, No. 1, pp. 45-59.

17. Breton, M. R. and Chorowicz, J. (1997). Utilisation de la Télédétection et des Systemes d'Information Géographiques dans la Recherche et le Suivi des Centres d'Enfouissement Techniques. In: *International Symposium on Engineering Geology and the Environment*. Athens, Greece, June 23-27, 1997, Vol. 1-3, pp. 1643-1648. Balkema, Rotterdam.

18. Irvine, J. M. , Evers, T. K., Smyre, J. L., Huff, D., King, A. L., Stahl, G., and Odenweller, J. (1997). The Detection and Mapping of Buried Waste. *International Journal of Remote Sensing*. Vol. 18, No. 7, pp. 1583-1595.

19. Warner, W. S. (1994). Evaluating a Low-Cost, Non-Metric Aerial Mapping System for Waste Site Investigators. *Photogrammetric Engineering and Remote Sensing*. Vol. 60, No. 8, pp. 983-988.

20. Rugge, C. D. and Ahlert, R. C. (1992). Ground and Aerial Survey of a Peninsular Landfill. *Water Research*. Vol. 26, No. 4, pp. 519-526.

21. Marsh, S. E., Walsh, J. L., Lee, C. T., and Graham, L. A. (1991). Multitemporal Analysis of Hazardous-Waste Sites Through the Use of a New Bi-Spectral Video Remote-Sensing System and Standard Color-IR Photography. *Photogrammetric Engineering and Remote Sensing*. Vol. 57, No. 9, pp. 1221-1226.

22. Lyon, J. (1987). Use of Maps, Aerial Photographs, and Other Remote Sensor Data for Practical Evaluation of Hazardous-Waste Sites. *Photogrammetric Engineering and Remote Sensing*. Vol. 53, No. 5, pp. 515-519.

23. Stohr, C., Su, W. J., DuMontelle, P. B., and Griffin, R. A. (1987). Remote Sensing Investigations at a Hazardous-Waste Landfill. *Photogrammetric Engineering and Remote Sensing*. Vol. 53, No. 11, pp. 1555-1563.

24. Evans, B. M. and Mata, L. (1984). Aerial Photographic Analysis of Hazardous Waste

Disposal Sites. In: *Hazardous Wastes and Environmental Emergencies* . Hazardous Materials Control Research Institute Publication, Silver Spring, Maryland.

25. Titus, S. (1984). Exemplary Projects of Environmental Assessment from Analysis of Remotely Sensed Imagery. Survey and Analysis of Present or Potential Environmental Impact Sites in Woburn, Massachusetts. In: *48th Annual Meeting of the American Society of Photogrammetry*. Denver, 1984, pp. 538-549. American Society of Photogrammetry, Falls Church.

26. Lyon, J. (1982). Use of Aerial Photography and Remote Sensing in the Management of Hazardous Wastes. In: Sweeney, T. et al. (Editors), *Hazardous Waste Management for the 80's*. Ann Arbor Science, Ann Arbor, MI.

27. Erb, T., Philipson, W. M., Teng, W., and Liang, T. (1981). Analysis of Landfills with Historic Airphotos. *Photogrammetric Engineering and Remote Sensing*. Vol. 47, No. 9, pp. 1363-1369.

28. Philipson, W. R., Barnaba, E. M., Ingram, A., and Williams, V. L. (1988). Land-Cover Monitoring with SPOT for Landfill Investigations. *Photogrammetric Engineering and Remote Sensing*. Vol. 54, No. 2, pp. 223-228.

29. Brivio, P. A. , Doria, I., and Zilioli, E. (1993). Aspects of Spatial Autocorrelation of Landsat TM Data for the Inventory of Waste-Disposal Sites in Rural Environments. *Photogrammetric Engineering and Remote Sensing*. Vol. 59, No. 9, pp. 1377-1382.

30. Stohr, C., Darmody, R. G., Frank, T. D., Elhance, A. P., Lunetta, R., Worthy, D., and O'Connor-Shoresman, K. (1994). Classification of Depressions in Landfill Covers Using Uncalibrated Thermal-Infrared Imagery. *Photogrammetric Engineering and Remote Sensing*. Vol. 60, No. 8, pp. 1019-1028.

31. Johnson, E., Klein, M., and Mickus, K. (1993). Assessment of the Feasibility of Utilizing Landsat for Detection and Monitoring of Landfills in a Statewide GIS. *Environmental Geology*. Vol. 22, pp. 129-140.

32. Hopper, A. J. (1996). Remote Sensing Detection of Landfill Pollutant Migration. In: *22nd Annual Conference of the Remote Sensing Society*. Durham, UK, 1996, pp. 281-289.

33. Jones, H. K. and Elgy, J. (1994). Remote Sensing to Assess Landfill Gas Migration. *Waste Management and Research*. Vol. 12, pp. 327-337.

34. Vincent, R. K. (1994). Remote Sensing for Solid Waste Landfills and Hazardous Waste Sites. *Photogrammetric Engineering and Remote Sensing*. Vol. 60, No. 8, pp. 979-982.

35. Brivio, P. A. , Doria, I., Gomarasca, M. A., Moriondo, S., Pagnoni, F., Tomasoni, R., and Zilioli, E. (1991). *Potenzialita del Telerilevamento da Satellite e da Aereo nella Ricerca di Aree Soggette ad Inquinamento e Degrado, anche Finalizzata alla Individuazione di Discariche Abusive, Tramite Analisi di Stress Ambientale e Alterazione delle Caratteristiche Pedologiche di Zone Campione.* L. 441/87 CNR-TEI-ENEA, Second and Third Progress Report. Ministry for the Environment of Italy, Rome.

36. Jones, H. K. (1991). *The Investigation of Vegetation Change Using Remote Sensing to Detect and Monitor Migration of Landfill Gas* (unpublished Ph.D. thesis). Aston University, Birmingham.

37. Jago, R. A. and Curran, P. J. (1996). Estimating Canopy Chlorophyll Concentration From Field and Airborne Spectra to Infer Levels of Land Contamination. In: *23rd Annual Conference of the Remote Sensing Society*. Reading, UK, 1996, pp. 274-279

38. Folkard, A. M. and Cummins, D. I. (1998). Hyper-Spectral Remote Sensing of the Spread of Soil Contaminants from Landfill Sites. In: *6th International Conference on Contaminated Soil*. Edinburgh, Scotland, May 17-21, 1998, pp. 153-161. Thomas Telford, London.

39. Bryce, D., Hall, R. S., and Young, R. I. (2003). *Greenhouse Gases Detection*. Technical Report E1-127. Environmental Agency, Bristol.

40. Long, T. (1999). *Surveillance of Greenhouse Gas Releases*. Project E1–058. Environment Agency, Bristol.

41. Kwarteng, A. Y. and Al-Enezi, A. (2004). Assessment of Kuwait's Al-Qurain Landfill Using Remotely Sensed Data. *Journal of Environmental Science and Health. Part A: Toxic/Hazardous Substances and Environmental Engineering*. Vol. A39, No. 2, pp. 351-364.

42. Perakis, K., Malliaros, D., Soulakellis, N., Silleos, G., and Kungolos, A. (2004). Remote Sensing and Statistics for the Investigation of Uncontrolled Landfill Sites: a Case Study in Lesvos Island, Greece. *Fresenius Environmental Bulletin*. Vol. 13, No. 5, pp. 378-384.

43. Dewidar, Kh. M. (2002). Landfill Detection in Hurghada, North Red Sea, Egypt, Using Thematic Mapper Images. *International Journal of Remote Sensing*. Vol. 23, No. 5, pp. 939-948.

44. Kirkland, J. (Waste Recycling Group Ltd) (2005). *Private communication in January 2005.*