What's wrong with pixels? Some recent developments interfacing remote sensing and GIS

ABSTRACT

While remote sensing made enormous progress over the last years in terms of improved resolution, data availability and public awareness, a vast majority of applications rely on basic image processing concepts developed in the 70s: per-pixel classification of in a multi-dimensional feature space. It is argued that this methodology does not make use of any spatial concepts. Especially in high-resolution images it is very likely that neighbouring pixels belong to the same land cover class as the pixel under consideration. The authors argue for classification of homogeneous groups of pixels reflecting our objects of interest in reality and use algorithms to delineate objects based on contextual information in an image on the basis of texture or fractal dimension.

ZUSAMMENFASSUNG

Was ist mit den Pixeln los? Neue Entwicklungen zur Integration von Fernerkundung und GIS.
Fernerkundung hat sich in den vergangenen Jahren bezüglich Bildauflösung, Datenverfügbarkeit und öffentlicher Präsenz enorm weiterentwickelt, trotzdem basieren nahezu alle Anwendungen auf den methodischen Grundlagen der Bildverarbeitung aus den 70er Jahren: individuelle Pixel werden im mehrdimensionalen Spektralraum klassifiziert, ohne irgendwelche räumlichen Konzepte zu berücksichtigen. Insbesondere bei hochauflösenden Bildern gehören benachbarte Pixel mit hoher Wahrscheinlichkeit zur selben Kategorie wie das aktuelle Pixel. Die Autoren argumentieren für Klassifikationsansätze homogener Gruppen von Pixeln, die realweltlichen Objekten entsprechen und aus kontextueller Bildinformation (Textur, fraktale Dimension) abgeleitet werden.

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1 Patterns do matter, or: the need for change

We start our considerations of recent remote sensing practice from the user's point of view and, more precisely, from a geographical or landscape ecology point of view: The world in its complexity and manifold relationships cannot easily be grasped in full depth. Creating models of the world or computer-based representations of its surface poses a series of problems. In landscape ecology, there is a growing awareness about continuity of phenomena and discontinuities of scales. Forman (1995) described this ambiguity through the metaphor of a person gradually descending with a spaceship or balloon. Human perception abruptly starts to discover patterns and mosaics. Many mosaics are quasi-stable or persistent for a while, separated by rapid changes that represent the "domains of scale". Each domain exhibits certain spatial patterns, which in turn are produced by a certain causal mechanism or group of processes.

Back to remote sensing: The ultimate goal is to mirror, elucidate, quantify and to describe surface patterns in order to contribute to an understanding of the underlying phenomena and processes. Since the start of the first Landsat satellite in 1972, we achieve this in more or less the same way: We measure some reflectance at the Earth's surface. The smallest unit is called a 'pixel'. In this paper, we do not question the pixel as an important and necessary entity. Instead, we argue for a somewhat different handling of our entities introducing the concepts of neighbourhood, distance and location. All these concepts are not new. In fact, entire disciplines like Geography are based on these con-

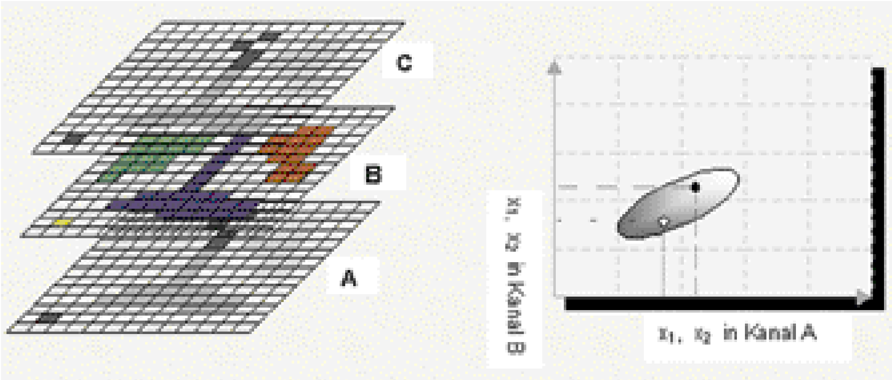
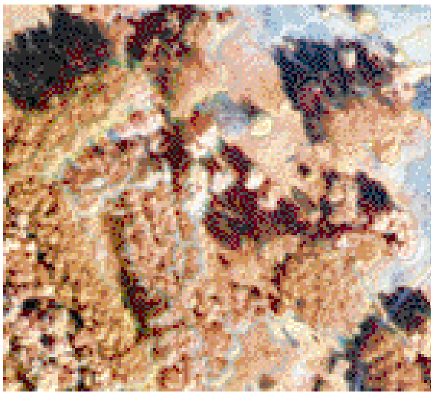


Fig. 1: Pixels vs. pattern

cepts. The question therefore is: Why are remote sensing and digital image processing still so much focused on the statistical analysis of single pixels rather than on the spatial patterns they build up? We will not answer this question but we will focus on the latter: How to build 'meaningful' objects which coincide with patterns of reality. The importance of spatial patchiness in both terrestrial and aquatic systems has been increasingly recognized over a wide range of scales (Whittaker and Levin 1977; Pickett and White 1985; Levin et al. 1993; Wu and Levin 1994). A patch, in a broad sense, refers to a spatial unit differing from its surroundings in nature or appearance (Wiens 1976; Kotliar and Wiens 1990). This patch is "a relatively discrete spatial pattern" which may vary in size, internal homogeneity, and discreteness (White and Pickett 1985) or "a spatial concept focused on a small area" as a basic structural and functional unit of the landscape (Forman and Godron 1986). We believe that the statistical analysis of pixels does not adequately represent this concept which is ontologically and epistemologically fundamental not just to landscape ecology but to many sciences dealing with ecological phenomena at various scales. As it will be argued later and in other papers of this issue, it is even more appropriate for built-up areas and artificial objects such as houses, roads or football fields. Automatic information extraction of the terrain surface in the fields of photogrammetry and remote sensing requires the formulation of procedures and knowledge that encapsulate the content of the images. In this paper, we concentrate on the non-photogrammetric aspects: the common denominator of both the geometric and the thematic



aspects of object generation is that recent trends in computer vision also try to recognise objects in images by first isolating components of objects and the relationships between them (Sowmya and Trinder 2000).
However, it must be stated clearly that this critique is very much generalised and does not adequately acknowledge the progress in remote sensing and digital image processing over the last couple of years. The reason is that we want to stimulate a discussion about 'new' approaches we will focus on later in this paper. For a review of existing advanced methods utilising the pixel approach such as linear mixing models, fuzzy set or neural net classifiers see Ichoku and Karnielli 1996, Schowengerd 1997, Skidmore et al. 1997, Milton 1999, Foody 1999, Blaschke et al. 2000 and many other publications. But even the 'per-pixel' approach has its limitations. As Townshend et al. (2000) point out, a significant, but usually ignored problem with per-pixel characterisation of land cover is that a substantial proportion of the signal apparently coming from the land area represented by a pixel comes from the surrounding pixels. This is the consequence of many factors including the optics of the instrument, the detector and the electronics, as well as the atmospheric effects. An alternative is to use contextual procedures in which observations from surrounding pixels are used to assist the characterisation. Although it might be desirable to integrate neighbourhood information continuously or in a fuzzy way, one operational method to work with relatively homogeneous areas is image segmentation.

2 Image segmentation: from pixels towards objects

The strong motivation to develop techniques for the extraction of image objects stems from the fact that most image data exhibit characteristic texture which is neglected in common classifications. The texture of an object can be defined in terms of its smoothness or its coarseness. One field of image processing in which the quantification of texture plays a crucial role is that of industrial vision. These systems are used to assess characteristics of products by measuring the texture of their surface. Most methods are based on the statistical properties of an image as well as the spectral or Fourier characteristics of airborne data, radar or VHR-satellite data which are playing an increasing role in remote sensing. But how to include neighbourhood information across several spectral bands for a pixel-based analysis? Several research groups tried to achieve this by using pre-defined boundaries ('per-parcel classification' or 'per-field classification', see Janssen 1993, Aplin et al. 1999). This classification technique is especially applicable for agricultural lots or other pre-defined, spatially discrete land cover classes. Distinct boundaries between adjacent agricultural fields help to improve the classification due to the fact that boundaries in an agricultural landscape are relatively stable while the cropping pattern (also within the lots) changes often. But what to do in case there are no boundary data readily available or exactly those boundaries should be updated? One solution is image segmentation. In many cases, image analysis leads to meaningful objects only when the image is segmented into 'homogeneous' areas (Gorte 1998, Molenaar 1998, Baatz & Schäpe 2000, Blaschke et al. 2000).
Segmentation is not new (see Haralick et al. 1973), but it is yet seldom used in image processing of remotely sensed data. Kartikeyan et al. (1998: 1695)

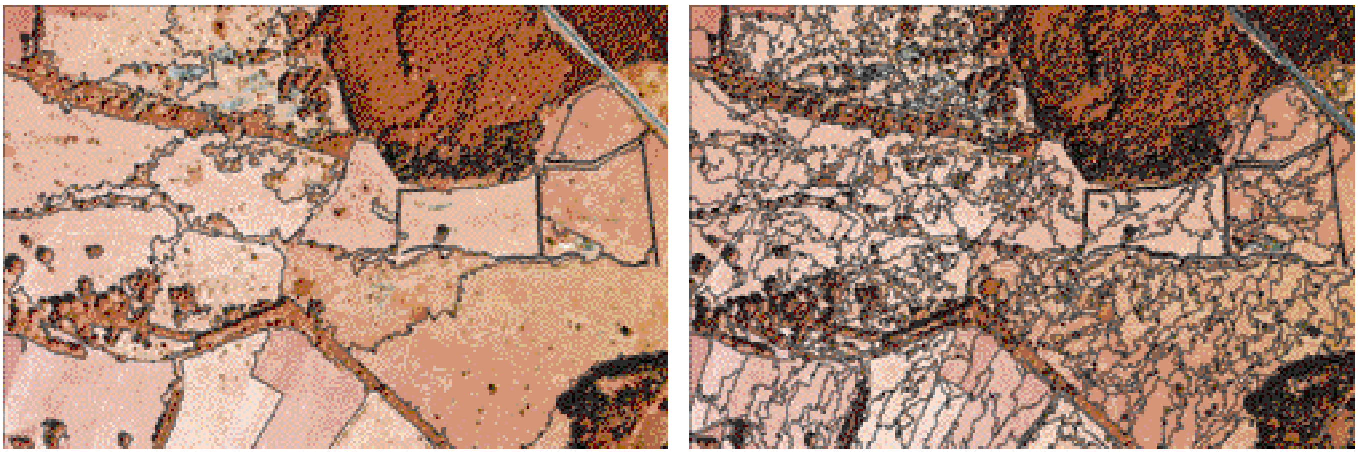


Fig. 2: Multi-scale image segmentation illustrated at only two levels of segmentation, a very coarse one aiming at pastures and enclosures and a very fine one aiming at groups of shrubs.

state: "Although there has been a lot of development in segmentation of grey tone images in this field and other fields, like robotic vision, there has been little progress in segmentation of colour or multi-band imagery." Especially within the last two years many new segmentation algorithms as well as applications were developed, but not all of them lead to qualitatively convincing results while being robust and operational. One reason is that the segmentation of an image into a given number of regions is a problem with a huge number of possible solutions. The high degrees of freedom must be reduced to a few which are satisfying the given requirements. A new algorithm, called "fractal net evolution approach" (Baatz and Schäpe 2000) could eventually revolutionize image processing of remotely sensed data and is used in several articles of this issue.

Technically, there are a number of possibilities how to segment an image. Most approaches can be grouped into two classes, namely edge-based algorithms and area-based algorithms. This classification also includes fractal-based approaches aiming at detecting discontinuities as well as fractal-based or texture-based algorithms (Salari and Ling 1995, Ryherd and Woodcock 1996) aiming at finding homogeneous areas. A recent survey of some competing approaches lists advantages but also some potential pitfalls for extracting geoinformation and useful landscape elements on real surfaces (Blaschke et al. 2000). Locally extracted histograms provide a good representation of the local feature distribution, which captures substantially more information than the frequently used mean feature values. The 'representativeness approach' (Hofmann and Böhner 1999) and other boundary-forming techniques (Schneider et al. 1997, Banko et al. 2000) and segmentation approaches (Gorte 1998, Molenaar 1998, Cheng 1999) provide good results in test areas but are not necessarily using all contextual information beyond the spectral information of neighbouring pixels such as texture, shape, directionality, spatial distribution within the study area, connectivity etc. However, from preliminary studies it is concluded, that the most promising recent developments are fractal approaches spearheaded by the developments of INRIA in Paris (Véhel and Mignot 1994) and Definiens AG in Munich (Baatz and Schäpe 2000). Context based image classification is the most promising development within integrated GIS/RS digital image analysis. The approach of minimising the overall heterogeneity in the image through heuristic optimisation of the boundaries of the resulting patches coincides with recent methodological achievements in landscape research. The idea of local homogenous patterns in a patch based landscape organisation recently triggered numerous studies, assuming the organisation of landscape patterns as a complex of local spectral distributions (Blaschke 2001).

Most researchers applying a segmentation approach argue that image segmentation is intuitively appealing. Human vision generally tends to generalise images into homogeneous areas first, and then characterises these areas more carefully later (Gorte 1998). Following this observation, it can be argued that by successfully subdividing an image into meaningful objects of the land surface, more intuitive features will result. One problem is to define the term 'meaningful objects': as stated above, nature hardly consists of hard boundaries but is also rarely a true continuum. There are clear, but sometimes soft, transitions in land cover. These transitions are also subject to specific definitions and subsequently dependent on scale. Therefore, segments in an image will never represent meaningful objects at all scales and for any application and we argue for a multi-scale image segmentation approach. Some researchers currently elucidate alternative ways towards the fuzzy delineation of objects or the delineation of fuzzy objects (e.g. Cheng 1999) or a probability-based image segmentation approach (Abkar et al. 2000).

3 Location and context: A 'new' paradigm?

Especially the new satellite sensor generation meeting strong market demand from endusers interested in image resolutions will help to observe and monitor specific objects of interest. The increasing variety of satellites and sensors and better spatial resolution influence a broad spectrum of applications but not automatically lead to better results. The technical terms are set by the existing sensors with ground resolutions from 15cm (airborne scanner, CASI, HRSC-A), the '1 m satellite generation' (e.g. Ikonos) over the intermediate (SPOT, Landsat) towards coarse resolution systems such as AVHRR and SPOT Vegetation. Direct insights regarding the correlation between signal characteristics per pixel and context-in-

Fig: 3 Digital orthophoto (a), classification resulting from an object-oriented multi-scale segmentation approach (b), percentage of sealed surface per parcel using the results from (b) and the existing cadastre (from Pilz 2001 with kind permission).

formation is expected from the new TERRA satellite with several new sensors on board. For the first time an operational direct linkage of optical sensors in a 'Landsat-like' resolution with hyperspectral data for the very same moment and atmospheric situation will allow for new cross-sensor models. The enormous amounts of data created a strong need for new methods to exploit these data efficiently (Hoffmann et al. 2000, Bauer and Steinnocher 2000, see also other articles of this issue).

Many central concepts in geography have until recently escaped operational use in image processing. While spatial relations like distances, topological connectivity and directional characteristics, spatial patterns as well as multiple scales or regional constructs were familiar approaches in many analysis tasks, they were not readily available to image analysis. While images often are legitimately seen as the most information-rich base data available, extraction of information frequently had to rely on human interpretation. Only now we are getting close to applying spatial thinking to image processing, paving the way to algorithmically formulate some more advanced aspects of cognition and inference.

In GIS-based spatial analysis, vector-based tools already have been able to support advanced tasks generating new knowledge. By identifying objects (as segmentation results) from images, we build a much needed bridge between the methodology domains of GIS and RS/IP. The idea of having an integrated 'geographical information processing' environment is becoming much more realistic now that 'GIS' objects can be used analysing an image and vice versa, new 'GIS' objects can be directly generated without ignoring the rich information environment of geographical concepts, relations and scales.

For most computer vision studies of aerial imagery, 2-D representations have been found to be adequate e.g., Shufelt and McKeown (1993), but 3-D models and pattern matching strategies are often employed in photogrammetry in applications such as building shape extraction (Henricsson and Baltsavias 1997, Sowmya and Trinder 2000). Current information retrieval methods in geographic image databases use only pixel-by-pixel spectral information. Texture is an important property of geographical images that can improve retrieval effectiveness and efficiency. The multi-level segmentation approach discussed in this paper provides a content-based methodology that utilizes the texture features of geographical images. One alternative approach to extract texture-defined features is presented by Sheikholeslami et al. (2000) using wavelet transforms. Based on the texture features, they design a hierarchical approach to cluster geographical images for effective and efficient retrieval, measuring distances between feature vectors in the feature space. Using wavelet-based multi-resolution decomposition, two different sets of texture features are formulated for clustering.

Applying GIS-based spatial analysis to the objects we derive from image segmentation opens up various possibilities. The key factor to a successful application still lies in the 'meaningful' delineation of objects. It is clear that the resulting objects will not serve all scales which might be applicable to an image. From a GIS point of view we are facing another obstacle: Conventional GIS database models do not readily support the representation of a geographic domain at a variety of levels of abstraction – e.g. from 'lower-level' observational data to 'higher-level geographic entities'. The multi-level image segmentation approach in an object-oriented environment aims to overcome some of these constraints and enables iterative refinement of objects and some experimentation which is necessary and somewhat intrinsic to any data exploration process.

4 Applications

4.1 Man-made features

The built environment has traditionally posed several severe challenges to the image processing of remotely sensed data. Sharp, discrete boundaries occur more often than in many

natural environments, vertical structures partially obstruct a scene according to the viewing angle, and shading from structures again obscures parts of the terrain. In addition reflectance often does not sufficiently differentiate between various kinds of surfaces, e.g. building roofs and pavement may exhibit nearly identical spectral signatures.
Contributions in this issue and e.g. work like Pilz 2001 demonstrate that object-based approaches are clearly superior to per-pixel analysis: only the former enable analysts to employ distinct spatial relations, to build an object-logic structure for any given domain. As a result, even shaded areas often can be reasonably categorized and the shape of an object may help discerning between a roof and a road of equal reflectance. Since cultural features in many environments tend to exhibit a higher rate of change than natural features, high accuracy automatic feature identification is even more important: mapping of change, monitoring a city for building code compliance, quantification of sealed surface extents and many other tasks are facilitated. Again, GIS-based tools can immediately support further analyses since resulting image objects carry a full complement of attributes within a defined application logic.

Fig. 4: Patterns of open grassland and various stages of encroachment caused by decreasing intensity of grazing. Exploring these patterns will help biologists understand grazing behaviour of the relevant 'landscape agents' (here mainly cattle) within this cultural landscape of high nature protection value and will guide planners to not only preserve this landscape but to control a sustainable use of this landscape. The figures here refer to an operationalisation of texture through sub-objects within objects. This is an alternative approach to moving windows defining texture. With this multi-scalar object-based texture exploration ("mean spectral difference between all sub-objects") different status of shrub encroachment could be characterised (for details see Blaschke in press).

4.2. Natural and near-natural features

Human perception does not observe, nor do we actually think in pixels. As illustrated in Fig. 4 for a pasture-dominated landscape, natural phenomena exhibit continuous transitions, complex patterns and complex situations. It is a highly active and integrated process, which unfolds in many steps between the direct sensual inputs on the one hand, and conceptual categories and our knowledge of the world on the other. An interesting perspective on this process is given by constructivism, one of the most influential streams in modern epistemology, which has a strong impact on the field of artificial intelligence. It describes each perception as a new, active construction of an 'imagination' about what is outside, invoked by the confrontation of sensual inputs with our knowledge base.
These inner 'images' include 'image objects' with manifold relationships to each other, to different kinds of contexts (e.g. functional, spatial or temporal), and to our knowledge base. Introspectively it is clear that for each situation there is a multi-scale representation of events, of spatial or temporal cognition. All the time we are switching between scales, focusing sometimes more on detail, sometimes more on the larger context. Therefore the ongoing 'scale' and 'hierarchy' discussion is much more than an academic discussion but ontologically leads us to reflections about WHAT we consider as 'objects'. Methodologically, we can create 'homogeneous' areas for the phenomenon under consideration at a specific scale and a 'within-patch diversity' as suggested by Blaschke (1995, 2001) while intrinsically utilizing hierarchy concepts following the idea of a 'scaling ladder' (Wu 1999). Hypothesizing the neatly decomposable nature of complex systems, this concept provides a key to a theory-driven simplification and manageability of complex environments.
Looking at environmental monitoring, the major tasks to perform are either to update existing geo-information (observing changes at t_1 in regard to conditions recorded at t_0) or to delineate land cover features in areas which haven't been mapped before (base-line data at t_0). In both cases knowledge about the nature of boundaries between adjacent objects (sharp or fuzzy) and their specific properties (texture, neighbourhood, relationship) exists, even though at various degrees of certainty. The methodology of multi-resolution image segmentation as described above offers the possibility to reproduce the boundaries across different data sets (e.g. medium and high resolution imagery, regional to local) and allow for a transparent inspection of results. To translate spectral characteristics of image objects to real-world features, the object-oriented classification approach uses semantics based on descriptive assessment and knowledge, i.e., it incorporates the wisdom of the user.
The most innovative aspect beyond technical improvement of image processing techniques is the arising potential to differentiate within the same image 'on demand' for different applications. Contrary to the static view of a map, in one case all forest areas can be treated as relatively homogeneous areas (although in reality they aren't) and open grasslands can be explored in detail (see Blaschke et al. 2000) or vice versa (see de Kok et al. 1999, Buck et al. 1999).

5 Conclusions

Experience from currently available applications demonstrates that segmentation-based classification is in many instances superior to traditional per-pixel methods. Not only in high resolution imagery, but predominantly in many complex situations like built environment, patterned landscapes and change detection results demonstrate clear improvement. Looking beyond enhancements to image processing like texture usage and contextualized approaches (which are available elsewhere, too!) segmentation into objects opens up an opportunity to apply various geographical concepts to the processing of images. This provides for a much more information-rich environment allowing for application-oriented logic from any relevant domain. Thus it can be expected that the current change in paradigms will lead to new applications and improved results, providing remote sensing with a much needed fresh impulse and geographical information users with enhanced input options.

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