Quantifying fuelwood biomass in savanna woodlands of southern Africa

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Abstract

Most rural communities in southern Africa rely on fuelwood or charcoal to meet their domestic energy demands. These energy sources are readily accessible and often the only affordable means. Nevertheless, rising population densities and poverty levels are exerting pressure on unprotected natural woodlands. In many electrified communities, high costs of electricity have prevented a move away from dependency on bio-energy. Quantitative data on available woody biomass is lacking, influencing negatively on energy planning policy and implementation. Conventional ground-based biomass assessment methods are tedious and time-consuming. Species heterogeneity of savanna woodlands poses challenges for both optical and radar remote sensing platforms. Optical remote sensing techniques are constrained by atmospheric conditions as well as spectral resolution to distinguish different tree species and woody biomass densities in large-scale applications. Although satellite borne radar remote sensing offers greater opportunities for quantifying above-ground biomass, it is inhibited by the medium spatial resolution and long repeat cycles of current platforms. A combination of allometric equations and vegetation parameters from synthetic aperture radar (SAR) data can be used to quantify standing biomass. However, allometric equations are often site specific and difficult to extrapolate to landscape scales. This paper will discuss opportunities and challenges faced by natural resource practitioners when attempting to assess and quantify woody biomass in southern African savannas. The data needs and current availability of appropriate imagery will be presented in the context of the VW Foundation Bio-fuels Modeling Project, covering Zambia, Mozambique and South Africa.

Biomass energy in low-income communities

Biomass, mostly in the form of charcoal and fuel wood, is the predominant source of bioenergy in low income of rural and urban households in southern Africa [*Banks et al*., 1996; *Wamukonya and Jenkins*, 1994]. In Mozambique, biomass (charcoal and firewood) provides up to 80% of energy consumption while 87% of rural households in Zambia use fuelwood for cooking [*Brouwer and Falcão*, 2004; *Chidumayo*, 2002]. Many rural households in South Africa use mainly fuelwood and paraffin for cooking and space heating. In some cases, rural settlements derive approximately up to 90% of their domestic energy from wood [*Banks et al.*, 1996]. Rising population growth and persistent poverty are increasing pressure on forest and woodland resources, thereby, threatening their sustainable utilisation. Signs of resource depletion as indicated by the distance of preferred species from households [*Howells et al*., 2003] are beginning to show in certain communal woodlands that are not subject to rigorous management regimes. Policy-makers in most developing economies lack knowledge about the factors that determine energy choices by rural consumers [*Von Maltitz and Scholes*, 1995; *Banks et al*., 1996].

Data on standing woodland biomass volumes, spatial distribution and quality, and rate of extraction is often lacking. Quantitative data on convertible fuelwood resources provides useful input for strategic energy planning and modeling purposes. Macro-level strategic energy planning is currently being compromised by the use of generalized biomass estimates [*Grabitzki*, 2004]. Knowledge of existing woody biomass stocks encourages the adoption of mechanisms for sustainable utilization of forest and woodland resources such as issuing concessions on standing volumes rather than harvested volumes [*Sebukeera et al*., 2006].

Rationale for quantifying fuelwood

Sustainable exploitation of woodland resources requires quantitative data relating to biomass for fuelwood and charcoal, land and forest cover, forest degradation, forest function allocation, forest types, tree species, forest products and land tenure among others [*Boyd and Danson*, 2005]. Consequently, governments need to undertake comprehensive inventories and valuation of forests and woodlands to ascertain if such resources are being sustainably exploited in line with the objectives of the Millennium Development Goals (MDGs) on sustainable environmental management. This information is also vital to militate against the increasing pressure from rising populations and poor economies. Biomass information and management information systems are essential to provide decision-makers with a better understanding of how wood resources are managed, harvested, transformed and eventually converted to energy. According to *Masera et al.* [2006], macro-level planning tools are necessary to articulate local heterogeneity at the regional and national levels when explicitly analyzing fuelwood supply and demand at multiple-scales. *Mabowe* [2006] laments about the fragmented approach to biomass data collection by various departments in Botswana and the lack of comparable woody biomass datasets to assist decision-making processes. The rural domestic energy sector is often given second priority in policy planning and implementation.

Southern African savanna woodlands are under increasing threat of over-exploitation due to higher demands for fuelwood and charcoal by low income communities. In Mozambique, Tanzania and Zambia, charcoal from communal woodlands is exported to urban centres for sale to low-income urban dwellers. Intensive harvesting practices and demands for arable farming land contribute to the continued decrease in the availability of plant specie preferred for fuel wood and charcoal [*Ellegård et al.*, 2002; *Watson*, 2002]. The exploitation of traditional biomass systems for cash and/or mercantile purposes (charcoal and lumber) is also leading to accelerated losses of natural forests and biodiversity, as well as creating local scarcity of biomass [*Lasten* 2002; *WEO*, 2006]. In most African rural areas, quantitative data on woody biomass such as preferred fuelwood tree species and their spatial distribution is often lacking. Where such information exists, it is too site specific and difficult to extrapolate macro levels for energy planning purposes. High costs of both ground-based assessment methods and high resolution satellite images tend to contribute to this scarcity of convertible biomass data [*Mabowe*, 2006]. The problem is compounded by the of lack access to integrated systems that can accommodate data from remote sensing, terrestrial observations, and socio-economic sources for assessing and monitoring sustainable extraction of biomass resources in communal woodlands [*Beerens*, 2002].

Specific tree species are targeted for either fuelwood or charcoal production according to their calorific value. Species heterogeneity of savanna woodlands poses great challenges in discriminating such preferred woody biomass trees on both optical and radar imagery. Conventional ground-based methods for assessing such woody biomass are tedious and time-consuming. Optical remote sensing techniques are constrained by spectral saturation and atmospheric conditions. While synthetic aperture radar techniques have shown increased potential for large-scale biomass assessment in temperate, boreal and tropical forests, their application to subtropical savanna woodlands is limited [*Imhoff*, 1995; *Wallington et al.*, 2006].

Spatial data for biomass estimation

There is a growing need for applications that feed quantitative data into bioenergy models to enhance energy planning for low-income communities in developing countries. The data includes temporal biomass data, preferred tree genus, spatial distribution of and access to woody biomass resources. Extracting data on specific trees for fuelwood and charcoal production from imagery requires data with high spatial resolution where preferred tree species and their spatial distribution can be discriminated and mapped respectively. Highly accurate ground truth surveys are necessary to correlate field positions with their corresponding aerial or satellite imagery positions when assessing and quantifying standing woody biomass. Recent advances in spaceborne synthetic aperture radar (SAR) remote sensing and Global Positioning Systems (GPS) technologies coupled with geographic information systems (GIS) offer innovative ways to quantify and assess available woody biomass. GIS environment provides a suitable platform for visualizing, analyzing and interpreting energy dynamics with a region and understanding inter-linkages between parameters that make up energy systems [*Biberacher*, 2006]. The combination of both field and remotely sensed data enables the calibration and large-scale extrapolation of biomass data from local through to global levels.

Terrestrial data

Tree species heterogeneity in savanna woodlands requires that training data has minimal target-to-image noise to enable the characterization of tree vegetation on both optical and SAR imagery. The absolute positioning of trees is critical for correlating ground survey measurements with the corresponding aerial photography or satellite image positions if spectral or polarization signatures are to be precisely mapped to corresponding tree genera. For radar-based surveys, corner reflectors which reflect the radar signal directly back to the sensor producing high returns and very bright spots on the imagery are normally set out along the flight path as part of the control points for site calibration network [*Santos et al*., 2003; *Short*, 1999]. The corner reflectors provide accurate georeferencing data to overlay field survey and SAR image data. The accurate position of the corner beacons and other topographical detail is fixed by Global Positioning Systems (GPS) and conventional Electronic Distance Meter (EDM) surveying techniques. While Differential Global Positioning Systems give highly accurate ground positions, EDM surveying techniques compliment GPS measurements because GPS accuracy is degraded when receivers are operated under dense tree canopies [*Paradzayi et al*., 2008]. Field surveys conducted for *in situ* biomass measurements are also useful for calibrating and validating remotely-sensed data and to demarcate the training areas with high spatial accuracy.

Site calibration field surveys must be tied to common reference frameworks such as national mapping systems or GPS networks to allow easy integration of spatial woodland information with data from other sectors. Although commercial GPS base stations are available, the required initial capital investment and annual maintenance charges often limit their use in developing countries. In Africa, GPS networks are not yet fully developed and South Africa is the probably the only country that has a well developed GPS infrastructure. A unified African Reference Framework (AFREF) is still in its formative stages [*Wonnacott*, 2005; *Ottichilo*, 2007].

Remotely sensed data

Many research efforts are contributing towards the development and use of remote sensing methods in forest biomass estimation and assessment of woodland dynamics [*Koch et al*., 2007; *Patenaude et al*., 2005; *Rosenqvist et al*., 2003]. A number of case studies have shown the suitability of airborne and spaceborne optical and radar sensors for assessing and quantifying biomass in forest and woodlands stretching from local to regional scales [*Hussin*, 2007; *Mette*, 2007]. Integration of data from various platforms such as L-band, high frequency C and X-band synthetic aperture radars and very high resolution optical remote sensing sensors is offering new possibilities for quantifying and assessing woody biomass. Although airborne and spaceborne Light Detection and Ranging (LIDAR) systems have demonstrated great potential for estimating tree canopy heights and providing high resolution digital elevation models, their widespread application is generally limited by high cost and small geographic coverage [*Hyde et al*., 2006; *Power et al*., 2006]. This paper is focussing on capabilities and limitations of spaceborne optical and radar sensors in providing suitable data for extracting woody biomass estimates. These platforms are capable of landscape assessment of available standing biomass.

Optical data

Optical remotely sensed imagery is well suited for capturing horizontally distributed conditions, structures and changes [*Koch et al*., 2007; *Patenaude*, 2003] but is constrained by adverse atmospheric conditions such as clouds and haze, and in any case surveys only the upper surface of the vegetation canopy. Optical data archives include data from LANDSAT missions [*Billingsley*, 1984] and declassified missions such as CORONA. Optical data can be used to generate very high resolution digital terrain models [*Bolon et al*., 2007; *Galiatsatos et al*., 2008] and can provide useful input for spatial-temporal analysis of woodland dynamics. Quantitative data on available biomass is indirectly related to image characteristics and usually have to be inferred from secondary parameters such as leaf area index and vegetation indices.

Capabilities

Remote sensing at optical and infra-red wavelengths has been successfully applied to the problem of delineating clear-cutting and deforestation in areas where cloud-free images are available [*Smith et al.*, 2002]. Optical remotely sensed data has been used to map broad vegetation types before allometric equations were applied for indirect biomass estimation. The allometric equations are derived from parameters deduced from vegetation indices and/or reflectance. *Patenaude* [2003] gives comprehensive review of satellite optical remote sensing platforms which have wide applications in woodland deforestation assessment and monitoring land cover changes. A number of commercial airborne and spaceborne platforms offer coarse to very high resolution optical remote sensing data that can be used for vegetation change detection. Examples include conventional aerial photography, PRISM, AVNIR-2, IKONOS, Quickbird, LANDSAT, SPOT, and MODIS, among others. There are many other sensors still under development.

Limitations

Although cases abound of where optical remote sensing has been successfully used for land cover detection, optical images are degraded by environmental conditions such as cloud cover and haze [*Hussin*, 2007; *Prakoso*, 2006]. Direct estimation of biomass volumes using optical remote sensing data is not possible although land cover changes can be correlated to biomass depletion or regeneration over given periods of time [*Patenaude*, 2003]. Such an approach is labour intensive as it entails collecting data at different times of the vegetation growth cycle and also across the vegetation gradients. The accurate representation of the magnitude and spatial variation in biomass is influenced by the accuracy of determining the allometric equations and also the ability to spectrally discriminate particular tree genera from remotely sensed optical data [*Lucas and Tickle*, 1999]. Results for biomass estimation have been less convincing, particularly in mature forests because the reflectance is mainly determined by canopy closure, tree-storey leaf area index (LAI), species composition, and background reflectance, which are only indirectly related to woody biomass [*Smith et al.*, 2002]. *Mabowe* [2006] also concluded that estimating woody biomass in savanna woodlands from optical remote sensing is difficult because of poor correlations between biomass quantities derived from field observations and vegetation indices from high resolution IKONOS imagery.

Optical sensors are limited to detecting upper canopies of woodlands and cannot detect under-storey woody biomass. Optical remote sensing classification and accuracies are limited by geometrical and spectral resolution of the sensor as well as heterogeneity of woodlands under investigation [*Billingsley*, 1984]. Features with more spectrally and ecologically unique characteristics will be more accurately discriminated. According to *Patenaude* [2003], discriminating between diverse land uses comprising forests, crops, and wetlands is likely to prove more accurate than studies aiming to discriminate the extent of selective destruction of vegetation within heterogeneous woodlands. This is an interesting observation given that in Africa and Asia, charcoal producers, timber and fuelwood collectors tend to practice selective cutting of trees based on size and species, and also shifting cultivation and selective logging has resulted in selected alteration of woodlands rather than wholesale clearance [*Boyd and Danson*, 2005]. In the case of savanna woodlands, grass-thatched dwellings and cultivated/grazing areas tend to give similar spectral values during dry seasons resulting in difficulties to distinguish between the two classes from optical images [*Palamuleni et al.*, 2007].

Radar sensors

The development and deployment of airborne and spaceborne microwave synthetic aperture radars (SAR) is improving the ability of natural resource managers to map and monitor woodland resources at landscape scales. Several X, C to L-band sensors that have been launched in the past include the ERS-1, JERS-2, Radarsat-1 and Radarsat-2 carrying the C-band sensor; JERS-1 and PALSAR L-band sensors; TerraSAR-X and COSMO-SkyMed with X-band sensor. The availability of three different frequencies for spaceborne radar data is leading to better retrieval of information on forest status and forest parameters because of increased spatial and temporal resolution and fully polarised data [*Imhoff*, 1995; *Kasischke et al.*, 1997; *Koch et al.*, 2007]. Vegetation parameters can be obtained from polarimetric and interferometric interpretation and analysis of the radar measurements.

Capabilities

SAR data is well suited for biomass assessment applications because signals of different wavelengths interact with particular parts of the vegetation structure, making it possible to account for both standing and under-storey biomass. Interferometric and polarimetric techniques are used to analyze SAR data and infer canopy height and density for biomass estimation. Estimation of vegetation parameters from interferometric measurements is affected by sensitivity of lower frequency signals to spatial variability of vegetation height and density [*Krieger et al.*, 2005]. Polarimetry utilizes the differences in the shape, orientation and dielectric constant of transmitted and received radar signal to classify and extract parameters of natural targets. Improved assessment of tree heights and three-dimensional forest structural information can be obtained by coherently combining interferometry and polarimetry techniques with data from optical sensors for forests with mixed structural forms [*Prakoso*, 2006; *Lucas et al*., 2006].

The X- and C-band are particularly sensitive to small components such as leaves and twigs of the canopy whereas longer wavelengths such as L-band and P-band tend to penetrate deeper into the canopy and interact strongly with the tree branches, trunks and ground [*Patenaude*, 2003; *Siqueira et al.*, 1999]. Polarization signatures can be used to automatically extract positions of trees of interest. Digital surface models can be generated from radar backscatter measurements from smaller wavelength (X- and C-band) signals while digital elevation models are computed from the interaction of the longer wavelength (L- and P-band) signals with ground surface. Vegetation heights and tree densities are then estimated from differences between the two models [*Viergever et al*., 2006; *Wallington et al.*, 2006; *Mette*, 2007]. This information is then applied to generalized allometric equations to estimate standing biomass over the mapped area. The input data for this approach still has to be calibrated and validated by corresponding ground measurements as different biomes have different allometric constants.

Several studies using airborne SAR have shown a linear relationship between radar signal wavelengths and biomass saturation levels with ranges from 20 - 200 t ha^{-1} for C and L-band sensors respectively, depending in the ecosystem under investigation [*Imhoff*, 1995; *Rauste*, 2005]. Typical savanna woodlands have estimated biomass densities of up to 70 t ha^{-1} [*Viergever et al*. 2007]. The ALOS PALSAR sensor offers opportunity to relate backscatter changes to clear-cut in forests and to analyze polarimetric coherence between satellite visits to detect areas cleared between the 46 day cycles [*Fransson et al.*, 2007; *Eriksson et al*., 2003].

Limitations

Quantifying woody biomass using radar remote sensing is an emerging discipline and various research efforts are underway to refine methods and techniques. The subsequent high hardware and software costs are hampering the adoption of technology in academic and natural resource management organization. This is further complicated by the long repeat cycles of current satellites e.g. 46 days for the ALOS PALSAR sensor. Future satellites are expected to reduce the visiting period by operating in constellation [*Koch et al.*, 2007], albeit at an increased operational cost.

Radar images are characteristically different from optical images. Many of the objects that are highly visible on optical images are not visible to radar sensors, making it difficult to identify suitable ground control points for precise georeferencing of radar images. *Power et al.* [2006] points out that although spaceborne radar data is geo-referenced using onboard GPS systems, manual geo-referencing allows a more accurate placement of the SAR image (and the interpreted results) in a coordinate system that is common with GIS layers, elevation models and topographic data from field surveys. Corner reflectors provide a possible solution, but their production and installation costs may add a considerable amount to the field survey budget.

Santos et al. [2003] summarizes some of the limitations of mapping vegetation using L-, C- and X-band data. Radiation at X-band penetrates only the upper section of the tree canopy, and as such radar backscatter is only related to the top layer and the crown. C-band penetrates the leaves but not the branches, while L-band encounters leaves and small branches. Higher frequency P-band signals are a possible solution [*Rauste* 2005] as they can penetrate right down to the ground. However, development of spaceborne P-band systems is hindered by signal interference with the ionosphere and most modern communication ultra-high frequency equipment [*Patenaude*, 2003; *Rosenqvist et al*., 2003]. The long wavelength also poses challenges in designing appropriate apertures which maintain high spatial resolution without overloading the orbital system. The interference with civilian communication systems poses the greatest political and technical challenge as it requires permission from individual countries to transmit in the UHF bands during satellite overpasses [*Siqueira et al*., 1999].

Implications for African savanna woodlands

Quantitative biomass data is increasingly becoming a critical component of plans and policies that address some of the millennium development goals such as sustainable environmental management and improvement of health. It is crucial for policy and decision-making makers to integrate spatial data from energy modeling, biomass potential, woodland dynamics and socio-economic applications to create energy demand

and supply scenarios. However, there is generally a lack of such quantitative biomass data for use in bioenergy modeling and at the same time, there seems to be a serious paucity of research on the application of modern techniques to quantify woody biomass in African biomes. Collecting biomass data is complicated by the sparse and heterogeneous nature of savanna woodlands and the high expenses associated with conventional biomass assessment techniques. Past efforts have concentrated on vegetation change detection without quantitative evaluation of standing biomass stocks [*Chidumayo*, 2002].

Optical remote sensing platforms have generated huge archives of data for coarse and medium resolution data but radar data is limited. The optical data is two dimensional and cannot be used to directly retrieve standing woody biomass. High resolution optical data is becoming increasingly available but must be used in conjunction with SAR to differentiate tree species which have spectrally similar signatures in the visible and near-visible infra-red ranges of the spectrum [*Billingsley*, 1984]. High resolution field data from ground surveys, high resolution optical remote sensing sensors and also high to medium resolution spaceborne radar imagery sensors are required to quantify woody biomass in savanna woodlands and to extrapolate to macro-scale applications.

Radar remote sensing is an emerging discipline in most developing countries and is characterized by low levels of expertise in both academic and governmental institutions involved in vegetation monitoring. This shortcoming is further compounded by the steep learning curves for SAR data acquisition, interpretation and analysis as most of the available personnel is trained in optical remote sensing. Other challenges include accessing data from current and past satellite platforms and the long revisit period of some sensors (e.g. 46 days for ALOS PALSAR). While high resolution airborne interferometry SAR systems [*Viergever et al*. 2006] are capable providing vegetation data at the tree level, such high resolution spaceborne systems are lacking for large-scale characterization of woodlands. The medium to coarse spatial resolution limits the accurate geo-referencing and mapping of subsequent SAR derived tree signatures before applying automatic feature extraction routines.

The processing, analysis and dissemination of quantitative environmental data (including woody biomass) requires massive investment in technical, institutional and human resources [*Paradzayi and Rüther*, 2002]. Data access and sharing are becoming major problems when compared to data availability due to underdeveloped spatial data infrastructures in most African countries. It appears that there is need to develop stronger institutional and technical interactions among sectors involved with biomass management [*Mabowe*, 2006]. One possible way of enhancing such data infrastructures is to advocate for the development of the geo-web that offers possibilities to share, integrate and leverage geographic knowledge related to biomass [*Dangermond*, 2007].

Concluding Remarks

Most African villages are located in remote places with very low economic potential that are not widely covered by both conventional and GPS network control points established by the national mapping organizations. Quantifying woody biomass from SAR data requires highly accurate ground control networks for site calibration to allow for the precise positioning of trees. The nature of SAR imagery makes it difficult to identify unique features on SAR images and ground control points (corner reflectors) are required for improved geo-referencing of SAR imagery. High precision EDM and/or Differential GPS surveys should be used to fix these control points because accurate tree positions are critical for the determination of polarization signatures of targeted trees.

More research effort must be addressed to the combination of spaceborne SAR data with high resolution field and optical data to quantify the amount of standing woody biomass in subtropical savanna woodlands. Fusing data from different platforms such as field surveys, high resolution optical and radar (ALOS PALSAR and TerraSAR) promises to improve classification and separation of different tree genera or agricultural crops [*DLR*, 2007; *Koch et al.*, 2007]. Research results from airborne SAR platforms have indicated that using a combination of sensors allows for better estimation of quantitative data on tree heights and standing woody biomass [*Cloude and Papathanassiou*, 2003; Lucas *et al.*, 2006; *Mette*, 2007]. This allows for the subsequent combination of polarimetric and interferometric, and automatic feature extraction techniques to quantify and extrapolate available biomass parameters according to preferred tree species in selected biomes [*Grabitzki*, 2004; *Laliberte et al.*, 2004].

In southern Africa, there is growing need for information on energy demand and supply in rural and low-income urban communities; to assess the fulfillment of millennium development goals and to assist with energy policies planning and implementation. The VW Foundation BioModels project is a multi-institutional and inter-disciplinary research effort seeking to provide decision-makers with quantitative data on available woody biomass in the region. The remote sensing component of the research is attempting to generate quantitative fuelwood biomass data in selected case study areas in South Africa, Mozambique and Zambia. The outcome of this research will contribute to integrated bioenergy policy planning and implementation processes by availing spatially accurate quantitative biomass information to drive multi-purpose applications such as bioenergy, socio-economic and woodland dynamics modeling.

References

Banks D. I., Griffin N. J., Shackleton C. M., S. E. Shackleton and J. M. Mavrandonis (1996), Wood supply and demand around two rural settlements in semi-arid savanna, South Africa, *Biomass and Bioenergy* 11(4), 319-331.

Beerens S. J. J. (2002), Towards a Geo-spatial information system for sustainable management of forests as part of the Geo-spatial Data Infrastructure, Proceedings of the International Workshop on Tropical Forest Cover Assessment and Conservation Issues in Southeast Asia, Dehra Dun, India, 12-14 February 2002.

Biberacher M. (2006) Fusion in the global energy system – GIS and TIMES, CIEMAT – EURATOM Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002 – 2006).

Bolon Ph., Trouvé E., Pétillot I., Vasile G., Gay M., Bombrun L., Nicolas J. M., Tupin F., Landes T., M. Koehl and P. Grussenmeyer (2006), Monitoring Alpine Glaciers with ALOS SAR and Optical data, http://gvasile.free.fr/Articles/Bolo-07_ALOS.pdf , accessed 1 March 2008

Boyd B. S. and F.M. Danson (2005), Satellite remote sensing of forest resources: three decades of research development, *Progress in Physical Geography* 29(1), 1-26

Brouwer R. and M.P. Falcão (2004), Wood consumption in Maputo, Mozambique, *Biomass and Bioenergy* 27, 233-245.

Billingsley F.C. (1984), Remote Sensing for Monitoring Vegetation: An emphasis on satellites in *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing*, edited by G. M Woodwell, John Wiley and Sons Ltd.

Chidumayo E. N. (2002), Charcoal potential in southern Africa – Final Report for Zambia, INCODEV, Stockholm Environment Institute, Stockholm.

Cloude S.R. and K.P. Papathanassiou (2003), Three-stage inversion process for polarimetric SAR interferometry, *IEEE Proceedings on Radar Sonar Navigation* 150(3), 125-134.

Dangermond J. (2007), Manage and Shape Our Changing World with GIS, http://www.esri.com/news/arcwatch/0307/feature.html, 20 March 2007.

DLR (2007), TerraSAR-X, The German Radar Eye in Space, German Aerospace Center, Bonn, Germany.

Ellegård A., Chidumayo E., Malimbwi R., C. Pereira and A. Voss (2002), Charcoal Potential in Southern Africa (CHAPOSA) Final Report, INCODEV, Stockholm Environment Institute, Stockholm.

Galiatsatos N., Daniel N.M., Donoghue and P. Graham (2008), High Resolution Elevation Data Derived from Stereoscopic CORONA Imagery with Minimal Ground Control: An Approach Using Ikonos and SRTM Data, Photogrammetric Engineering and Remote Sensing Journal of the America Society for Photogrammetry and Remote Sensing 74(1).

Grabitzki S (2004), Classification of Miombo Forests Based on SPOT 4 Image Analysis I-TOO Working Paper No. 19, Indicators and Tools for Restoration and Management of Forests in East Africa, Albert-Ludwigs - Universitaet Freiburg, Freiburg, Germany.

Eriksson L.E.B., Santoro M., A. Wiesmann and C. Schmullius (2003), Multi-temporal JERS repeat-pass coherence for growing stock volume estimation of Siberian forest, *IEEE Transactions on Geoscience and Remote Sensing* 41(7), 1561-1570.

Fransson J.E.S., Magnusson M., Folkesson K., Hallberg B., Sandberg G., Smith-Jonforsen G., A., Gustavsson, and L.M.H Ulander (2007), Mapping of wind-thrown forests using VHF/UHF SAR images, paper presented at IGARSS, 23 - 27 July 2007, Barcelona, Spain.

Howells M. I., Alfstad T., David G. Victor D. G., G. Goldstein and U. Remme (2003), An Energy Model for a Low Income Rural African Village - Working Paper 18, Program on Energy and Sustainable Development, Stanford University, http://pesd.stanford.edu/, accessed 25 February 2008.

Hussin Y. A. (2007), Synthetic aperture radar and optical satellite images for detecting and monitoring tropical deforestation and forest degradation in Southeast Asia, ITC, The Netherlands.

Hyde P., Dubayah R., Walker W., Blair J. B., M. Hofton and C. Hunsaker (2006), Mapping forest structure for wildlife habitat analysis using multi-sensor (LiDAR, SAR/InSAR, ETM+, Quickbird) synergy, *Remote Sensing of Environment* 102, 63-73.

Imhoff, M. L. (1995), Radar backscatter and biomass saturation: Ramifications for global biomass inventory, *IEEE Transactions on Geoscience and Remote Sensing* 33, 511-518.

Kasischke E. S., J. M Melack and C. M. Dobson (1997), The use of imaging radars for ecological applications – A review, *Remote Sensing of the environment*, 59(2), 141-156.

Krieger G., K. P. Papathanassiou and S.R. Cloude (2005), Spaceborne Polarimetric SAR Interferometry: Performance Analysis and Mission Concepts, *EURASIP Journal on Applied Signal Processing* (20), 3272–3292.

Koch *et al.* (2007), Forestry applications, ISPRS Congress Book Chapter, in press.

Laliberte A. S., Rango A., Havstad K. M., Paris J. K., Beck R. F., R. McNeely and A. L. Gonzalez (2004), Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico, *Remote Sensing of the Environment* 93, 198-210.

Lasten M. (2002), Rural Energy in Zimbabwe – Focus on Biomass, in *Proceedings of the Latin America Thematic Network on Bioenergy – LAMNET Joint Workshop*, edited by Janssen R, Durban 19 – 21 August 2002, South Africa.

Lucas R. M. and P. K. Tickle (1999), Ground Measurements, Remote Sensing and Biomass Estimation in the Australian Context, in *A review of remote sensing technology in support of the Kyoto Protocol* by Rosenqvist A., Milne A., Lucas R., M., Imhoff and C. Dobson (2003), *Environmental Science and Policy*.

Lucas, R.M., Cronin N., A. Lee, M. Moghaddam, C. Witte and P. Tickle (2006), Empirical relationships between AIRSAR backscatter and LiDAR-derived forest biomass, Queensland, Australia, *Remote Sensing of Environment* 100, 407-425.

Mabowe B. R. (2006), Aboveground biomass assessment in Serowe woodlands; Botswana, Masters Thesis, 91 pp., ITC, The Netherlands.

Masera O., Ghilardi A., D. Drigo and M. A. Trossero (2006), WISDOM: A GIS-based supply demand mapping tool for woodfuel management, *Biomass and Bioenergy* 30, 618-637.

Mette, T. (2007), Forest biomass estimation from polarimetric SAR interferometry, PhD thesis, Technische Universität München, Munich, Germany.

Ottichilo W. K. (2007), Report of the AFREF Working Group to CODI V Meeting, Addis Ababa, Ethiopia, 29 April – 04 May 2007.

Palamuleni L., Annegarn H., M. Kneen and T. Landmann (2007), Mapping Rural Savanna Woodlands in Malawi: a Comparison of Maximum Likelihood and Fuzz Classifiers, paper presented at IGARSS, 23 - 27 July 2007, Barcelona, Spain.

Paradzayi C. and H. Rüther (2002), Evolution of Environmental Information Systems in Africa, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 34.

Paradzayi C., Annegarn H. J., R. Matsika and B. Erasmus (2008), Field surveys for biomass assessment in African Savanna Woodlands, paper to be presented at IGARSS 09, Boston, MA, USA.

Patenaude G. (2003), Remote sensing and LULUCF carbon inventories in the UK, University of Oxford, University of Sheffield.

Patenaude G., R. Milne and T.P. Dawson (2005), Synthesis of remote sensing approaches for forest carbon estimation: reporting to the Kyoto Protocol, *Environmental Science and Policy* 8, 161-178.

Power D., Youden J., English J., Russell K., S. Croshaw and R. Hanson (2006), InSAR Applications for Highway Transportation Projects, U.S Department of Transport.

Prakoso K., U., 2006, Tropical forest mapping using Polarimetric and Interferometric SAR data – a case study of Indonesia, *PhD Thesis,* Wageningen Agricultural University, The Netherlands.

Rauste Y. (2005), Techniques for wide-area mapping of biomass using radar data, Espoo 2005, VTT Publications 591.

Rosenqvist A., Milne A., Lucas R., M. Imhoff and C. Dobson (2003), A review of remote sensing technology in support of the Kyoto Protocol, *Environmental Science and Policy* 6, 441-455.

Santos J. R., Freitas C. C., Araujo L. S., Dutra L. V., Mura J. C., Gama F. F., L. S. Soler and S. J. S. Sant'Anna (2003), Airborne P-band SAR applied to the aboveground biomass studies in the Brazilian tropical rainforest, *Remote Sensing of Environment* 87, 482-493.

Sebukeera C., Muramira E., Momokama C., Elkholei A., Elbagouri I., B. Masumbuko and V Rabesahala, (2006), *Chapter 6: Forest and Woodlands* In UNEP Africa Environment Outlook 2

Short N. (1999), Mapping the Margins of the Barnes Ice Cap using SAR imagery, Masters Thesis, Memorial University of Newfoundland, Canada.

Siqueira P., T. Freeman and S. Hensley (1999), Challenges Associated with Spaceborne Low-Frequency for Achieving the Goals of Kyoto Protocol, in *Remote Sensing and the Kyoto Protocol: A Review of Available and Future Technology for Monitoring Treaty Compliance - Workshop Report*, Ann Arbor, Michigan, USA, October 20-22, 1999, edited by Rosenqvist A., Imhoff M., A. Milne and C. Dobson.

Smith G., Folkesson K., Fransson J.E.S., Frölind P.-O., Gustavsson A., Hallberg B., Magnusson M., L.M.H. Ulander and F. Walter (2002), Forestry applications of CARABAS, paper presented at ForestSAT Symposium Heriot Watt University, Edinburgh, August 5th-9th of August 2002.

Viergever K. M., I. H. Woodhouse and N. Stuart, (2006), Airborne Synthetic Aperture Radar for Estimating Above-ground Biomass in Tropical Savanna Woodland – A case study of Belize, presented at IGARSS, 31 July – 4 August 2006, Denver, Colorado, 2006.

Viergever K. M., I. H. Woodhouse and N. Stuart (2007), Backscatter and Interferometry for Estimating Aboveground Biomass in Tropical Savanna Woodland, paper presented at IGARSS, 23 - 27 July 2007, Barcelona, Spain.

Von Maltitz G. P. and R. J. Scholes (1995), The burning of fuelwood in South Africa: When is it sustainable?, *Environmental Monitoring and Assessment* 38, 243-251.

Wallington E., Viergever K.M., Stuart N., D. Moss and I. Woodhouse (2006), SAR remote sensing for natural resource management – retrieving spatial extent and height of savanna vegetation, *Geomatics World* July/August 2006.

Wamukonya L. and B. Jerkins (1995), Durability and relaxation of sawdust and wheat-straw briquettes as possible fuels for Kenya, *Biomass and Energy* 8(3), 175-179.

Watson H. (2002), Reliance of traditional rural livelihoods in KwaZulu-Natal on biomass resources, in *Proceedings of the Latin America Thematic Network on Bioenergy – LAMNET Joint Workshop*, edited by Janssen R., Durban 19 – 21 August 2002, South Africa.

WEO (2006), World Energy Outlook 2006, OECD/ International Energy Agency.

Wonnacott R. (2005), AFREF: Background and progress towards a Unified Reference System for Africa, June 2005Article of the Month, International Federation of Surveyors.