RANGELANDS

Assessing degradation across a land-use gradient in the Kruger National Park area using advanced remote sensing modalities

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Land degradation is regarded as one of the most important environmental issues facing sub-Saharan Africa and is especially relevant in the former communal 'homeland' areas of South Africa. Although it has been a topic of intense research, efforts have reached a juncture at which regional modelling and monitoring are constrained by the relatively coarse scale and sensitivity of traditional remote sensing technology as compared to the fine scale at which many processes occur. However, two relatively novel remote sensing approaches, namely imaging spectroscopy (hyperspectral remote sensing) and light detection and ranging (lidar), have the potential to alleviate this constraint. Specifically, the Carnegie Airborne Observatory, a state-of-the-art integrated imaging spectrometer-lidar platform operated by the Carnegie Institution for Science, is being used by South African and international researchers to gain a better understanding of degradation and its impact on rural livelihoods and environmental protection in South Africa.

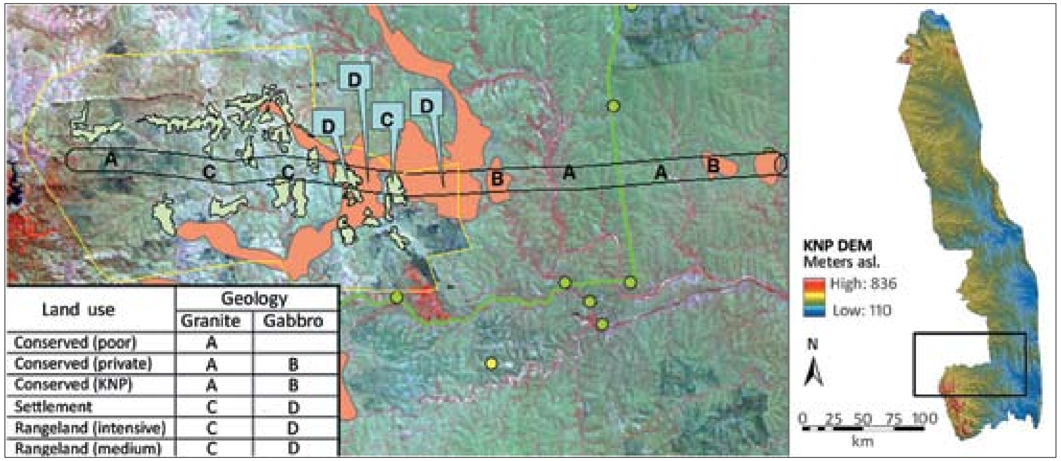
Introduction

Land degradation is defined as a persistent reduction in the capacity of the ecosystem to deliver ecosystem services to the broader community, for example, grazing, fuelwood, or habitat for wildlife. The process could involve a reduction in grass production, changes in plant species composition, and soil erosion as a result of overgrazing, as well as increases in tree cover (bush encroachment) or reductions in tree cover due to excessive wood removal. It is regarded as one of the most important environmental issues facing sub-Saharan Africa and is especially prevalent in the communal lands of the former 'homelands' [1]. It is therefore understandable that land degradation has been a topic of intense research [2, 3], but has approached a point at which regional modelling and monitoring are limited by the capabilities of traditional satellite remote-sensing technology. One of the limiting factors is the reliance on high revisit times, low to moderate spatial resolution (30-500 m pixels), multispectral (3-20 wavebands) remote-sensing data. Sensors, such as 1 km/pixel AVHRR, 500 m/pixel MODIS and 30 m/pixel Landsat TM sensors, serve best as regional or continental assessors of vegetation production. These spectrally and spatially coarse resolution data cannot unravel changes in the land surface (specifically reduced grass cover, increases in bare soil and reductions in tree biomass) at the scale at which the processes actually occur (a few meters), nor can they identify fine-scale vegetation composition and structure.

The need for fine-scale degradation assessment helped to define a new breed of sensors that (a) have a broader wavelength range, defined in narrower wavelength bins (imaging spectroscopy, also called 'hyperspectral' remote sensing) and (b) are capable of describing the three-dimensional vegetation structure, for example, lidar remote sensing. One such sensor platform is the Carnegie Airborne Observatory (CAO) operated by the Carnegie Institution for Science, shown in Figure 3.28.

Figure 3.28
TOP: The CAO system in operation (Dr. Greg Asner, the CAO principal investigator, left, and Ty Kennedy-Bowdoin, system engineer, right). BELOW: The imaging spectrometer and lidar sensors mounted in the aircraft for data collection.

More than two million people reside within 50 km of the western boundary of Kruger National Park, with the vast majority concentrated in the former homelands which are widely regarded as degraded. Previous work in these communal areas has raised the concern that excessive wood removal and transformation of woodlands by subsistence cultivation may be threatening the tree resources [4]. This provides the opportunity to investigate the impacts of contrasting land uses on ecosystems along a land-use gradient, from the Kruger National Park (conserved area) to private game reserves (managed for eco-tourism) and former homeland areas (subsistence livelihoods) in the Lowveld (Figure 3.29). Local and international researchers have collected hyperspectral and lidar data using the CAO during a six-week flight campaign in 2008. These data allow us to investigate how imaging spectroscopy and lidar can improve our understanding of local, fine-scale land degradation by looking for subtle changes in grass and tree species composition (spectral) and structure (lidar) along this land-use gradient. This will provide measures of ecosystem state variables that can be monitored to establish if the ecosystem can sustain ecosystem services and products such as fuelwood and grazing in the long term. Ultimately this work will support the development of operational, management solutions by helping researchers and managers to better understand how degradation manifests at such scales and to extract information from regional and space-based sensors for savanna degradation monitoring and management.



Land use	Geology	
	Granite	Gabbro
Conserved (poor)	A	
Conserved (private)	A	B
Conserved (KNP)	A	B
Settlement	C	D
Rangeland (intensive)	C	D
Rangeland (medium)	C	D

Figure 3.29 The study area in the Kruger National Park that shows the flight line spanning conservation, private game reserve, and communal lands, as well as a variety of geological strata.

The Carnegie Airborne Observatory (CAO)

A brief introduction to hyperspectral and lidar remote sensing modalities, onboard the CAO system, is warranted before looking at early results of this project.

- Imaging spectroscopy (hyperspectral data) provides a large number (>100) of narrow-band and contiguously sampled wavelengths for an area, usually in the range of 400-2 500 nm (blue to shortwave-infrared regions). Such a sensor is analogous to the human eye in the visible domain. Humans can see not only blue, green, and red, but subtle variations of these hues and combinations thereof – in other words, your eye is a hyperspectral sensor! This is in stark contrast to multi-spectral sensors. For example, the well-known Landsat satellite with six bands in the 400-2 500 nm range, which, in our analogy, can in fact only see blue, green and red (Figure 3.30). Hyperspectral data are typically useful for mapping vegetation stress, species composition, nutrient status, minerals, and such like. These are applications that require narrow spectral channels for extraction of very specific spectral features.
- Light detection and ranging (lidar), on the other hand, involves the emission of a laser pulse from an airborne sensor, the measurement of the laser pulse's return-travel time from sensor to target and the calculation of the distance travelled by the laser beam [5]. You can compare this to a high-tech range finder one buys at a local hardware store, except a lidar typically pulses more than 70 000 times per second and can accurately measure distances from as far as 4 km for large areas. A distinction can be made between 'discrete return' and 'waveform' lidar sensors. Discrete return sensors measure x,y,z (height) coordinates per laser pulse (Figure 3.31), while waveform systems capture the 'energy wave' of the laser as it interacts with a target, for example, a tree or building. The denser and more abundant materials make for a bigger wave and vice versa. Figure 3.32 shows an example of the hyperspectral imagery and lidar-based height data captured by the CAO.

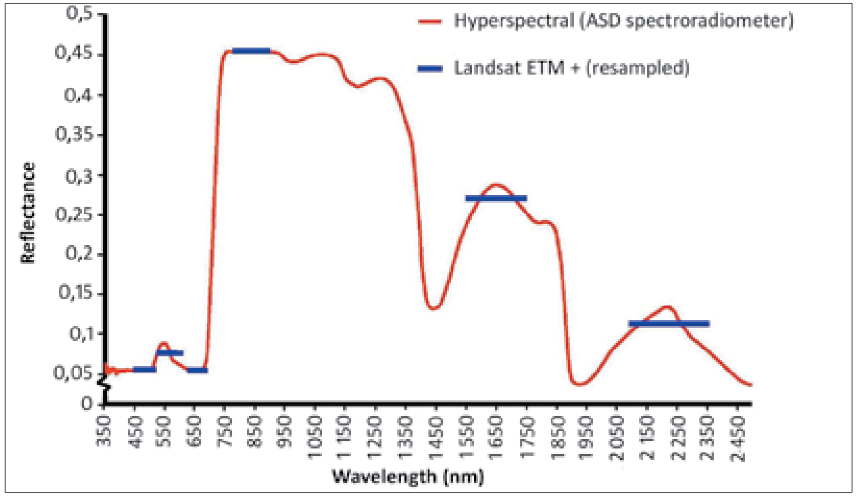


Figure 3.30 An example of hyperspectral data (ASD spectroradiometer) versus Landsat spectral sampling characteristics for a typical green vegetation spectrum.

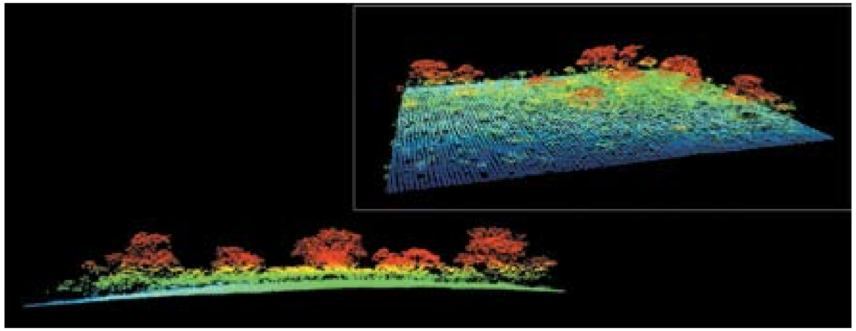


Figure 3.31 CAO discrete return lidar data that illustrate the concept of multiple lidar 'returns' or 'hits'. Each return has a defined x- and y-coordinate, as well as a z, or height value. We can use this information to better understand and improve characterisation of savanna vegetation structure.

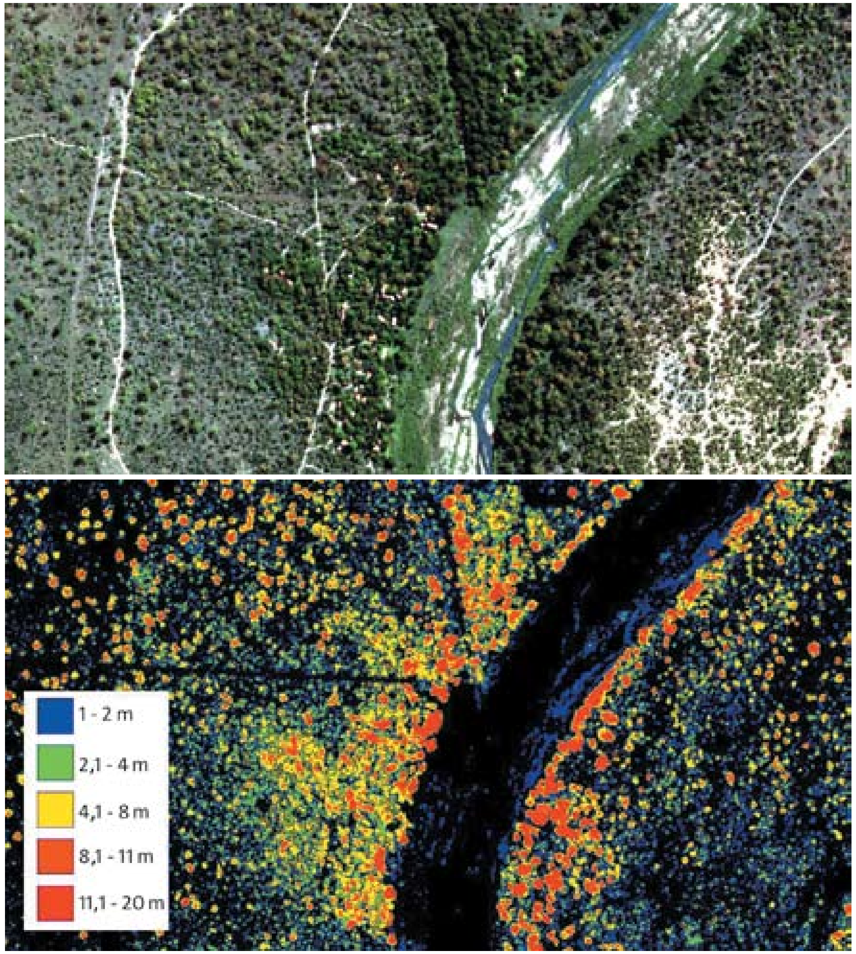


Figure 3.32 TOP: Sample of hyperspectral true colour composite imagery and of Sabi River. BELOW: Lidar imagery of same area indicating tree canopy height (low-green to high-red). Both data sets were captured simultaneously by the Carnegie Airborne Observatory.

The CAO is an airborne platform that includes, over and above the hyperspectral and lidar sensors, the navigational and computational capacity to integrate them virtually in real time. The CAO is designed and operated by Dr. Greg Asner (Carnegie Institution for Science) and is primarily a research instrument. This system makes use of the data properties of both hyperspectral and lidar technologies for describing any target (or natural system in our case) in spectral and structural domains. Such a novel approach presents significant benefits to ecosystem research, especially to the widespread and complex process of land degradation in South Africa.

Local research questions

A key set of research questions are being addressed collaboratively by the Council for Scientific and Industrial Research (CSIR) Ecosystems Earth Observation (Drs. Renaud Mathieu and Moses Cho), Meraka Remote Sensing Research Unit (RSRU; Dr. Konrad Wessels), and Ecosystems Processes and Dynamics (Dr. Bob Scholes), along with the Wits Animal, Plant, and Environmental Science department (APES; Dr. Barend Erasmus), Kruger National Park (KNP) Scientific Services (Dr. Izak Smit), Rochester Institute of Technology (RIT; Dr. Jan van Aardt), and the CAO team (Dr. Greg Asner) groups (Figure 3.33).

Figure 3.33 The core team that heads up various aspects of the CAO research effort (from left-to-right): Drs. Shaun Levick (CAO), Izak Smit (KNP), Jan van Aardt (RIT), Konrad Wessels (CSIR), Greg Asner (CAO) and Barend Erasmus (Wits). (Renaud Mathieu and Moses Cho (CSIR) are not pictured here.)

The main research questions and their impacts are:

- What differences in ecosystem state variables (for example, woody vertical structure, cover, and composition, grass biomass) can be observed across a KNP-rural settlement gradient? *Such information might address tree biomass changes due to wood removal and browsing and contribute to management policies in this region.*
- Can the quantitative measures of land degradation (for example, fractional area of bare ground versus grass cover; leaf area, leaf nitrogen and secondary chemicals) across such a gradient be improved using the spectral-structural interaction derived from the CAO? *Researchers will be able to gain a better understanding of land degradation processes and interactions by answering this question.*
- Which key spectral/structural indicators are necessary to address the questions posed above – how do we go from over-sampled spectral and structural data volumes to manageable solutions and quantitative measures of degradation, and how might future sensors be optimised? *This will allow managers to implement more operational versions of the expensive sensing modalities, especially once we know exactly what we need to effectively 'sense' remotely.*
- Can this package of information and integrated modelling be used to predict the annual production of ecosystem services, such as grazing and fuelwood, and therefore help to determine sustainable levels of utilisation? *Answers to these questions have distinct implications in terms of conservation and rural management policies.*

Recent project outcomes

The CAO mission to South Africa has presented an opportunity for research collaboration at the cutting edge of ecosystem state assessment. As noted previously, vegetation structure and composition, for example, tree density and size distributions, cannot be sufficiently measured and monitored with existing optical remote sensing; however, high spatial resolution lidar and hyperspectral technology provide a viable, reliable, and fine-scale alternative.

The project has thus far led to exciting preliminary results, many of which are truly novel, for example:

(a) Improved understanding of ecosystem degradation through the development of hyperspectral and lidar based metrics at the appropriate scales: A collaborative team has shown that bare soil, as well as woody and grass cover, can be mapped using the hyperspectral sensor onboard the CAO. This fractional representation of these different covers is a prime indicator of land degradation and is expected to differ across the Kruger National Park-game reserve-homeland land-use gradient. Figure 3.34 shows the difference between woody, grass and bare soil cover for (a) a rangeland site in the Kruger National Park and (b) a site of similar rainfall in the private game reserve. Note the change in especially woody versus grass cover due to different management regimes. The west-to-east rainfall gradient could also have had a marginal impact.

(b) Results that have management and policy applications: If we could better understand how the different management scenarios impact the natural systems, this should lead to improved management of conserved and highly altered ecosystems. Researchers have shown that structural differences in woody cover exist along the studied land-use gradient. There is evidence that not only woody cover but also the height distribution of the remaining trees in highly impacted communal areas are significantly different from those of comparable sites in the private reserves and Kruger National Park. Most notably, the total tree canopy cover is less than half in highly impacted communal areas, while in other communal areas the canopy cover is much higher due largely to increases in shrubs lower than 2 m (Figure 3.35).

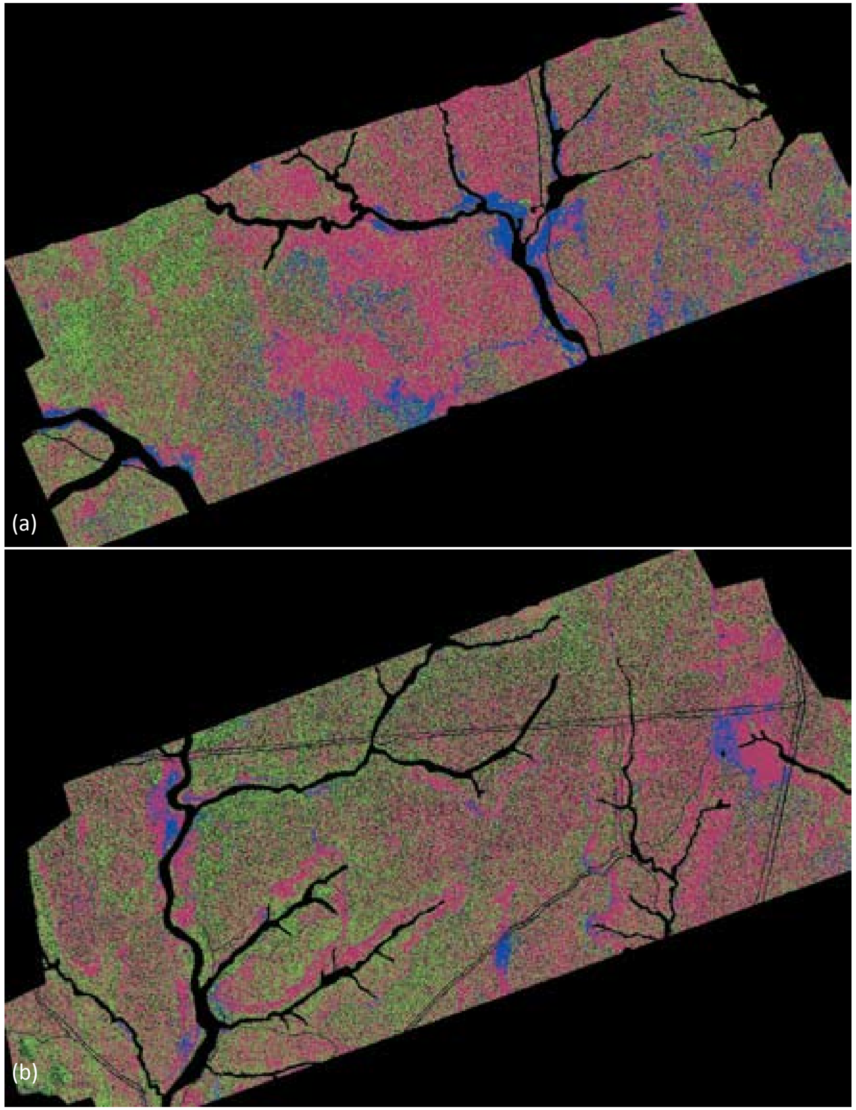


Figure 3.34 Thematic maps that show the woody (green), grass (red) and bare soil (blue) cover for (a) the Kruger National Park and (b) a private game reserve. These representations are for sites with a similar annual rainfall and show changes in cover, as driven by different management regimes.

Figure 3.35 (a) Very low tree cover (2%) in highly-impacted communal area on gabbro substrate as a result of long-term fuelwood removal. (b) Expected tree cover (11%) in conservation area on gabbro substrate near photo (a).

(c) Finally, metrics of vegetation structure are being developed based on cutting-edge waveform lidar data to provide indicators of degraded ecosystems. Figure 3.36 on the next page shows one such example, extracted by the team at RIT (Dr. Jan van Aardt), of a typical lidar waveform visualisation showing the 3D vegetation structure and foliar biomass.

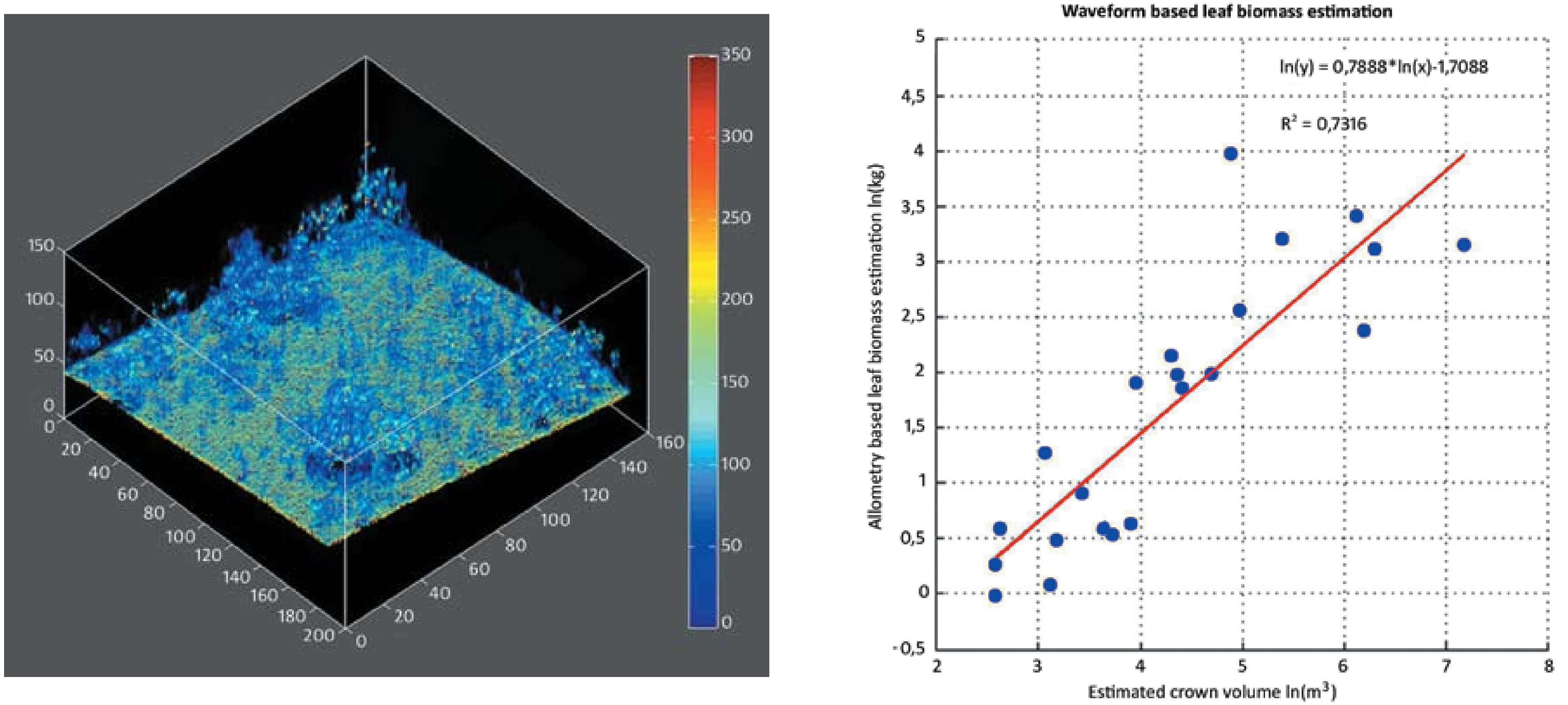


Figure 3.36 LEFT: A representation of the lidar intensity at a given x,y,z location (intensity refers to the bulk of matter that is returning a signal to the sensor; the legend shows the range of intensity values). RIGHT: A plot of the relationship between modelled field leaf biomass and crown volume, derived from the waveform lidar data. Note that we are able to explain 73% of the variation (information) in foliar biomass using a single sensor.

Imaging spectroscopy (hyperspectral) and lidar (structural) research are in their infancy in South Africa. However, as we rapidly develop methods to extract valuable information from these data and this technology becomes more affordable, future monitoring systems can be based on lidar and hyperspectral imagery. In fact, lidar provides the only viable option for monitoring tree density, structure, and biomass across large areas. The work juxtapositions efforts by the CAO team and their focus on tropical forests; local research is designed to increase our understanding of animal and plant dynamics and interactions in a *savanna/rangeland environment*. Although certain principles are transferable across such diverse ecosystems, there are few substitutes for local knowledge and environment-specific data exploration. Such an approach and its associated outcomes are therefore especially critical, especially in terms of improved management and decision making of the natural resource base upon which many rural livelihoods depend.