COMPARISON OF AUTOMATED METHODS FOR IDENTIFICATION OF URBAN SURFACES USING AIRBORNE HYPERSPECTRAL DATA OF REFLECTIVE AND THERMAL WAVELENGTH RANGES

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KEY WORDS: hyperspectral, urban biotope mapping, linear spectral unmixing, endmember selection, multispectral classification, shape-based classification

ABSTRACT

The urban environment is characterised by an intense multi-functional use of the available space, where the preservation of open green spaces is of special importance. For this purpose area-wide urban biotope mapping based on CIR aerial photographs has been carried out for the large cities in Germany during the last 10 years. Because of dynamic urban development and high mapping costs, the municipal authorities are interested in effective methods for mapping urban surface cover types which can be used for evaluation of ecological conditions in urban structures and supporting updates of biotope maps. Against this background airborne hyperspectral remote sensing data of the DAIS 7915 instrument have been analysed for a test site in the city of Dresden (Germany) with regard to their potential for material-oriented identification of urban surface cover types. Previous investigations have shown that the high spectral and spatial variability of these data require the development of special methods which are capable of dealing with the resulting mixed pixel problem in it's specific characteristics in urban areas. Earliest methodological developments led to an approach based on a combination of spectral classification and pixel-oriented unmixing techniques to facilitate sensible endmember selection based on the reflective bands of the DAIS instrument. This approach was extended by a shape-based classification technique including the thermal bands of the DAIS instrument to improve the detection of buildings during the process of identifying of seedling pixels which represent starting points for linear spectral unmixing. In this paper the results for both approaches are presented and compared. These investigations show that the quality of seedling identification has a strong influence on the final unmixing result. This new approach increases the reliability of differentiation between buildings and neighbouring streets leading to more accurate results for the spatial distribution of surface cover types. Thus, the new approach significantly enhances the exploitation of the information potential of the hyperspectral DAIS 7915 data for an area-wide identification of urban surface cover types.

1 INTRODUCTION

Urban areas are characterised by an intense multi-functional use of the available space which leads to a high spatial frequency of surface cover changes. The resulting small-sized urban structures are mostly dominated by various types of artificial surface materials. Under these conditions preservation of remaining green spaces is one of the main tasks in ecological urban planing. For this purpose detailed mapping of urban biotopes is carried out based on analog interpretation of CIR aerial photographs and field investigations (Elscher, 1988; Sukopp and Weiler, 1988; Sukopp and Wittig, 1993). Because of the high pace of city development and limited financial means of the municipal authorities these conventional mapping approaches are too time consuming and expensive in order to accomplish updates on a regular basis. Under these conditions the potential of airborne hyperspectral data for automated spectrally-based classification of urban surfaces into ecologically relevant categories is investigated. Such classifications can form the basis for the development of effective digital approaches for evaluation of biotope types and for change detection to support updates.

In the past, automated analysis of digital scanner remote sensing data within urban areas was restricted due to limited spectral and spatial resolution of satellite remote sensing data (Bähr et al., 1993; Jensen et al., 1994; Ormsby, 1992; Spitzer and Heinz, 1997). These problems have been overcome with the wider availability of airborne hyperspectral scanner data (AVIRIS, DAIS, HYMAP) and high resolution satellite data (IKONOS). Although these data represent urban surfaces in high spatial and spectral detail, their automated analysis is strongly affected by the mixed-pixel problem, since the recorded radiation is an integrated sum of radiances of all types of surfaces within the instantaneous field of view (IFOV) of the sensor. Thus, there is a strong need for the development of automated approaches which are capable of dealing with the high spectral and spatial variability of urban surfaces.

In this study data of the Digital Airborne Imaging Spectrometer DAIS 7915 are analysed for a test site in the city of Dresden (Germany). Previous methodological developments for the analysis of hyperspectral DAIS 7915 data of urban areas resulted in an approach for identification of urban surface cover types which is based on a combination of spectral classification and pixel-oriented unmixing techniques using the reflective wavelength range (Segl and Roessner, 1999). This way, sensible results could be obtained for mixed pixels. However, evaluation of the results also showed limitations of material oriented identification of urban surfaces which mainly consist of confusion between buildings and open spaces covered by similar artificial materials (Roessner et al., 1998). This paper describes the extension of this developed approach by incorporating a new algorithm for shape-based detection of buildings and new rules for an optimised pixel-oriented endmember selection. The development of a shape-based technique is motivated by inclusion of image data of the thermal wavelength range which are characterised by a relatively sharp thermal contrast between buildings and open spaces. The results of this new approach are compared to results of previous investigations which were obtained only using the reflective wavelength range of the DAIS 7915 data.

2 DATA AND OBJECTIVES OF HYPERSPECTRAL IMAGE ANALYSIS

The hyperspectral image data were obtained for a 10 by 4.5 km north-south transect in the city of Dresden (Germany) by the 79-channel Digital Airborne Imaging Spectrometer DAIS - 7915 (Strobl et al., 1997) during a DAIS-LSF (DAIS-Large-Scale-Facility) flight campaign carried out by the DLR (Deutsches Zentrum für Luft- und Raumfahrt e. V.) in July 1997. The DAIS 7915 instrument records data in 72 reflective bands covering the VIS/NIR (32 bands) and SWIR (40 bands) part of the spectrum. The sensor also enables measurements in the thermal part of the spectrum by 7 thermal bands in the wavelength range between 3 and 13 μm which were used in this study. The data were recorded on July 23, 1997 between 11:23 and 11:38 A.M. local summer time (solar zenith angle of 37.5°) from an altitude of 3500 m resulting in a GFOV of 11.5 m (IFOV of 0.189°) and a pixel size of 6.1 m (scan angle of 0.1°). The test site is situated east of the historic centre of Dresden and reaches from the city centre south of the river Elbe in the north to suburban areas at the southern end.

The city of Dresden is one of the largest cities in Germany. In its function as the capital of the state of Saxony the city represents the political, administrative and economic centre for a large region leading to an intense multi-functional use of the available space. Under these conditions, municipal authorities which are responsible for urban planing have to deal with a wide range of economic and ecological interests. In this connection the preservation of open green spaces is of special importance, since such spaces play a key role for the environmental quality of a city. For this purpose the city of Dresden has been carrying out detailed mapping of urban biotope types in the scale of 1:5000 based on CIR aerial photographs and field investigations.

Categories of urban biotope mapping originate from main types of urban landuse, such as non-industrial built-up areas, industry and business, areas of traffic, areas of special use (e.g. waste disposal), green spaces of intense maintenance, wetlands, forests or water. These categories are further distinguished by functional and structural aspects. Function is playing the major role in built-up areas, whereas mostly vegetated areas are classified according to leading plant communities up to single species. Mapping of biotope types is a complex process in which a wide range of parameters has to be evaluated. Decisions often have to be made on the basis of quantitative estimates of the coverage of various surface types, such as vegetation, buildings and open spaces. Areas of traffic are of special importance as boundaries between biotopes.

Because of the high pace of urban development the municipal agency for the environmental protection of Dresden has already carried out the second complete urban biotope mapping in 1999 after the first inventory in 1993 (Landeshauptstadt Dresden, 1993). Since the costs for complete inventories based on analogous mapping approaches are very high, municipal authorities are interested in effective methods for mapping of urban surface cover types which can form the basis for the determination of quantitative parameters for ecological evaluation of urban structures. In this connection multitemporal inventories of urban surface cover types also yield the potential for identification of areas of change which then can be subject to selective detailed biotope mapping.

Against this background high resolution hyperspectral remote sensing data are regarded as a valuable source of information for material-oriented identification of urban surface cover types. In this context, the goal is to develop methods for image analysis which are capable of exploiting the full potential of spectral and spatial information of these data for an area-wide detailed inventory of surface cover types. Based on the categories of urban biotope mapping, the main surface cover types of interest are buildings, areas of traffic, non-vegetated open areas with artificial coverage, bare soil, water and vegetated areas. Due to the small-sized urban structures and limited spatial resolution of hyperspectral imaging systems special attention has to be paid to the problem of mixed pixels, representing a challenge to standard methods for multi-band image classifications.

3 APPROACH AND ITS APPLICATION TO TEST SITE

Previous investigations have shown that standard spectral classification methods – Maximum-Likelihood-Classification, Spectral Angle Mapper and Linear Spectral Unmixing – have limitations in identification of urban surface cover types based on high resolution hyperspectral image data (Segl and Roessner, 1999). These problems are mainly caused by the big variety of distinct urban surface cover types which partly show similar spectral characteristics. The spectral variability is further increased by the high number of mixed pixels. This situation leads to problems for classification approaches which require spectral template classes for each surface cover type and its mixtures. In contrast, the spectral unmixing approach requires less a priori information, because the spectrum of a pixel is modelled by the mixture of different endmember (EM) spectra (Shimabukuro and Smith, 1991). Although, linear spectral unmixing seems to be the more suitable approach for hyperspectral data analysis, its successful application in the urban environment requires the development of problem-oriented techniques for endmember selection.

Linear mixture models which are described in more detail in Segl et al. (1999) require the determination of spectrally distinct endmembers which must not be described as linear combinations of other endmembers. Additionally, a high number of simultaneously used endmembers increases the likelihood of false identification. These mathematical constraints do not meet the real conditions in the urban environment which require a wide range of endmembers to perform an area-wide meaningful identification of urban surface cover types. Therefore, the number of possible endmember combinations has to be reduced for each pixel. For this purpose a multi-technique approach (Fig. 1) was developed which combines spectral classification and linear spectral unmixing (Segl et al., 2000).

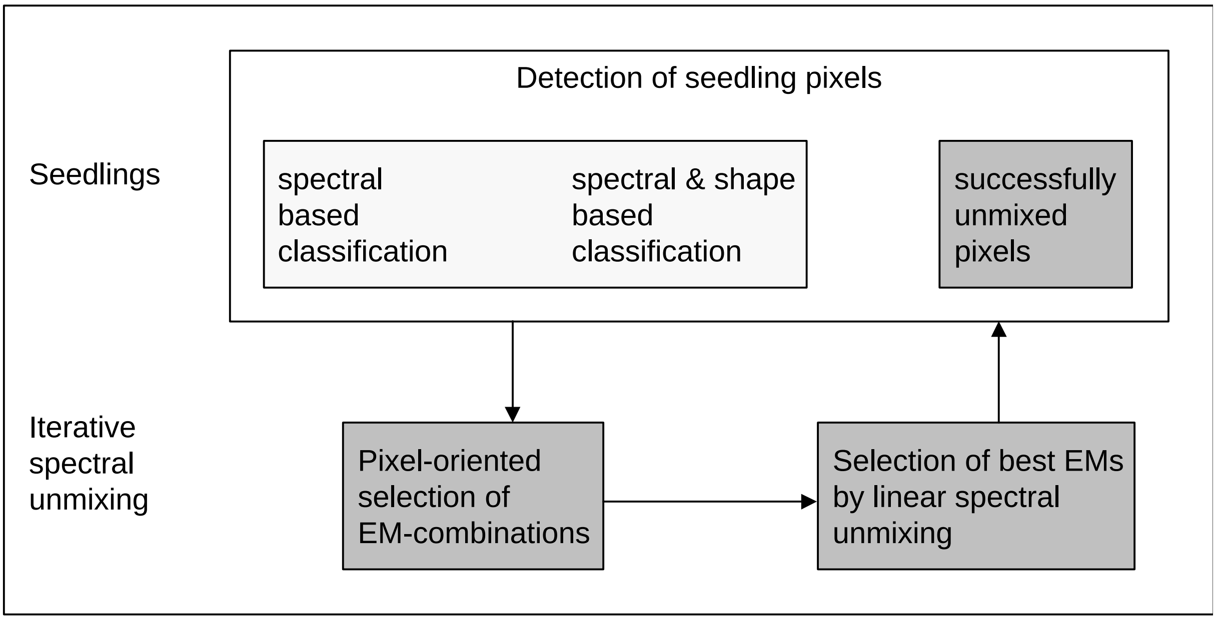

Fig. 1 Overall approach for identification of urban surface cover types combining spectral and shape-based classification with pixel-oriented unmixing technique for optimised endmember (EM) selection

The first step is the thematic and spectral determination of endmembers (surface cover types). In a second step spectrally pure pixels representing these endmembers are identified in the image data as spectral and spatial seedlings for the following unmixing procedure using a supervised Maximum-Likelihood classification (Segl and Roessner, 1999) or a combined shape-based and spectral classification technique (Segl et al., 2000). These seedling information represent the a priori knowledge for the definition of the most likely endmember combinations of mixed-pixels in the neighbourhood of the spectrally pure pixels during an iterative spectral unmixing procedure. In the following this approach is described in more detail in its application to the test site in the city of Dresden

3.1 Determination of training and endmember information

Thematic and spectral assessment of training (classification) and endmember (unmixing) information for the relevant surface cover types (Tab. 1) was based on field investigations including spectral field measurements with an ASD field spectrometer, 1:5000 land register maps, CIR aerial photographs and spectral analysis of the hyperspectral image data. Vegetated areas were differentiated into the two main groups of tree/bush and grassy vegetation, whereas the latter group was further distinguished by the intensity of maintenance (meadow and lawn). Non-vegetated areas were subdivided into open spaces and buildings and further differentiated by their material properties and colour. In case of non-vegetated open spaces with artificial coverage areas of traffic were distinguished from the other ones due to their great ecological importance as boundaries between biotopes. Final determination of training and endmember information leading to the determination of subtypes and their variations listed in Tab. 1 was an iterative process which included evaluation of spatial distribution and material-oriented identification of the resulting seedling pixels (3.2).

surface cover types	subtypes	variations	number of pixels	colors in legend (Fig.3)
water	rivers	2	157	Blue
	lakes/ponds	2	238	
trees/bushes	trees/bushes	4	1258	Dark green
lawn/meadows	meadow	2	155	Light green
	well tended lawn	1	208	
bare soil	natural soil	3	110	Light brown
	agricultural soil	1	67	
roofs	tiles - new	1	96	Orange
	tiles - old	1	143	
	tar paper - bright	1	477	Red
	tar paper - dark	1	59	
	metal	1	166	Dark red
	glass	2	79	Magenta
	other materials	4	125	Cyan
areas of traffic	asphalt	1	36	Brown
	pavement	1	24	
	mixed surfacing	2	160	
other open spaces	loose chippings - dark	1	42	Dark yellow
	loose chippings - red	3	138	
	concrete	1	70	Yellow

Tab. 1 Training information for spectral-based identification of seedlings and spectral characterisation of endmembers

3.2 Identification of seedlings for pixel-oriented unmixing

The quality of the initial spatial and spectral determination of seedlings is crucial for the success of the following unmixing procedure (3.3). For this purpose, two methods have been developed which were both applied to the test site (Fig. 3). Using only the reflective bands of the DAIS instrument, seedling identification is performed by a supervised Maximum-Likelihood classification using very low Mahalanobis distances based on the training information for all surface cover types listed in Tab. 1. For this classification only a selected number of reflective DAIS-bands (6, 11, 15, 33, 40, 50, 60) is used which contain the most contrasting spectral information for all relevant surface cover types.

The results (Fig. 3) show best identification of seedlings for relatively large and homogenous areas, such as lawns and open non-vegetated grounds. Problems occur in the identification of small and/or spectrally ambiguous surfaces, such as buildings and streets. Only large buildings are represented as seedlings. In areas of roads a number of seedlings are identified as buildings (mostly confusion between asphalt and roofing tar paper). Heterogeneous areas dominated by small-sized structures are characterised by a lack of seedling pixels. These observations indicate that additional parameters have to be considered to improve area-wide identification of seedlings.

Incorporation of the thermal bands of the DAIS instrument allows the extraction of object shapes as an additional parameter for seedling identification using image segmentation techniques. A special method for shape-based classification was developed (Segl et al., 2000) to achieve a better spatial and spectral representation of buildings among seedlings. Since the developed method contains an iterative segmentation approach which is based on grey-value thresholds, single-band images are required where the objects of interest – in this case buildings - show a distinct spectral contrast to their surroundings. Due to the large variety of roofing materials, different single bands and ratios including the thermal and reflective wavelength ranges had to be determined and classified to obtain a complete building mask (Fig. 2).

In a second step this mask was applied to the original DAIS-bands which were selected for the Maximum-Likelihood classification. For those pixels which represent buildings in the mask, a Maximum-Likelihood classification was performed which only uses the training information for buildings (Tab. 1). Seedling pixels for buildings are determined according to their spatial position and their spectral characteristics. The non-building pixels of the mask are classified separately using the remaining training information. Both results are combined and form the seedlings for the iterative unmixing process (Fig. 3).

The comparison of the two methods for seedling identification (Fig. 3) shows a clear improvement by including shape-based parameters into the identification of seedlings. This way spectral ambiguities between buildings and sealed open spaces could be resolved and the number of buildings which area represented by seedlings was significantly increased.

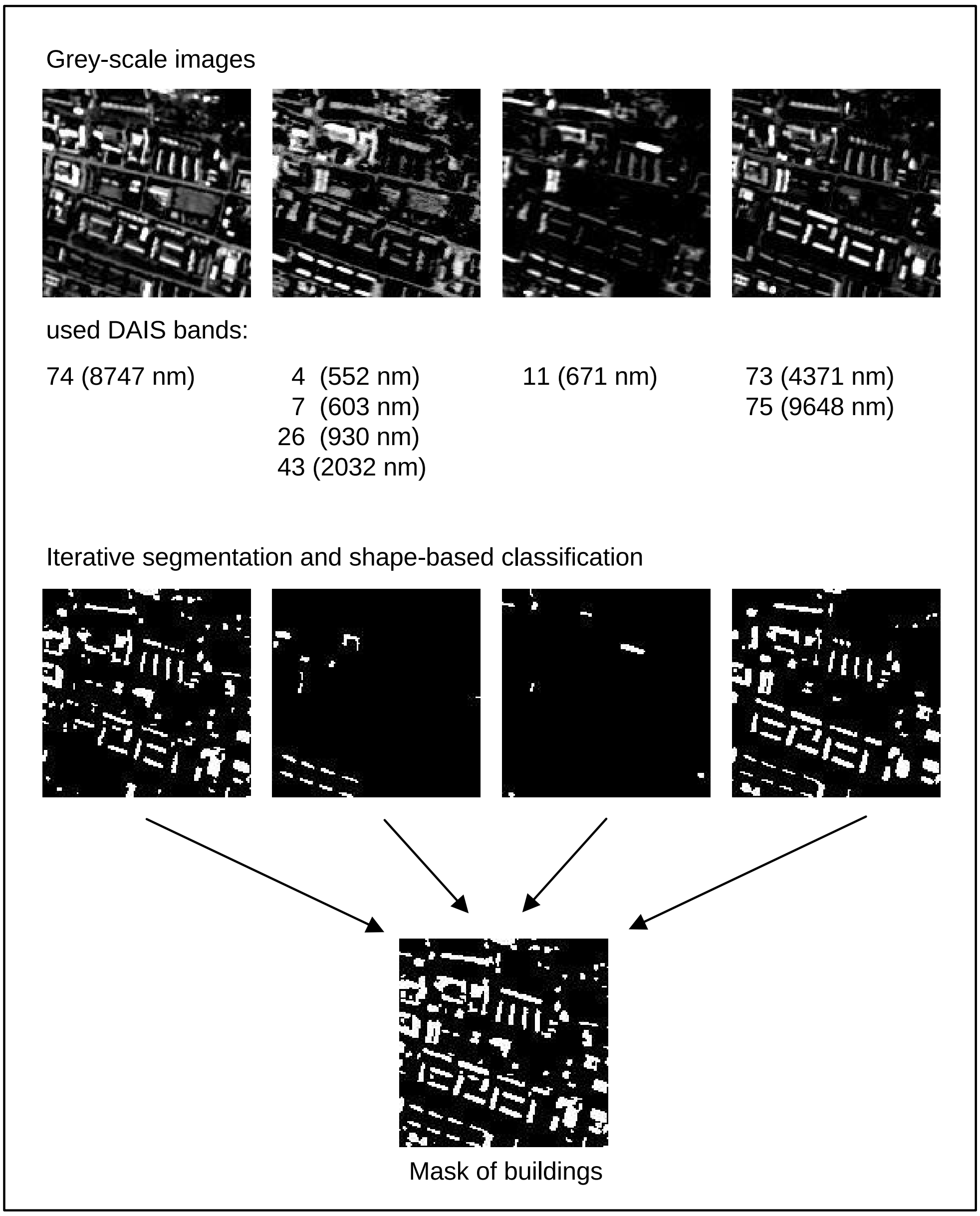

Fig. 2 Iterative segmentation and shape-based classification for identification of buildings using selected DAIS bands of the reflective and thermal wavelength ranges

3.3 Pixel-oriented selection of endmember combinations and iterative spectral unmixing

The area-wide determination of seedlings is the first step to introduce spatial and thematic control into the unmixing procedure which has the goal of reducing the number of possible endmember combinations during linear spectral unmixing. Based on a standard method for linear spectral unmixing – the constrained least-squares method (Shimabukuro and Smith, 1991) - a new approach was developed which takes into account the special conditions of urban areas consisting of a large number of endmembers (Tab. 1) and small-sized heterogeneous spatial structures (Segl and Roessner, 1999). In this method unknown pixels are unmixed in an iterative way based on the spatial distribution of initially classified seedlings or already successfully unmixed pixel in their neighbourhood. An additional constraint is the limitation to a maximum of two endmembers for each pixel. The iterative unmixing procedure contains additional rules to guide the selection of endmember combinations. First, all possible endmember combinations are defined and stored in a list which includes the option to exclude certain endmember combinations which do not make sense from a thematic point of view or which have a very low likelihood of appearance. This way, the influence of possible spectral similarities between endmembers is decreased during the unmixing procedure. Based on the spatial distribution of seedlings and this list of all possible endmember combinations, the most likely endmember combinations are analysed for each pixel. In the search for suitable endmember candidates, seedlings in a predefined neighbourhood range have first priority and their spectral combinations are tested based on the root-mean-squared (rms) residuals. If none of the combinations passed the test, the neighbourhood is extended and additional directional constraints are introduced (Segl et al., 2000). However, if no endmember is found in the neighbourhood, the pixel is ignored during the current stage of the process. This iterative approach leads to the spatial growing of identified pixels around classified seedlings or pixels

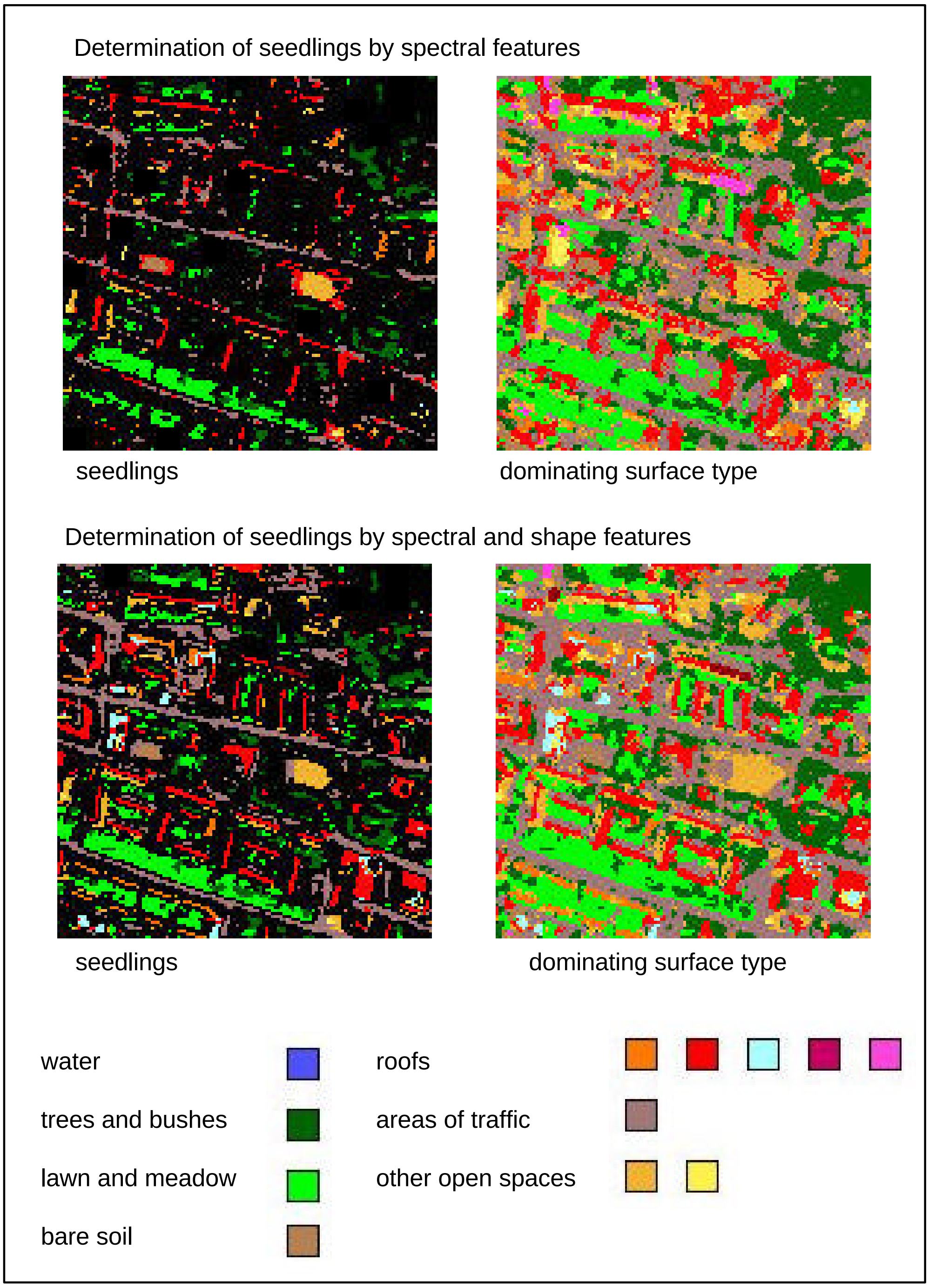

Fig. 3 Comparison of results of pixel-oriented unmixing for the two different methods of seedling identification (see Tab. 1 for detailed key to colours)

which were successfully unmixed during earlier iterations. In contrast to classification techniques, the result of unmixing-based identification can consist of two endmembers which both have to be considered during further selection of endmember candidates. This iterative procedure is repeated until no more pixels are left which can be unmixed under the condition of fulfilling the test criterion. For each pixel the final result consists of the identified endmember(s) and their abundances which vary between 50 and 100 % for the dominating endmember and 1 and 49% for the endmember of subordinate influence. The final results which were obtained for both methods of seedling identification are shown in Fig. 3 and further discussed in the following section. Note that the 2-D representation of the results in Fig. 3 requires a simplification assigning 100% pixel coverage to the class with the dominating abundance for each pixel.

4 RESULTS AND DISCUSSION

In this study two results are presented for identification of urban surface cover types which are based on two different methods for identification of seedling pixels as the starting point for iterative linear spectral unmixing (Fig. 3). The first result is obtained using only spectral parameters for identification of seedlings based on a Maximum-Likelihood-classification of selected DAIS bands covering the reflective wavelength range. In the process of thematic and spectral determination of representative endmembers 35 spectral categories could be defined (Tab. 1) which resulted in the identification of seedlings covering about 33% of the study area. Because of the described problems in identification of seedlings by this method (3.2), a second method was applied where identification of seedlings is additionally assisted by a shape-based detection of buildings which includes DAIS bands of the thermal wavelength range. This way a spectrally and spatially improved identification of seedlings could be achieved within areas of buildings and sealed open spaces (mainly streets). Using this method the area covered by seedlings amounts to about 35% of the area.

For both sets of seedlings linear spectral unmixing was performed using every second DAIS band covering the reflective part of the spectrum. For both methods the algorithm stopped after 10 iterations when 100% of the study area was classified. A comparison of both final results (Fig. 3) shows that the improvement in identification of seedlings has a strong influence on the final unmixing result. It especially increases the reliability of identification of buildings and their separation from neighbouring streets which also leads to more accurate results for the spatial distribution of surface cover types. Statistical analysis of such distributions (Roessner et al., 1998) can be used as one parameter for the evaluation of ecological conditions in different urban structures. Thus, the new approach for spectral and shape-based unmixing significantly enhances the exploitation of the information potential contained in the hyperspectral DAIS data whereas incorporation of data recorded in the thermal wavelength range play a key role for improved identification of non-vegetated urban surface types.

The obtained results show the great potential of hyperspectral image data for detailed inventories of urban surface cover types. However, successful exploitation of these data for area-wide analysis of such highly heterogeneous surfaces requires special approaches which allow a combination of different image processing techniques including the possibility of incorporating expert knowledge in the identification process. At the present stage of development limitations mainly occur due to the rather large pixel size of the used DAIS data (GFOV of 11.5 m). This leads to problems especially in areas of small-sized structures such as suburban neighbourhoods with single small houses surrounded by densely vegetated areas. Insufficient spatial resolution also decreases the quality of statistical analysis because of complex mixing situations. During future work the influence of the pixel size on the quality of the unmixing result will be studied using higher resolution hyperspectral DAIS and HyMap data. Improved spatial resolutions will also require the development of more flexible algorithms for shape-based classification of various urban objects.

ACKNOWLEDGEMENTS

We would like to thank the municipal agency for the environmental protection of Dresden (Untere Naturschutzbehörde, Grünflächenamt) for providing CIR aerial photographs and the results of the 1993 urban biotope mapping for the city of Dresden.

REFERENCES

Bähr, H.-P., Jacobs, H., Sties, M., 1993. Mehrfache Landnutzungsklassifizierung und Analyse der Nutzungsänderung im Oberrheingraben. Report 1. Statuskolloquium des Projektes "Angewandte Ökologie" (PAÖ)., Landesanstalt für Umweltschutz Baden-Württemberg, Karlsruhe - Germany, vol. 7, pp. 411-422.

Elscher, T., Tielbaar, H.-C., 1988. Einsatz von Colour-Infrarot-Luftbildern in der Landschaftsplanung. Landschaft und Stadt, 1, pp. 26-34.

Landeshauptstadt Dresden, Dezernat für Umwelt und Kommunalentwicklung (Hrsg.), 1993. Report Landschaftsplan Teil1: Bestandeserfassung und Bewertung; Teil2: Entwicklungs- und Maßnahmekonzept.

Jensen, J.R., Cowen, D.J., Halls, J., Narumalani, S., Schmidt, N.J., Davis, B.A., Burgess, B., 1994. Improved urban infrarstructure mapping and forecasting for Bellsouth using remote sensing and GIS technology. Photogrammetric engineering and remote sensing, 60(3), pp. 339-346.

Ormsby, J.P., 1992. Evaluation of natural and man-made features using Landsat TM data. International Journal of Remote Sensing, 13, pp. 303-318.

Roessner, S., Segl, K., Heiden, U., Munier, K. and Kaufmann, H., 1998. Application of Hyperspectral DAIS Data for Differentiation of Urban Surfaces in the City of Dresden, Germany. 1st EARSel Workshop on Imaging Spectroscopy, Zürich, pp. 463-472.

Segl, K., Roessner, S. and Heiden, U., 2000. Differentiation of urban surfaces based on hyperspectral image data and a multi-technique approach. Proeceedings of IGARSS (in print).

Segl., K. and Roessner, S., 1999. Pixeloriented Selection of Endmember Combinations for Linear Stochastic Spectral Unmixing Applied to Urban Environments. Proceedings of the International Symposium on Optical Science, Engineering, and Instrumentation (SPIE), Denver, pp. 327-338.

Spitzer, F. and Heinz, V., 1997. Bestimmung der Überbauungsdichte aus digitalen Satellitenbilddaten. Methodik und Anwendungen. Regensburger Geographische Schriften, 28, pp. 15-23.

Shimabukuro, Y.E. and Smith, J.A., 1991. The Least-Square Mixing Model to Generate Fraction Images From Remote Sensing Multispectral Data. IEEE Transactions on Geoscience and Remote Sensing, 29(1), pp. 16-20.

Sukopp, H., Weiler, S., 1988. Biotope mapping and nature conservation strategies in urban areas of the Federal Republic of Germany. Landscape and Urban Planning, 15, pp. 39-58.

Sukopp, H. and Wittig, R., 1993. Stadtökologie. Gustav Fischer Verlag, Stuttgart.

Strobl, P., Mueller, A.., Schlaepfer, D., Schaepman, M., 1997. Laboratory Calibration and In-flight validation of the Digital Airborne Imaging Spectrometer DAIS 7915. SPIE Proceedings, vol. 3071, Orlando Fl.