MONITORING WOODLANDS FROM SPACE
The Possible Role of Modern Remote Sensing and Geo-Informatics in Monitoring of Southern African Woodlands and Indigenous Forests

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Abstract

Remote sensing is used as a tool in forest inventory for decades. Forest stands or single trees can be counted, measured or assessed employing sophisticated and to a certain degree fully automatic digital image analysis techniques, depending on the sensor’s spatial and spectral characteristics. With upcoming new sensors like the hyperspectral imagers allowing a deep look into bio-physical and bio-chemical properties of trees, a new dimension of qualitative assessment of forests will be opened.

Despite all technical advances in remote sensing and digital image processing until today, forest inventory cannot rely on image analysis only. Management or even monitoring of natural forests requires detailed information on tree composition, growth and production capacity and its dynamics in order to ensure a sustainable use and development of this sensitive resource. Not all data necessary for deriving suitable sets of information can be gathered using remote sensing. Sophisticated inventory concepts are required to combine some terrestrial measurements with image analysis and spatial modelling approaches provided by modern Geo-Informatics.

This paper aims to present state of the art digital image analysis techniques and its role in multi-phase inventory concepts. It gives some examples for their potential use in combined forest inventory systems of southern African savannah woodlands and natural forests. As most modern image processing techniques have mainly been tested in forests of the moderate climate zones, a comprehensive research programme considering specific properties and needs in Southern African Forest Management is recommended.

1. Introduction

Monitoring of forests normally aims to gather data about the actual state of the forest resources and to track changes in order to make sure that sustainable practices are applied. The findings of these inventories form the base for planning future measures to be taken in order to achieve long and medium-term goals as set by the forest owner or national, regional and local authorities.

Due to a very broad and multifunctional orientation of woodland and natural forest management, monitoring concepts need to cover very diverse information requirements with strong implications for the inventory concepts and the tools to be employed when running the measurements. Beyond this, woodlands and forests are integrated parts of the landscape in a more or less diverse land use pattern. The role or function of forests within this network needs to be taken in consideration, leading to a more widened thematic orientation of the inventory. Main clients will be national, provincial or local authorities with a wide variety of information needs including social, economical and ecological aspects in forest development.

Modern forest inventory concepts can make use of a powerful set of tools provided by the wide scientific fields of statistics, informatics and remote sensing. Modern statistics and geo-statistics provide the methodological framework for assessing the precision of sample data and for calculating indices describing the forest situation. At its “high end”, interesting methods for predicting and regionalizing the data found on sample plots can be applied.

Informatics and Geo-Informatics in particular provides the IT-base for handling and analyzing spatial data in order to make the information derived from it accessible to the potential users. Finally modern Remote Sensing can help to produce a host of information about forest resources by opening a unique perspective from above and by allowing deep insights into the world of electromagnetic radiation which is invisible for humans in most parts of the spectrum.

The application and proper use of these technologies however requires comprehensive and well planned monitoring concepts. On the one hand these concepts have to be strictly oriented towards clearly defined information needs and on the other hand the limitations of modern technology need to be considered in an appropriate manner. By doing so modern technology can help to gather more objective and more accurate data while reducing costs for inventorying forests significantly.

This paper aims to give an overview about most recent developments in the scientific field of forest inventory with the focus on the role that remote sensing and other techniques of digital image processing and spatial data analysis can play in inventorying woodlands and natural forests in Southern Africa.

2. Remote sensing in forest inventory

The role of remote sensing technology in inventorying forests, woodlands and landscapes is manifold but often limited by high costs. Without these limitations most of the forest stand and even single tree variables can be measured or estimated with high accuracy. Table 1 gives an indication about the accuracy achievable for some information groups usually taken in forest inventories.

Table 1. Technique and accuracy achievable for different Information groups in forest inventory derived from remotely sensed data

Information Group	Information	Technique/Accuracy
Area	• Forest area • Forest area by type • Forest area by function	Classification of images/ 10-12 land use classes (multispectral), up to 25 classes (hyperspectral); 2 -3 forest type classes
Structure	• Diversity • Mixture • Fragmentation	Remote sensing & landscape metrics statistics
Site	• Terrain • Soil and vegetation • Water	Stereo photogrammetry Terrestrial assessment Radar remote sensing
Environment/Ecology	• Function • Health status	Terrestrial assessment Image classification
Social	• Settlements • Accessibility	Image classification
Forest Management	• Timber volume • Age classes • Tree height/diameter • Growth & yield (MAI)	Regression estimators (10-15%) Image classification ±0,5 m/±10% Multi-temporal image analysis

The table clearly indicates that most of the information groups normally taken during forest inventories can be collected using remotely sensed data. The achievable accuracy however depends on the images spectral and spatial resolution and the intensity in which images are analysed.

Trees and forest stands are 3-dimensional objects and obviously it is the spatial resolution which limits the thematic depth to be derived from the images. The spatial resolution includes the pixel size as the smallest unit on the ground detectable by the sensor and its stereo imaging capabilities. For getting single tree information which might be of interest in single tree based silvicultural concepts (e.g. “Plenter Forest”), one normally would need stereo images with a pixel size in decimetre range. Figure 1 gives a good impression that real visibility of single trees starts at ground resolutions of about 40 cm.

The intensity to which the images are analysed is normally used to classify the role of remotely sensed data in forest inventory within a framework of 4 different intensity levels (I-Level):

- I-Level I: Remotely sensed data (mostly as printout) used as aid for orientation in a forest (reduce time consumption by up to 40% e.g. for planning and supporting field work)
- I-Level II: Simple Forest Inventory with remotely sensed data only (stratification, forest type mapping, stereogram, yield table, etc...)
- I-Level III: Forest Inventory as a combination of remote sensing and terrestrial measurements (using photogrammetric variables, greyscale values as auxiliary variables, etc.)
- I-Level IV: Automatic Forest Inventory, fully based on remotely sensed data and a model-based estimation of forest tree and forest stand data.

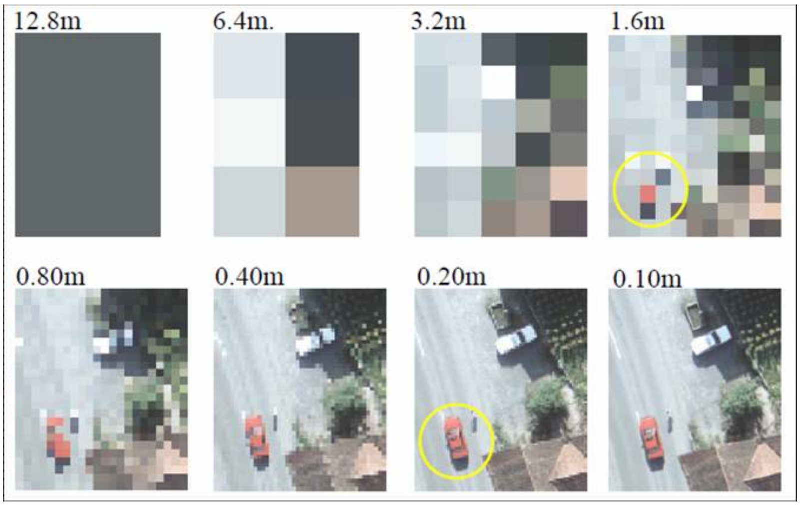

Figure 1. Image series indicating the visibility of objects at different pixel sizes (Fricker *et al.*, 2001).

The current use of remotely sensed data in practical forest inventory concentrates on the intensity levels I, II and – in some cases on I-Level III. Typical applications are forest area mapping and forest type determination which is often done by classification of satellite images. Several applications at this level have been reported for South African forests. One of the first forest maps derived from satellite imagery was produced by Van der Zel (1988). Wannenburgh and Mabena (2002), for example, undertook a national indigenous forest inventory for South Africa based on Landsat ETM data using a hybrid approach based on semi-automatic classification and visual interpretation. From other parts of the globe similar investigations have been reported showing that 10 to 12 land use classes can be derived from multispectral satellite images whereas 2 to 3 forest types or age classes, depending on the general forest environment, can be mapped with high accuracy.

Multiphase inventory concepts given as example for I-Level III applications make use of different data sources which are linked to each other by mathematical models. The basic idea behind these concepts is to replace expensive terrestrial measurements with taking auxiliary variables from images at different scales. Under European and North-American conditions these concepts have proven themselves to be much more efficient than fully terrestrial inventories without losing accuracy (Kätsch, 1990; Scheer *et al.*, 1997). Depending on the number of samples to be taken and the relation between the auxiliary variable and the variable of interest, the costs can be reduced by more than 50% (Figure 2).

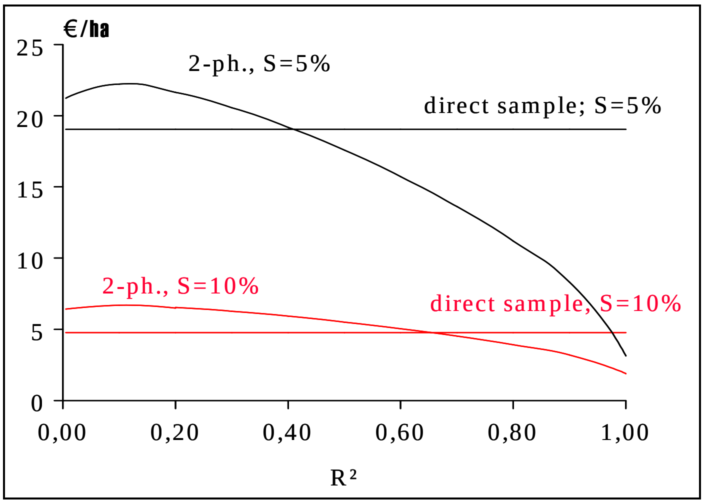

Figure 2. Cost (€/ha) above R² for different inventory intensities (s=±5% and s=±10%) (Kätsch 1990).

Typical concepts include a terrestrial phase on a smaller number of sample plots taken in the field and a big sample measuring auxiliary variable from a set of different imagery. Auxiliary variables can be *stand heights*, *number of stems per ha* or *crown diameters* which can be derived from high resolution imagery using modern digital photogrammetry.

Beside the more intensive application of photogrammetry it might be possible to use spectral signatures from multispectral images as auxiliary variables. Multiphase sampling concepts can also integrate interesting concepts provided by modern Geo-Statistics. Data from relatively coarse terrestrial sample networks can be regionalized and estimated for the whole area of interest.

I-Level III applications are rarely found in South Africa. Some investigations have been carried out in planted forests dealing with the use of high resolution stereo satellite images for detailed forest assessments. Vogt (2000) and Kätsch (2000) applied stereo photogrammetry on high resolution stereo satellite imagery and Kätsch and Van Laar. (2002) used a 2-phase sampling design for estimating timber volumes and other forest stand related variables in Mpumalanga based on spectral signatures derived from the French Spot-5 satellite.

I-Level IV applications have not yet reached a practical stage, but results from several investigations show the possible direction (e.g. Pollock, 1994, 1996; Kätsch, 2002; Persson *et al.,* 2002; Straub, 2003). The full automatic mensuration of forest stands on high-resolution imagery has been realized for specific forest types but full reliable, robust methods do not yet exist. In particular natural, mixed and uneven-aged hardwood stands with closed crown cover are difficult to be mapped automatically. Nevertheless, ongoing research in this field shows possible directions for further research which may lead to at least semi-automatic forest inventories in the future. Automatic feature extraction from images, for example allows detecting a single tree in order to measure its height and to estimate the timber volume or the biomass the tree represents. Furthermore, crown surface models which can be seen as a valuable variable for estimating growth and yield can be derived from stereo images in a fairly automatic manner.

Considering the technical capabilities given, it becomes obvious that most concepts for monitoring woodlands and forests will have to rely on a combined approach using remotely sensed data sets together with some terrestrial measurements. By combining both methods the thematic restrictions and limitations when using remote sensing data can be minimized while the high cost of terrestrial surveys in large areas can be reduced to a certain degree.

3. Future research & development in inventorying woodlands

Although some of the investigations listed have been carried out in natural or near-natural forests, profound experiences in mapping tropical and subtropical forests are missing thus far. Beyond this the extraordinary diversity in African woodlands and indigenous forests causes additional challenges for any kind of image-based inventory.

From the scientific perspective further research and development should focus on four major issues regarding inventories in woodlands and natural forests:

- Assess the suitability of modern remote sensors like imaging spectrometry (hyperspectral remote sensing) and radar remote sensing
- Develop sophisticated digital image processing approaches dealing with automatic feature extraction, pattern recognition and knowledge-based image classification methods
- Investigate the potential of multi-temporal remote sensing which on the one hand side may improve the separability of different tree species and on the other hand may enable regular monitoring of changes in forested areas
- Assessing the potential of regionalising raster data in order to get a full coverage of South African forest areas

Imaging spectrometry is currently one of the most promising emerging technologies. Hyper-spectral imaging is the simultaneous acquisition of images in many narrow, contiguous, spectral bands (Figure 3).

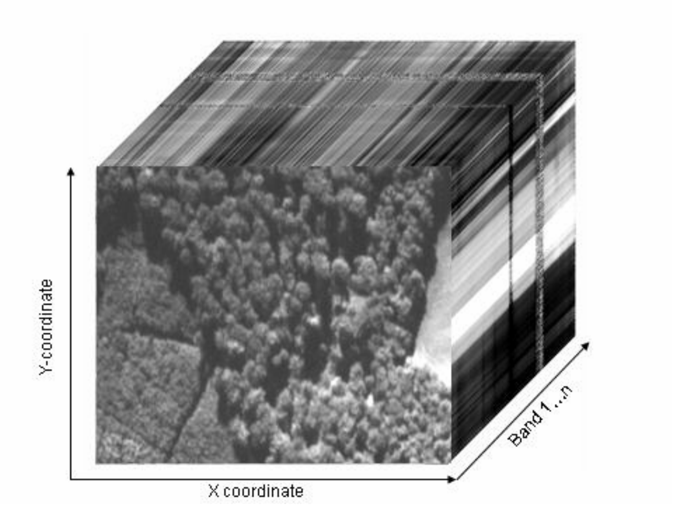

Figure 3. **Hyperspectral data cube.**

Each pixel in the remotely acquired scene has an associated spectrum similar to the spectra of the material/mineral obtained in the laboratory. These capabilities open the door to a more qualitative assessment on the different objects shown on the images.

Spectrometry of plants is a well known application that has gained importance in several fields. Modern precision agriculture, for example, uses spectrometers mounted on a fertilising device travelling through the crops for real-time determination of the amount of fertiliser which should be applied to a specific plant. Imaging spectrometry based on complex airborne or space-borne sensor systems uses basically the same technical approach, but with another spatial orientation. It combines the advantages of having a better perspective when looking from above with a deep view into the whole range of reflectance spectra of the objects shown. The expectations of this technical concept are, on the one hand, that it will make it easier to classify different objects on an image with much higher reliability and, on the other hand, to generate data on the current physiological or bio-physical and biochemical status of living vegetation.

Several results published on mapping living vegetation using traditional cluster-analytical approaches show that the thematic depth or resolution of classifications can be significantly improved when using hyper-spectral data. Whereas multi-spectral images can be classified into 10 to 12 categories (Forest, Agricultural Crops, Water…) when using supervised classification (Schmitt-Fürntratt, 1991), a hyper-spectral dataset can basically be classified into 25 or more categories, allowing a much more detailed insight into the land use pattern. For that reason hyper-spectral remote sensing is the only available approach to get information on biodiversity in natural vegetation types. Nevertheless, intensive research is required to improve spectral analysis and un-mixing in order to unlock the full potential of the data.

A more difficult situation must be reported when talking about evaluating the biophysical and biochemical properties of living vegetation with the modern technology. Besides the basic difficulties with atmosphere and mixed pixels, the leaves of a tree differ very much in their spectral reflectance properties. Even under very clearly defined conditions in a laboratory, spectra will vary depending on the sun's angle, the leaf's position and, of course, its current physiological status. Figure 4 gives an indication of what happens to the reflectance curves of Beech leaves (*Fagus silvatica*) if the incoming radiation meets the leaves' surface at different angles. Although the general shape of the spectra doesn't change dramatically, there are some specific changes in small parts of the curve which are quite important to establish distinct differences between two tree species or a healthy and a damaged leaf from the same species.

The scientific community is currently arguing about the correct approach on how to solve these problems. Under discussion are two different approaches: the one is a more empiric one, the other a more deductive one.

The classical empirical approach, which was in some parts developed for analysing multispectral images, uses indices or ratios from specific bands of the spectra which have been identified as being of particular importance for any biophysical or biochemical property of a plant. As example two chlorophyll indices called the Pigment Specific Simple Ratio (PSSRa) and the Pigment Specific Normalised Difference (PSNDa), as proposed by Blackburn (1998), should be mentioned. The PSSRa is a simple ratio of reflectance at two optimal wavelengths, in this case 810.4 nm and 676.0 nm for chlorophyll a. PSSRa = R810.4 / R676.0. Another method is proposed by Chapelle *et al.* (1992). The Ratio Analysis of Reflectance Spectra (RARS) uses an empirically derived mean "reference" spectrum from a chlorophyll-saturated plant in order to divide each hyper-spectral pixel spectra of the image to highlight specific absorption features of chlorophyll a, b and major carotenoid pigments. McNairn *et al*. (2001) applied these methods to several corn and bean fields in Canada.

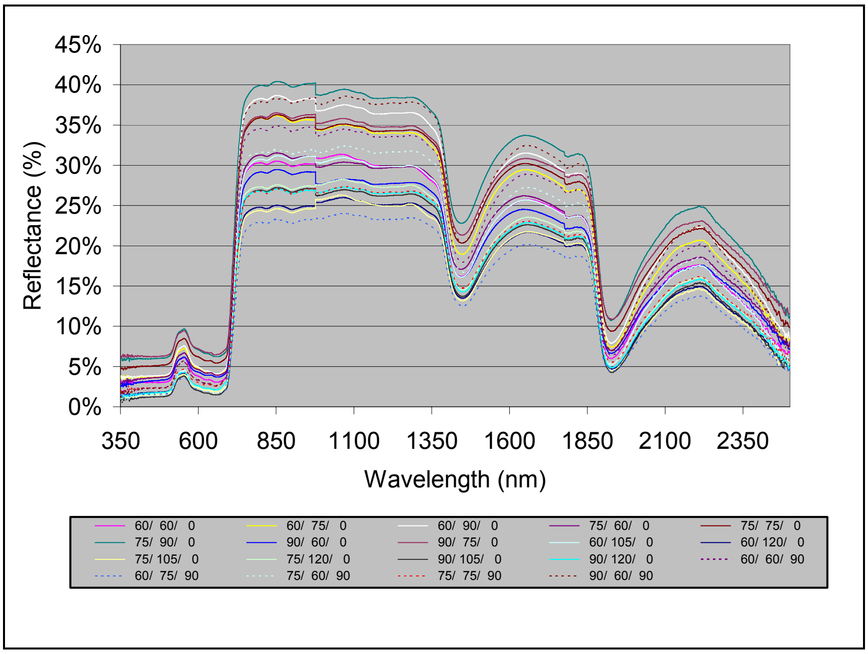

Figure 4. Reflectance curves for a leaf of European Beech measured with changing sun angles and sensor orientation (Horn, 2005).

The second approach, which is in particular promising for the retrieval of biophysical parameters of vegetation, uses radiative transfer model inversion. These models provide a theoretical collection of typical spectra for different crops, plants and land covers, depending on their properties. Furthermore, the two factors mentioned above, namely the sun angle and the view angle, which changes the spectra significantly, can be included. By inverting the model, biochemical or biophysical properties of vegetation can be predicted. These models have been successfully tested for forestry purposes. Atzberger (2000, 2005) used reflectance models to derive canopy variables for European forest stands. A model to derive biophysical properties of landscapes with different land uses based on hyperspectral data and additional land use information was proposed by Dorigo *et al*. (2005). The analysis of hyperspectral imagery will form a major part of future research in the field of remote sensing as it forms the only promising technology which may be of help when looking into the running processes of living vegetation. If this technology becomes a feasible alternative to terrestrial approaches, it holds great potential in the whole agricultural sector, forestry and the global environmental assessment, which needs to be done in order to supervise measures taken within the framework of the Kyoto Protocol.

Digital image processing technology forms the base of all automatic and semi-automatic data capture from remotely sensed imagery. Modern informatics provides a host of different tools which allow extracting single objects from an image, to recognize, to classify or to measure objects in all its three dimensions. Although fairly advanced these methods require adaptation when dealing with manifold and diverse objects like forests and trees. The potential of these methods might be demonstrated by 2 examples:

Forest type mapping using image classification methods can be significantly improved by using a hybrid approach incorporating spectral and pattern related image information. The following figure shows preliminary results achieved in an ongoing project in the Knysna forest (Figure 5). The slide shows two thematic maps produced from multispectral images from the American Aster Satellite. By using the three high resolution bands (GSD[1] 15m) a set of 4 different classes can be found within the forest area. The second map was produced by classifying the image with the sample cluster analytical approach but with a fourth layer produced from filtering the near infrared spectral band with a WMMR-Med[2]-Filter algorithm. This algorithm is a nonlinear edge-enhancement filter that also suppresses image noise (Anonymus, 2001). It enhances changes in pattern or texture which resulted in a much more detailed classification of the forest.

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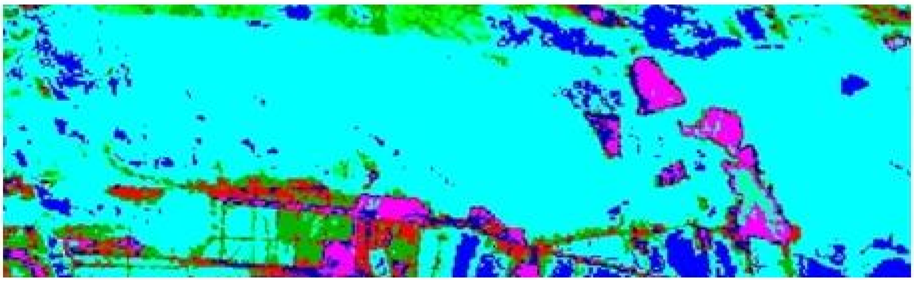
[1] GSD: Ground Sample Distance (pixel size)

2 WMMR-Med: weighted majority with minimum range - median

The classification fits well to the compartment boundaries which normally form management units related to forest types. Although the results have not been verified so far, this example shows that modern digital image processing may allow a more detailed mapping and inventorying of forests.

An example indicating the possible use of high resolution satellite imagery in mapping woodlands is shown in figure 6. The slide shows the results of an automatic tree count in open woodlands in northern Botswana. The satellite image used was taken by the American Quickbird satellite with a ground resolution of 2.6 m in the multispectral bands.

Aster Bands 1-3 Isodata-Classification: 4 forest classes



Aster Bands 1-3 + WMMR-Med-Filter Isodata-Classification: 10 forest classes

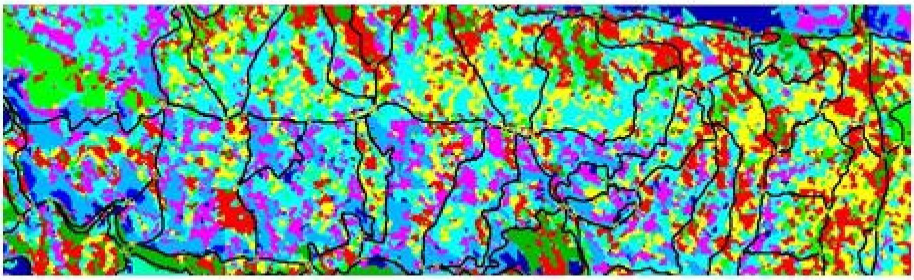


Figure 5. Forest type classification in the Knysna Forests using different image layers of the American Aster Satellite.

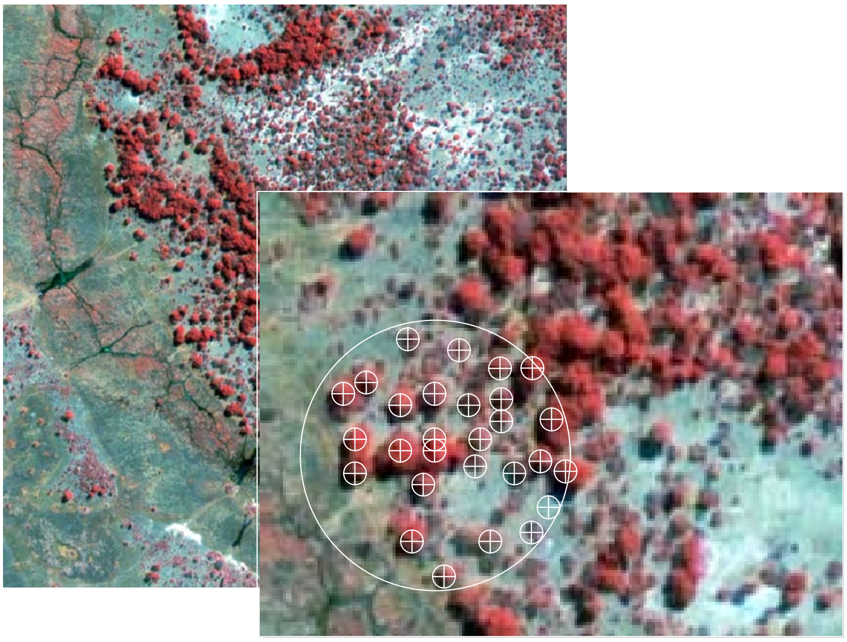


Figure 6. Tree count on Quickbird satellite image on a sample plot in northern Botswana woodlands.

An area-based segmentation approach searches for tree crowns by looking for local maxima in the greyscale-pattern representing the image. The algorithm developed so far works quite reliable when solitary trees are shown. As soon as tree crowns are closely meshed this approach will fail. Beyond this the ground resolution determined by the sensor is close to the limit as reliable delineation of tree crown requires a minimum of 3 by 3 pixels to cover the tree's crown.

Despite the restrictions mentioned both examples show the potential of sophisticated image processing technologies which should be followed up in future research. Several basic algorithms are available which require adaptation to Southern African natural forests and woodlands.

Monitoring of forests includes detecting and analysing changes in the forest. Depending on the specific user requirements this would normally require a more or less dense network of permanent sample plots. Remotely sensed data can play a significant role in this task as every image includes a comprehensive documentation of the current forest situation. High resolution stereo images allow an accurate observation of single trees or forest stands including the fairly accurate estimation of height- and diameter growth over a period of time. Changes in forest area and species composition in order to monitor ongoing natural processes can be assessed to a certain degree by automatic change detection procedures. These methods have already reached a fairly advanced stage but some more intensive research is required as the representation of objects on the ground differs depending on atmospheric conditions, the sun angle and other parameters.

The fourth issue mentioned above touches the interesting possibilities of regionalizing raster data using geo-statistical methods. Natural forests and woodlands are normally distributed according to specific site conditions given by the natural landscape. Once a more or less coarse network of well known sample plots is known, regionalizing using methods like Gradient-Kriging, or Minimum Curvature Interpolation may allow predicting the situation in the unknown parts of the forest. These methods are well known in soil science but the possibilities of predicting the distribution of vegetation has only been investigated in some cases. A closer look into the possibilities of the methods for southern African forest monitoring may open up new roads towards an effective forest inventory and monitoring system.

4. Conclusions

During the past decades remote sensing has become an essential tool for the inventorying and monitoring of forests. Although a fairly comprehensive set of tools for gathering forest data from digital imagery has been developed so far, its use in practical forest inventories remains far behind what is possible. Booming developments in sensor-technology will widen the spectrum of possible applications in forestry by allowing deeper looks into forest structures as well as into ongoing biochemical and biophysical processes.

When preparing the application of remotely sensed data in forest inventory the use of airborne data should be considered. High resolution aerial images have a big potential in all kinds of forest inventories and the higher costs of acquisition may be well invested as the overall inventory costs can be reduced to a certain degree. Beyond this aerial images form the only base for an objective documentation of the current situation in the forest on large areas which will allow an easy combination of time series. High resolution aerial images can also provide significant scientific information supporting ongoing research on biodiversity or forest ecology. Experiences from other parts of the globe show that this is the only way to learn and understand ongoing natural processes and to monitor the impact of human actions in the forests.

Nevertheless the use of remotely sensed data must be seen as complementary to terrestrial forest inventories. Especially in structured, uneven-aged natural forests only a small proportion of the data to be taken can be gathered from digital images from above. Closed crown cover obstructs the view to hidden parts of the stand like natural regeneration or suppressed trees. By linking both field data and remotely sensed data in multiphase inventories the benefits when looking from above can be combined with the more detailed information taken on the ground while reducing overall costs significantly.

In order to unlock the whole potential of remotely sensed data the important scientific field of geo-informatics needs to be mentioned as well. Modern Geographic Information Systems provide powerful tools for combining, analysing and visualizing spatial data allowing to monitor, to model or to predict ongoing processes in the forests. This forms the core of any monitoring approach and should become an integrated part of any forest information system. This however requires clearly focused research efforts in both directions; the analysis and assessment of remotely sensed data on the one hand side and spatial data analysis and modelling on the other hand.

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