

Advanced Remote Sensing Technology for Sustainable Land Development in Arid Lands

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Abstract

Researchers have recognized the potential use of multi-sensor remote sensing as one of the main data sources for monitoring and assessing the impact of rapid land use changes especially in fragile ecosystems such as drylands. Most mapping methods have been developed for multi spectral images since this type of imagery currently provides the longest Earth Observing (EO) records that can be used to construct time series for monitoring the status of arid and semi-arid ecosystems. The spatial resolution of older generation EO sensors imposes, however, a problem in relation to the spatial variability of ecosystem components and status, especially in urban areas. Several techniques have been developed to improve the detection and mapping of surface features that occur at sub-pixel resolution so that their spectral information can be used for feature identification and extrapolated in space and time. However, ground observation is often needed to characterize and verify the land surface components making up a pixel as well as to relate their spectral response to their actual physical stage (e.g., vegetation health, soil salinity and moisture content etc.). When ground information is not available or feasible, high resolution imagery can provide the required spatial information. This paper discusses current techniques in multi-sensor data analysis by illustrating their applications in urban and agricultural settings of arid lands.

Keywords: *multispectral, hyper spectral data, object-based classification, spectral angle mapper, arid land applications*

1. Introduction

Monitoring and management of land and water resources in arid lands is becoming a growing concern in many countries such as the United Arab Emirates that are experiencing a dramatic growth in recent decades. Fresh water resources in these regions are scarce in the absence of regular rainfall, permanent streams or lakes. At present, conventional water resources are not sufficient to satisfy the increasing demands from agriculture, oil and tourism industry (Rizk and Alsharhan, 2003). Although unconventional water resources such as desalination water and reclaimed (recycled) water are increasingly being used to supply the industry and large parts of the population (including farmers) with much needed water, this comes at a

relatively high cost. Coastal areas can be supplied with these unconventional water sources but inland areas are too far away from desalination plants and pipelines are a costly and often not feasible solution.

Agriculture is the principal consumer of global fresh water resources and the United Arab Emirates is no exception to this rule (CSIS, 2011). Currently more than half of its groundwater resources are being used for irrigation especially in inland areas. This has triggered a series of problems, such as the lowering of the groundwater table, which can ultimately lead to the depletion of the aquifer, soil and water salinization due to poor

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irrigation practices, and vegetation stress, which leads to a decline in crop productivity. Consequently, improved water-resources monitoring and management methods are needed in order to implement better water conservation measures, identify water and soil quality problems in a promptly manner, and restore depleted or deteriorated aquifer systems.

Recent advances in the study of arid and semi-arid ecosystems and their response to human activities have been made as a result of the adoption of innovative methodologies. The use of remote sensing technology is the most time- and cost-efficient way to monitor and assess the effect of land use changes on land degradation processes, such as soil pollution, erosion, crusting, salinization, and loss of near-surface water due to evapotranspiration. Such degradation processes are often triggered by none sustainable land use practices (e.g. inappropriate implementation of irrigated agriculture, inadequate waste water treatment by industry) and exacerbated by natural processes (e.g. extreme weather events, long-term climate change).

Researchers have recognized the potential use of multi-sensor remote sensing as one of the main data sources for monitoring and assessing the impact of rapid land use changes especially in fragile ecosystems such as drylands. Most mapping methods have been developed for multispectral images (e.g., Landsat TM/ETM+) since this type of imagery provides currently the longest Earth Observing (EO) records that can be used to construct time series for monitoring the status of a variety of ecosystems including arid lands. The spatial resolution of older generation EO sensors imposes, however, a problem in relation to the spatial variability of ecosystem components and status. Several techniques have been developed to improve the detection and mapping of surface features that occur at sub-pixel resolution so that their spectral information can be used for feature identification and extrapolated in space and time (Adams and Gillespie, 2006). One important aspect of remote sensing mapping is to extrapolate findings of in-situ studies (field spectroscopy, geophysical surveys) to larger areas. Field measurements are needed to characterize and verify the land surface components making up a pixel as well as to relate their spectral response to their actual

physical stage (e.g., vegetation health, soil pollution, salinity and moisture content etc.).

This paper discusses some current advances in remote sensing technology of arid lands by illustrating their potential applications in coastal urban and agricultural settings. Typically land surface characterization is done using spectral information from a single sensor. However, two factors underlie why multi-sensor data analysis is becoming increasingly important in land surface characterization. First, there are substantial improvements in land cover/use characterization using more information from multi-sensor data sets obtained at various spatial resolutions (from local to regional) as well as at various spectral and angular resolutions. Secondly, there is an exponential growth in the availability of data. A range of advanced EO sensors are expected to be launched in the next few years, including high resolution optical, hyper-spectral and microwave sensors. This opens up new opportunities to develop improved spatio-temporal analysis methods of urban and agricultural areas that currently show one of the highest rates of rapid changes in arid environments.

2. Monitoring Agriculture with Multi-Sensor Data

Satellite remote sensing techniques are very useful tools for detecting and mapping terrain features that may indicate the presence of surface and/or subsurface water in arid lands. One of the features that serve as direct evidence of favorable groundwater occurrence is vegetation. Monitoring its spatial and temporal distribution (seasonal/cyclical or progressive change) may provide useful clues about the type of water resources that are being tapped, i.e., runoff water, shallow groundwater or irrigation water from deeper aquifers. Knowing the extent and type of vegetation cover and its changes over time can help in determining (1) rates of evapotranspiration, (2) amount and type of water resources used in agriculture (all year irrigation or seasonal water resources), and (3) potential water-bearing structures or buried paleo channels that may serve as preferential flow paths for subsurface water.

To illustrate the use of multi-sensor satellite data the following example is given from a pilot study

conducted in the northern United Arab Emirates (UAE) where hyper spectral and multispectral images were combined to map and monitor agricultural areas. In this study (Koch et al., 2005) used Hyperion satellite data to extract the spectral signatures of various types and stages of vegetation patches (i.e. irrigated vs. non-irrigated agriculture, natural vs. planted vegetation) in order to improve the classification results of multispectral images such as those produced by the ASTER instrument.

Hyperion is one of the few currently available hyper spectral satellite sensors that produces images with numerous and narrowly spaced spectral bands (220 bands). Although the sensor's spatial resolution and global coverage is relatively low (pixel size is 30 m and image swath width is 7.5 km), it generates spectral signatures with a high degree of definition compared to multispectral sensors such as ASTER (9 reflective bands). Figure 1 shows a comparison between two spectral curves (Hyperion vs. ASTER) extracted from the same pixel area (black cross in Figure 1 left side). This is an area that corresponds to a coastal mangrove zone in UAE. While the ASTER spectral curve consists of few spectral measurements (9 bands), the Hyperion spectral curve shows a better defined curve with an almost continuous spectrum (158 useable bands). Both

spectral signatures do show similar shapes that are characteristic of healthy vegetation. However, numerous absorption and reflection features visible in the hyper-spectral curve can provide important clues about the identity of the type of vegetation, in this case mangroves. This high resolution spectral information can be used to improve classification results of multispectral data by using hyper-spectral curves as reference vectors or end members. The classifier then matches the unknown multispectral image pixel spectra against a set of reference vectors or end members and labels them according to the best fit.

One of the reasons for using higher resolution spectral data in conjunction with lower resolution spectral data is that multispectral images such as ASTER have the advantage of providing the spatial and temporal coverage of extended areas required for mapping and monitoring large areas undergoing rapid and often irreversible changes. Examples of such changes are seasonal changes responding to plant phenology and/or crop rotation, or progressive changes such as urban sprawl and land degradation process (e.g. soil salinization or contamination). In order to translate the hyper spectral information into a lower spectral resolution image, (Koch et al., 2005) adopted the following approach:

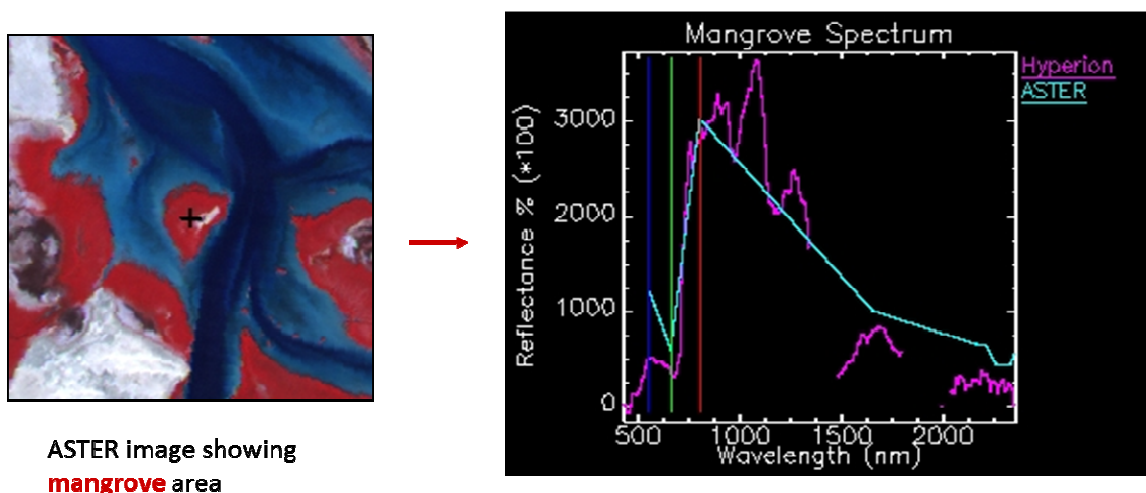


Figure 1: Comparison of ASTER and Hyperion spectral curves for a coastal mangrove area

(1) selection of same image acquisition dates (Hyperion and ASTER), (2) conversion of DN to reflectance values and removal of the haze component, (3) application of a NDVI mask to limit the collection of spectral signatures (end members) to vegetated areas, (4) derivation of vegetation end members from the hyper spectral data (Hyperion) and translation to the multispectral resolution (ASTER) using a spectral filter, (5) application of a supervised classification procedure, for example, the Spectral Angle Mapper (SAM), (6) validation of the classification results using field observation (photographs) as well as a high resolution image (Ikonos) covering part of the data set, and finally, (7) evaluation of the classification results in terms of detecting and characterizing vegetation type and condition as related to water resources availability. This procedure is schematically outlined in Figure 2. The results indicate that the SAM classification method using hyper spectral end members produced better results than the same method using multispectral end members. Figure 3 gives an example of the SAM classification result for the coastal zone of Ras Al Khaimah in northern UAE. Here the vegetation map clearly differentiates coastal mangrove vegetation from two types of agricultural fields, namely

crop fields (e.g. alfalfa) and tree plantations (e.g. fruit and palm trees). In addition, some large grassy areas such as parks in the city were picked up by the SAM classifier. This improved separation of vegetation types was made possible by using Hyperion spectral end members to train the classifier applied to ASTER.

The increased spectral resolution of hyper-spectral imaging systems provides the opportunity to better discriminate between surface components (vegetation, soil, rock types) as well as subtle variations within them. This results in a better selection of end members or reference vectors, which can be used to construct site-specific spectral libraries. Spectral libraries contain a set of unique spectral signature of surface materials that can be used for classification and change detection studies using broader band images (e.g. Landsat TM/ETM+, ASTER) that provide better spatial and timely coverage of large areas. When coupled with field observation and sampling, spectral libraries can be used to quantify important physical and chemical properties of surface materials (mineral composition, grain size, vegetation species) as well as their abundances (end member fraction maps) (Schmid et al., 2004, 2005).

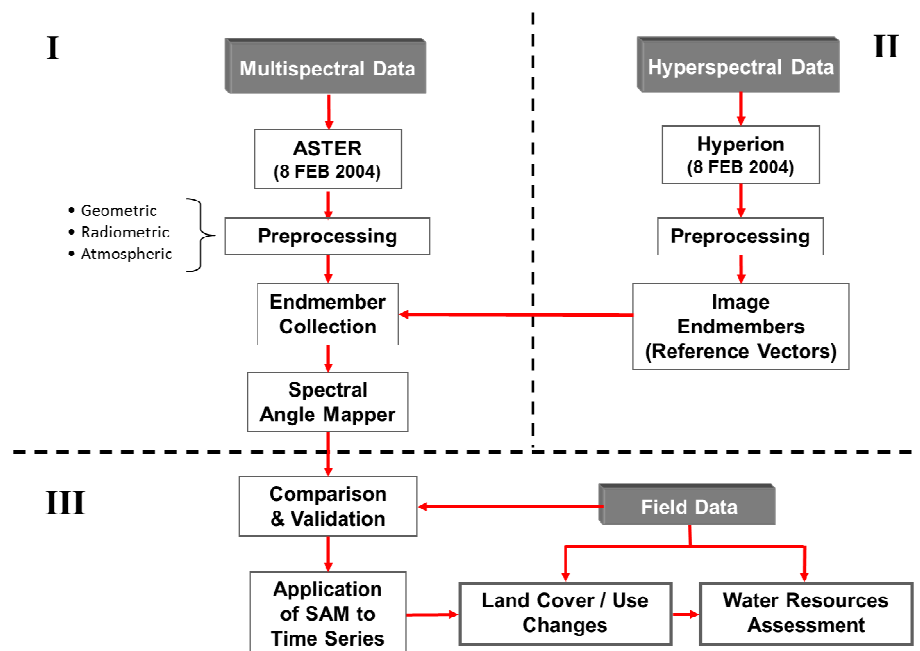


Figure 2: Flow diagram of multi-sensor data analysis (stages I & II) and field validation (stage III) of resulting classification outputs

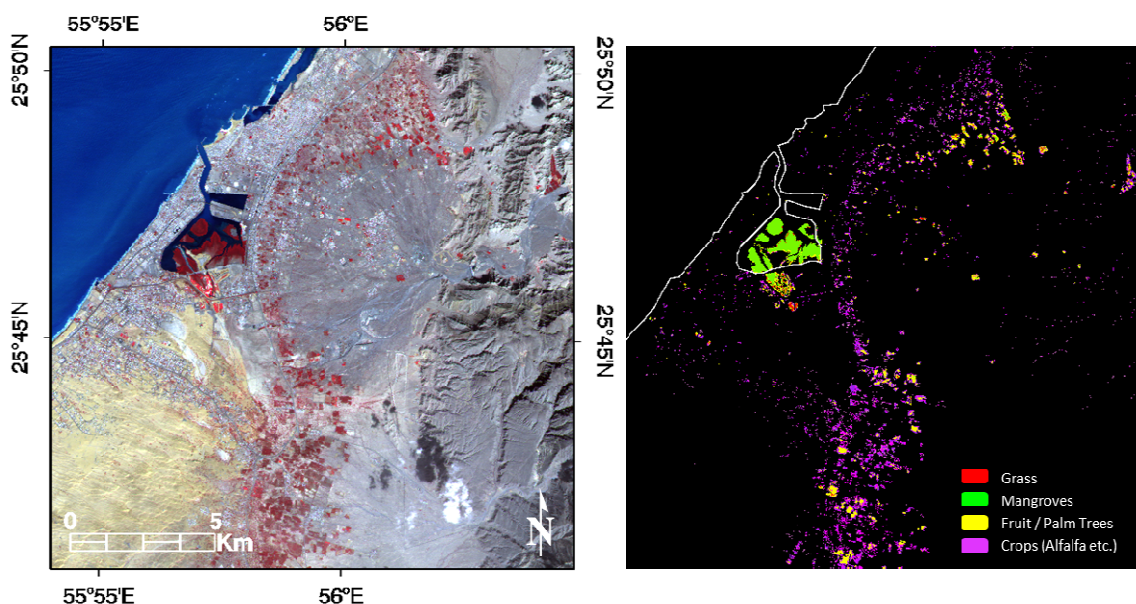


Figure 3: Classification of coastal area vegetation in UAE. By spectrally matching multispectral pixels with hyper-spectral reference vectors four distinctive vegetation groups were mapped.

For environmental applications (e.g. water resources) the construction of a spectral library requires the acquisition of hyper-spectral data over a well-characterized study area for which detailed field observation exist. Extrapolation of well-defined spectral signatures (end members) to areas outside the test sites can be achieved through spectral matching, spectral un-mixing and other analytical techniques.

One of the applications of spectral libraries in water resources studies is mapping and monitoring salt-affected soils and vegetation as related to irrigation. Salt-affected soils are known to reduce the productivity of agricultural land. The processes leading to soil and eventually groundwater salinization are generally a combination of geologic and climatic factors coupled with inappropriate irrigation practices. The UAE has seen a substantial increase in the development of large irrigation projects in the last 30 years. First signs of vegetation stress and soil salinization have been reported in recent years along the eastern coast of UAE and are believed to be largely due to agricultural practices and not to salt water intrusion (Murad and Krishnamurthy, 2004). Time series analysis of broad-band images together with detailed spectral information on soils and vegetation types may confirm the relationship

between land use change (irrigation) and increased levels of soil and water salinity (Schmid et al., 2009).

3. Multi-Sensor Data Fusion for Water Resources Mapping

Another important aspect related to monitoring changes in soil and near surface water salinity levels is the groundwater flow system. Certain agricultural areas may be less affected to changes in soil/water quality than others simply because the aquifer system receives direct recharge from the mountain areas through preferential groundwater flow paths. Radar images of sand desert areas have revealed channels of ancient rivers, formed during pluvial climate periods, which are buried beneath accumulations of sand. It follows that much of the water collecting in the depressions is stored in the underlying porous sandstone rocks and their fracture zones that are connected to the recharge areas in the mountains. Identifying and understanding the relationship between paleo-channels and fracture systems may lead to the discovery of large concentrations of groundwater in the substrate (Gaber et al., 2011).

In this context, data fusion of multi-source satellite images promises to improve feature extraction by:

1. Combining visible/infrared (VNIR) optical data with data from active synthetic aperture (SAR). This will enable correlation of surface and subsurface features.
2. Combining high resolution with medium resolution sensor images. This will allow the use of archival imagery for land surface change detection and monitoring.

The motivation behind data fusion is that images from microwave and optical sensors contain complementary information that can be used synergistically to better discriminate different surface material classes as well as to establish relationships between surface and subsurface features (e.g., sand deposits and fracture systems mapped from VNIR data and subsurface paleochannels recognized from SAR images).

4. Feature Extraction in Urban Areas

The previous sections highlighted the benefits of using hyper-spectral, multispectral and microwave satellite data for mapping and assessing land and water resources in arid regions. In most cases the spatial resolution of current hyper spectral and multispectral sensors is adequate for detecting and mapping surface features such as large-scale irrigated agriculture and geological structures and landforms. However, for urban areas mapping the spatial and spectral heterogeneities require a different approach. In those areas high resolution imagery is the preferred mapping means because smaller scaled features such as building blocks, street patterns and greenways can be more readily identified and extracted. Hence, a new classification method called object-based classification or feature extraction has gained popularity in recent times (Blaschke et al., 2008).

According to (Heldens et al., 2011) remote sensing technology can contribute enormously with its data collection capacity to four main urban applications, namely (1) urban development and planning, (2) urban growth assessment, (3) urban risk and vulnerability assessment, and (4) urban climate. Furthermore, there are two important aspects of remote sensing technology that when combined increases its potential application in urban planning and monitoring. Very high spatial resolution sensors (e.g. Ikonos, QuickBird, WorldView-2) pro-

vide spatial information required to characterize and monitor cities while very high spectral resolution sensors, also called imaging spectroscopy, enables urban surface material mapping. The spatial information is needed to discriminate the shapes and boundaries of features and produce a spatial inventory of the urban landscape (i.e. urban structure and layout). The spectral information is needed for surface material mapping to identify features based on their physical and chemical compositions. The combination of both mapping technologies is desired but still a challenge because of the disparate scale at which high spatial and high spectral resolution sensors operate.

To illustrate the complementary nature of both high spatial resolution and high spectral resolution sensors the following example is given of an urban area in Sharjah, UAE. A section of an Ikonos image shows an industrial zone at the outskirts of Sharjah (Figure 4A). At its center is a large disturbed surface area that represents water (or brine) collection basins with patches of exposed saline soils. Surrounding the area are building blocks and streets as well as a sport field (upper left corner). In order to map and monitor the disturbed surface area a supervised classification was performed using an object based approach. The procedure is illustrated in Figure 4 and follows like this: first the image is segmented into relatively homogenous regions by using a set of criteria such as edge detection or intensity gradients (texture). The objective is to effectively delineate the boundaries of major homogeneous features (Figure 4B). Next training sites (segments) are chosen that best represent the features to be mapped (Figure 4C), followed by the selection of an appropriate classifier, in this case the K Nearest Neighbor classifier was used (Figure 4D). The resulting classified image shows eight classes with significant class confusion occurring mainly in the disturbed surface area and less in the surrounding urban area. Clearly the lack of spectral information of the Ikonos data (with only four spectral bands) contributed to the classifier's poor performance in the water/soil polluted area, whereas the urban structures are relatively well defined by regular patterns of buildings, streets and sandy or vegetated patches.

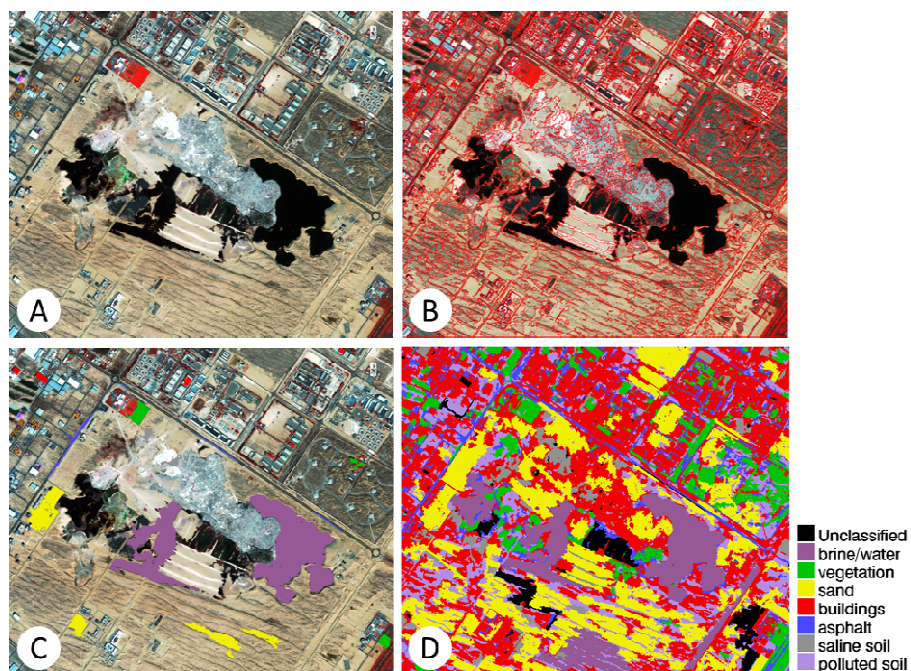


Figure 4: (A) Ikonos image of an industrial area in Sharjah, UAE; (B) image segmentation; (C) training site selection; (D) object based classification result

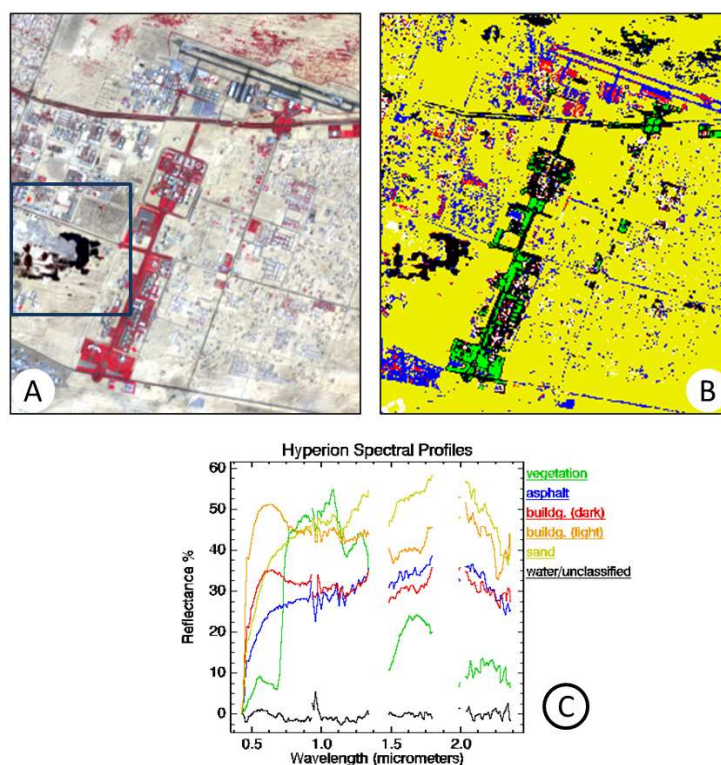


Figure 5: (A) Hyperion image enclosing Ikonos image area of industrial site; (B) supervised classification result using reference vectors shown in (C); note that the spectral curve legend is color coded and corresponds to class colors in (B)

In the second classification example a Hyperion image was used to extract reference vectors or spectra of characteristic urban features and surrounding surfaces. A section of the Hyperion image was selected that encloses the same area as in the Ikonos image (rectangular box in Figure 5A). Figure 5B shows the classification result produced by the spectral angle mapper classifier using the reference spectra in Figure 5C. The colors of the six spectral curves match the class colors of the classification result. The reference spectra show clearly contrasting features that helped reduce class confusion in the resulting classification. However, the low spatial resolution of the Hyperion image (30 m) compared to the Ikonos image (4 m) meant that small objects such as individual buildings or small patches of soil polluted areas could not be discriminated and therefore, could not be identified. Both imagery types have their pros and cons and a combination of both would be desirable to solve feature detection and identification problems due to low spatial or spectral definition.

5. Conclusions

As more people continue to migrate and live in cities than in rural areas more attention needs to be paid to sustainable development of urban areas and their surroundings. In arid lands this means that scarce resources such as fertile soil and water are at higher risk of getting depleted and/or polluted as population increases in those regions. Advanced remote sensing technology enables and continues global mapping and monitoring of land and water resources at increasing spatial and spectral resolutions. Examples of applications of high spatial and high spectral resolution imagery were presented in this paper. It is expected that in the coming years data fusion and analysis of disparate data sets (from very high resolution optical, hyper-spectral, thermal and microwave sensors) will become the norm and not the exception in order to take advantage of complementary sensors' strengths. For urban applications this means that urban surface material mapping and urban feature extraction will enable better characterization and monitoring of urban growth, resources demands and usages.

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