|  |  |  |
| --- | --- | --- |
|  | RESEARCH PROPOSAL  PhD in Geography & Environmental Studies  **VERY HIGH RESOLUTION REMOTE SENSING OF CARBON STOCKS IN SUBTROPICAL THICKET** |  |
|  | DUGAL HARRIS (MSC ELEC ENG)  (17447585) |  |
|  |  |  |
|  | SUPERVISOR: PROF A VAN NIEKERK  Department of Geography & Environmental Studies  Stellenbosch University |  |
|  |  |  |
|  | 11 OCTOBER 2014  DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES |  |
|  |  |  |

# BACKGROUND

The Subtropical Thicket biome is found in the Eastern Cape and Little Karoo. “Subtropical Thicket habitat types are most easily recognized by the occurrence of woody trees, spinescent shrubs and a relative abundance of succulents.” (Vlok, Cowling & Wolf 2005: 41). It can form continuous, dense stands but frequently occurs as scattered bush-clumps in a matrix of some other vegetation type. Poorly managed livestock browsing, particularly by goats, has resulted in substantial degradation of thicket habitat throughout much of its range (Thompson et al. 2009; Powell et al. 2005). When degraded, thicket is transformed into sparsely scattered clumps, isolated trees and a covering of herbs (Mills et al. 2005). Figure 1‑1 shows an example of degraded and intact thicket across a fence-line in the south-eastern Cape. Severely degraded thicket is not able to recover spontaneously if livestock pressure is removed (Mills et al. 2007; Vlok, Cowling & Wolf 2005).



Figure 1‑1 Intact and degraded subtropical thicket

Source: (Restoration Research Group 2012)

*Portulacaria afra* (Spekboom) is an important species in the Subtropical Thicket biome. It is an evergreen succulent tree growing to 2.5m, with small fleshy leaves and is the dominant species in the arid and valley thicket habitat types (Vlok, Cowling & Wolf 2005). *P. afra* is an attractive browse plant for indigenous herbivores but is highly susceptible to over-browsing by goats (Marais, Cowling & Powell 2009; Sigwela et al. 2009; Mills et al. 2007; Mills et al. 2005). *P.afra* appears to act as a nurse plant, creating a favourable environment for the establishment of other species (Mills & Cowling 2010). The dense canopy of *P. afra* facilitates an accumulation of soil organic matter which in turn improves the water-holding capacity and fertility of the soil (Mills & Cowling 2010; Lechmere-Oertel et al. 2008; Mills & Fey 2004). It has been observed that over a period of 40 years, woody canopy and other species re-establish in *P. afra* restoration areas to a degree that restored thicket is compositionally identical to intact thicket (Vyver et al. 2012). *P. afra* is unusually effective at storing carbon compared to other arid region vegetation. It has the uncommon ability to switch between C3 and CAM photosynthetic mechanisms depending on season (Guralnick & Ting 1986). This means it is productive year-round which likely contributes to its substantial sequestration abilities (Mills & Cowling 2010). Comparison of degraded and intact sites has shown that *P. afra* restoration could sequester up to 85 t C ha-1 (Powell 2009; Marais, Cowling & Powell 2009; Mills et al. 2005). This number competes with the carbon storage capacity of mesic forests (Mills et al. 2005).

There is considerable interest in act**i**vely restoring degraded thicket habitat. Average rates of carbon sequestration have been measured at two restoration sites as 4.2 ± 0.08 t C ha-1 yr-1 and 1.2 ± 0.03 t C ha-1 yr-1 (Mills & Cowling 2006). Carbon captured through restoration of *P. afra* can be traded as credits on the international carbon market. While marginal in some circumstances, using this as a source of funding for landscape-scale restoration has been shown to be economically viable (Mills et al. 2007; Marais, Cowling & Powell 2009). *P. afra* propagates vegetatively and can be grown from cuttings (Stuart-Hill 1992), thus avoiding nursery expenses (Mills & Cowling 2010). It is a hardy and drought-tolerant plant making restoration a relatively simple and maintenance-free process.

Subtropical Thicket provides an important source of food for many herbivores, including domesticated livestock (Thompson et al. 2009; Vlok, Cowling & Wolf 2005). Re-establishment of *P. afra* in degraded areas will help prevent soil erosion and reduce flood severity (Mills & Cowling 2006). It is also attractive from an employment perspective; potentially creating thousands of jobs in impoverished areas, if implemented on a large scale. Increased biodiversity could help improve income from tourism and provide sustained access to wood, fruit, and medicines for local communities (Mills et al. 2007).

The Subtropical Thicket Restoration Project (STRP) was established to investigate the feasibility of thicket restoration and establish cost effective methods of determining carbon stocks (Powell 2009). “To evaluate methods of spekboom restoration, a partnership has been forged among scientists, government and an implementing agency. The South African government’s Working for Woodlands Programme … has engaged a group of scientists to assist in evaluating effective ways of using spekboom cuttings for restoration under different conditions …. The programme is being managed by an implementing agency, the Gamtoos Irrigation Board (GIB), rated as one of the best agencies used by Working for Water.” (Mills et al 2010: 9) *P. afra* restoration is actively being conducted and monitored in the Baviaanskloof Nature Reserve, Addo Elephant National Park and the Fish River Reserve in the Eastern Cape (Mills et al. 2010). Approximately 1630 ha had been restored in these areas in 2012 (Vyver et al. 2012).

Under the Kyoto Protocol, currently in the second commitment period, participating countries agree to reduce CO2 emissions to capped levels. If these levels are exceeded, countries can make up the deficit by buying carbon credits from another country that was able to reduce its emissions below its target level (Mills et al. 2010). The Clean Development Mechanism (CDM) is a means by which developing countries can run sequestration projects and trade carbon credits on the international market. There are also the Voluntary Carbon Standard (VCS) and Community, Climate and Biodiversity Standard (CCBS) which work on a similar basis to the CDM, but don’t require authorisation by the host country. Under these schemes there are legal provisions that require rigorous accounting of stored carbon.

Carbon stock measurements are generally performed using field-based allometric techniques which are extremely time consuming and costly when performed manually and are not practical on a large scale (Eisfelder, Kuenzer & Dech 2012; Powell 2009; Lu 2006). Allometry in this context refers to the establishment of relationships between plant characteristics (such as canopy area, stem width and basal area) and the above-ground biomass (AGB) or above-ground carbon (AGC) (Goetz et al. 2009). The AGC is determined through destructive sampling, oven-drying and weighing of vegetation. The impracticality of allometry for large areas is confounded in the Subtropical Thicket biome due to its density, heterogeneous nature and complex growth forms (Powell 2009).

Supporting spatial information is needed to aid the *P. afra* restoration process. Candidate restoration areas need to be identified. There are many factors to consider when selecting appropriate sites (Curran et al. 2012; Knight et al. 2011). A map of *P. afra* canopy cover would assist in this decision-making process. Measures of intact canopy cover in a similar habitat to the restoration area are used to determine an appropriate planting density. Restoration progress can be monitored by updating the canopy cover map over time which would also assist in the carbon accounting required for trading credits on the international market (Mills et al. 2010). Canopy cover is also an important predictor of biomass and carbon stocks (Eisfelder, Kuenzer & Dech 2012; Powell 2009; Suganuma et al. 2006), and can thus serve as a first step towards a method for the direct mapping of AGC. Ultimately, maps of carbon stocks are required to qualify for trading under the CDM and similar schemes. These maps would also help indicate the economic feasibility of restoration for candidate sites. In addition, canopy cover and AGC maps would be useful as research tools for deepening the present understanding of the Subtropical Thicket biome.

A detailed vegetation map of the Little Karoo has been created at a 1:50000 scale (Vlok, Cowling & Wolf 2005). Using this map, a degradation mapping study was conducted in the Little Karoo (Thompson et al. 2009). It was successful at using MODIS data to estimate intact, moderate and severe degradation levels of *P. afra* thicket at a 250m pixel resolution. Currently, there is an initiative to involve private land-owners in the restoration project in order to broaden its impact (Curran et al. 2012; Mills et al. 2010). Restoration planning at farm-level will require map scales of 1:10000 or better to provide sufficient spatial detail for working with expected stand sizes of the order of 50 hectares. To achieve sufficient accuracy for carbon storage estimations, it will be necessary to estimate canopy cover in finer detail than the three levels of degradation used in Thompson et al. (2009) and at a finer spatial resolution. There is thus a need to further the work of Thompson et al. (2009) to produce maps of both a higher spatial and canopy cover level resolution.

A means for the accurate remote sensing of carbon stocks would allow restoration projects to qualify for income generation through the generation of carbon credits under the CDM and other schemes. Such a method would provide a substantial improvement in cost effectiveness over manual allometry and is probably the only practical way of satisfying carbon accounting requirements on a landscape scale. Allometric AGC relationships for fourteen common thicket species in the Baviaanskloof Nature Reserve (BNR) were established through the extensive work of Powell (2009) and colleagues. These relationships were used to produce detailed carbon stock ground truth for 191 5x5m grids covering various thicket habitat types and levels of degradation. The availability of this data will be invaluable to the development of an automated remote sensing technique for carbon stock measurement.

# PROBLEM STATEMENT

Subtropical Thicket has been degraded by overgrazing over much its range. There is significant interest and a growing body of research in thicket restoration. Restoration projects will generate employment, restore ecosystem services and produce carbon credits that can be traded to offset restoration costs. There is a need for spatial information, in the form of total above-ground carbon (TAGC) stock maps, to support restoration projects in the quantification of carbon stocks required for trading under schemes such as the Clean Development Mechanism (CDM). *P. afra* canopy cover is an important predictor of TAGC in Subtropical Thicket. *P. afra* canopy cover maps are also useful in isolation for the identification of suitable areas to plant and in the monitoring of restoration progress over time. Restoration is planned for large areas of the Little Karoo and Eastern Cape. Map scales of at least 1:10000 are required to provide sufficient accuracy for farm-level restoration planning. The production of detailed, carbon stock and canopy cover maps using manual methods is prohibitively time-consuming and expensive, particularly for large areas. An automated or semi-automated image analysis technique that is robust to the inherent temporal, topographic and radiometric variations in VHR aerial imagery is needed to monitor TAGC and *P. afra* canopy cover dynamics in the Subtropical Thicket biome.

# AIM(S) AND OBJECTIVES

The research aim is to develop an automated or semi-automated image analysis technique to accurately estimate *P. afra* canopy cover and TAGC in pristine and transformed Subtropical Thicket, over large areas. A secondary aim is for the mapping techniques to make use of freely available, uncalibrated, very high resolution (VHR) aerial imagery from Chief Directorate: National Geospatial Information (NGI).

To achieve the research aims, the following objectives have been set:

1. Review the literature on *P. afra* restoration, canopy cover and carbon stock mapping in arid environments, as well as canopy cover and carbon stock mapping using VHR imagery.
2. Carry out a field study to establish suitable reference sites and determine the actual (ground truth) canopy cover for each site.
3. Source and rectify raw aerial imagery of the study area from NGI. Develop a technique for radiometric correction of the NGI aerial imagery.
4. Design a canopy cover mapping algorithm that uses a classifier to accurately distinguish *P. afra* from surrounding vegetation.
5. Apply the classifier to imagery of the study area and interpret and evaluate the results.
6. Conduct a second field study to accurately locate the BNR carbon stock ground truth plots in the aerial imagery.
7. Using the available BNR carbon stock ground truth, develop a regression technique to determine TAGC from aerial imagery. Evaluate and interpret the carbon stock results.

# SIGNIFICANCE AND RATIONALE

In the context of climate change, carbon stocks (directly related to biomass) are important for monitoring ecosystem carbon dynamics. Carbon absorbed by vegetation and soils will play a significant role in efforts to reduce atmospheric CO2 and in determining the development of future climate change (Eisfelder, Kuenzer & Dech 2012; Powell 2009; Lu 2006). Canopy cover and carbon stocks are also important from a perspective of understanding environmental processes and ecosystem services. Improved biomass is related to increased biodiversity (Lu 2006; Fabricius, Burger, and Hockey 2003), reduced erosion and improved soil fertility and water-holding ability (Eisfelder, Kuenzer & Dech 2012; Mills & Cowling 2010; Lechmere-Oertel et al. 2008; Mills & Fey 2004).

The benefits of *P. afra* restoration are manifold and include benefits for local communities. The STRP has placed a strong emphasis on stakeholder engagement and community development (Marais, Cowling & Powell 2009). Restored areas will provide increased capacity for supporting judiciously managed livestock and employment for thousands of workers if restoration is implemented on a large scale (Mills et al. 2010). Employment is particularly relevant for the Eastern Cape where unemployment rates are amongst the highest in South Africa at roughly 27% (Statistics South Africa 2011).

Mapping of *P. afra* canopy cover represents a practical first step towards a technique for remote sensing of Subtropical Thicket carbon stocks. Powell (2009) found that *P. afra* canopy cover was strongly correlated with TAGC (R2=0.516). While carbon stock mapping typically uses vegetation indices, such as the Normalised Difference Vegetation Index (NDVI), for building regression models (Eisfelder, Kuenzer & Dech 2012; Goetz et al. 2009; Lu 2006), one can conclude from the results of Powell (2009) that *P. afra* canopy cover will potentially be a more informative variable for determining TAGC. *P. afra* canopy cover measurements are also useful in isolation as *P. afra* is the target species for planting and is also a significant contributor to carbon storage.

This research presents a number of challenges from a technical remote sensing perspective. There is VHR (0.5m/pixel) multi-spectral data with national coverage available from National Geo-spatial information (NGI) (National Geo-spatial Information 2012). This imagery represents a rich source of information, but to date it has only been used for topographical mapping and photo-interpretation. To the best of the author’s knowledge, this will be the first study to exploit this imagery for automated vegetation monitoring. While receiving increasing attention, use of VHR imagery for estimation of environmental variables is still fairly uncommon, especially over large areas such as the Little Karoo or Eastern Cape (Eisfelder, Kuenzer & Dech 2012; Lu 2006).

The NGI imagery has had no radiometric calibration applied to it and requires correction for atmospheric and Bi-directional Reflectance Distribution Function (BRDF) effects before it can be used for quantitative remote sensing. While techniques for correcting atmospheric and BRDF effects are reasonably well established for individual images, correction of mosaics of aerial imagery is still an open and challenging problem (Markelin et al. 2012; Collings et al. 2011; López et al. 2011; Chandelier & Martinoty 2009; Honkavaara et al. 2009). The large view angles of aerial imaging cameras mean that solar and viewing geometry varies significantly within the image. Mosaics are usually captured over many days resulting in significant variation in BRDF and atmospheric effects. Another difficulty arising with aerial imagery is that land covers in the scene each have their own unique BRDF. This research will need to address these issues.

Dealing with sources of unwanted variation is a recurring difficulty reported in the remote sensing literature (Eisfelder, Kuenzer & Dech 2012; Baraldi et al. 2010; Lu 2006). Achieving accurate canopy cover and carbon stock mappings over a large spatial scale and using a mosaic of images acquired at different times will require algorithms that are robust to many of the variations commonly encountered. These will include varying topography and thicket habitats, possible phenological changes and shadow variations. Results of dealing with these challenges will likely be of interest to the remote sensing community.

A significant portion of stored carbon in Subtropical Thicket lies below the ground. In Powell (2009), it was found that root and soil carbon contributed 5.6 % and 57.0 % to total carbon stocks respectively. Bayer (2013) had success in using hyperspectral aerial imagery to measure soil carbon in Subtropical Thicket. This was with HyMap imagery which covers the 440 to 2500 nm spectral range. This spectral range is well beyond the sensitivity of typical multi-spectral aerial cameras, such as the one used by NGI (Intergraph 2008), whose spectral range ends at 850 nm. It is not envisioned that any feature derived from multi-spectral aerial imagery will be well-correlated with below ground carbon due to the importance of the short wave infrared (SWIR) portion of the spectrum in describing soil carbon. For this reason, only the above ground carbon component will be addressed in this research.

# RESEARCH METHODOLOGY

Canopy cover and carbon stock estimations are currently being conducted manually in the field. While this is a common approach for measuring environmental indicators, it is time consuming and only practical for small areas (Eisfelder, Kuenzer & Dech 2012; Lu 2006). *P. afra* restoration is envisioned for large areas of the Eastern Cape and Little Karoo and will require monitoring of plant growth over time. Repeatability and accuracy constraints on carbon measurements are stringent in order to achieve the necessary accreditation for carbon trading in schemes like the CDM. This research will investigate the use of quantitative remote sensing methods for estimating *P. afra* canopy cover and TAGC in Subtropical Thicket. Remote sensing methods are common for carbon stock estimation (Eisfelder, Kuenzer & Dech 2012; Goetz et al. 2009; Lu 2006) and will help facilitate cost-effective canopy cover and carbon stock estimation of large areas at repeated intervals. Using the categorisation of Mouton (2001), this research can be regarded as a methodological study that is experimental in nature.

The work is intended to be applied research. Emphasis will be placed on producing maps that are both useful and usable (Pierce et al. 2005). This will require interaction and communication with stake-holders (Knight et al. 2011), specifically environmental practitioners currently involved in thicket restoration, the STRP and the GIB, who are the restoration implementing agents (Mills et al. 2010).

There is a tendency for environmental remote sensing to be conducted in an isolated way that does not allocate adequate importance to understanding complex human and ecological processes affecting the data being analysed (Hein et al. 2011; Turner 2003). This naïve approach can lead to models that do not generalise well over varying spatial and temporal conditions. Recognition of the value of multi-disciplinary teams incorporating expert knowledge of local conditions and field experience is given in Knight et al. (2011) and Thompson et al. (2009). The *P. afra* canopy cover portion of research will be undertaken in collaboration with a botanist, Jan Vlok, who has a wealth of experience in the Little Karoo (Thompson et al. 2009; Forsyth, Vlok & Reyers 2008; Vlok, Cowling & Wolf 2005) and with *P. afra* in particular. The carbon stock estimation work will be done in collaboration with an ecologist, Mike Powell, who has been deeply involved in thicket restoration work and co-ordination of related research for many years. His thesis (Powell 2009) and associated carbon stock ground truth will be of great value to this study.

# RESEARCH METHODS

## Study Area

The study area as shown in Figure 6‑2, is divided into two portions for the two main components of the research. The first portion is in the Little Karoo, as defined in Vlok, Cowling & Wolf (2005), and will be used for testing and implementing the *P. afra* canopy cover mapping technique. The second portion is in the Baviaanskloof, where the carbon stock ground truth of Powell (2009) is located. The TAGC mapping technique will be developed and applied to this data.

The Little Karoo is a semi-arid region of great biodiversity lying between two mountain ranges. Three biomes considered to be biodiversity hotspots of global significance intersect in the Little Karoo (Thompson et al. 2009). A total of 54 habitat types were identified by Vlok, Cowling & Wolf (2005) in their vegetation map, of which ten support *P. afra*. The Subtropical Thicket biome makes up 35.3% of the Little Karoo which has a total area of 2 343 900 ha (Vlok, Cowling & Wolf 2005). It was found that 89.3% of the *P. afra* thicket was degraded to some extent in a study area comprising roughly half the area of the Little Karoo (Thompson et al. 2009). The Little Karoo was chosen as a study area because it contains a significant portion of *P. afra* suited and degraded habitat and has been targeted for restoration. It is also beneficial that a number of relevant studies have been performed in the area (Thompson et al. 2009; Forsyth, Vlok & Reyers 2008; Vlok, Cowling & Wolf 2005).

To expedite computing times and reduce storage space required for the VHR imagery, a smaller portion of the Little Karoo was chosen as the study area. This area was chosen to be as representative of the variation in the Little Karoo as possible. It consists of four different aerial survey jobs flown at different times and thus still poses a challenge from a remote sensing perspective. It also includes examples of all the different biomes and nine of the ten habitat types supporting *P. afra* as defined by Vlok, Cowling & Wolf (2005).

The Baviaanskloof “is arguably one of the most bio diverse areas within Southern Africa with representation of all seven of South Africa’s biomes in the planning domain of the mega-reserve. It is at the convergence of 2 of the world’s top 25 biodiversity hotspots (Cape Floristic Region and the Succulent Karoo). A further biodiversity rich area, the Subtropical Thicket Biome also converges in the area.” (Baviaanskloof Mega-reserve Project 2006: 2) The carbon stock ground truth was restricted to sites within the Baviaanskloof Nature Reserve (BNR) as indicated in Figure 6‑2. The BNR consists of 19 000 ha of Subtropical Thicket of which 95% is degraded, making this a suitable restoration area (Powell 2009).

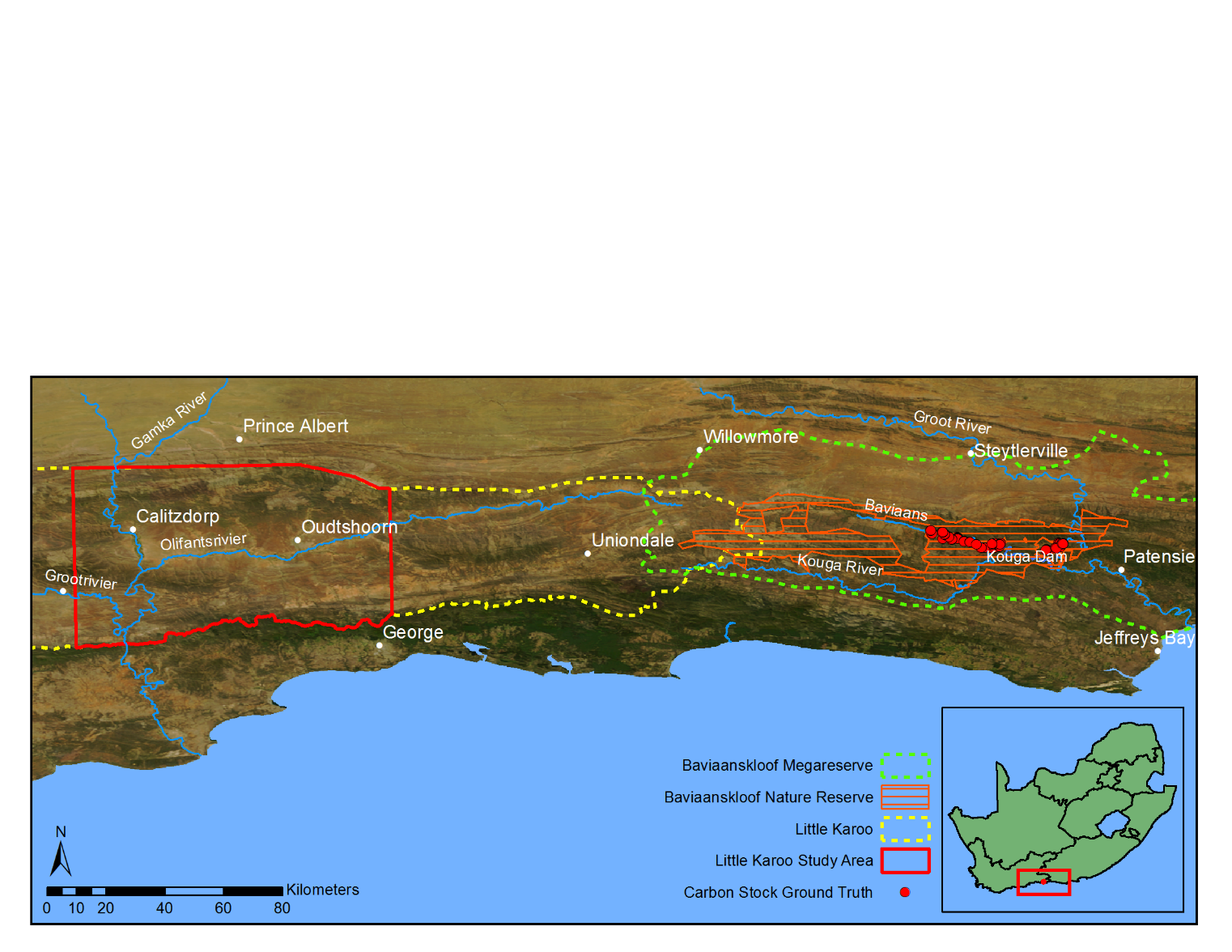


Figure 6‑2 Study area

## Little Karoo Field Study and Ground Truthing (Objective 2)

In collaboration with Jan Vlok, a number of field sites will be identified. These sites will be of the order of one ha in area and should encompass the various thicket habitat types and levels of degradation. Canopy cover ground truth will be established for each site using the current system of visual inspection. To achieve a robust, transferable model, it is desirable for these study sites to represent as much habitat and degradation variation as possible. The extent of the field work will be limited by time, accessibility and available funds.

## Image Calibration (Objective 3)

The NGI imagery will be sourced in a raw four-band format and orthorectified using the existing aero-triangulation information from NGI with standard software. A benefit of performing the rectification is that a digital surface model (DSM) or height map can be constructed in conjunction with this procedure (Zhang & Gruen 2006). This DSM would contain coarse plant height information which could prove useful as feature or ancillary data for the canopy cover and carbon stock mapping algorithms.

Some success in the correction of atmospheric and BRDF effects in large VHR aerial image mosaics has been reported (Collings et al. 2011; Laliberte et al. 2011; Chandelier & Martinoty 2009; Lelong et al. 2008). These calibration techniques will be researched and applied if appropriate. In addition, the feasibility of a technique based on the concept of cross-calibration will be investigated. In the cross-calibration approach, a well-calibrated collocated and concurrent satellite image is used as a reference to which the aerial imagery is calibrated.

## Canopy Cover Mapping Algorithm (Objective 4)

The 0.5m/pixel NGI imagery has the advantage of making individual trees and clumps of *P. afra* resolvable. *P. afra* trees or tree clumps will be distinguished from the surrounding vegetation. As we expect a wide diversity of surrounding vegetation, a one class classification approach may be appropriate (Tax & Juszcak 2003). A comprehensive feature study will be conducted. Particular attention will be given to texture features in an attempt to make the most of the high spatial resolution. Vegetation indices commonly used for biomass and degradation estimation will be included (Eisfelder, Kuenzer & Dech 2012; Thompson et al. 2009; Lu 2006). The discriminative power of various feature sets will be evaluated with feature space visualisations and separability measures including classifier performance. In conjunction with the feature study, feature selection and dimensionality reduction techniques will be evaluated for their effectiveness (Jain et al. 2000). The performance of a set of typical classifiers on the feature set will be compared.

## Canopy Cover Mapping Application (Objective 5)

A canopy cover map will be produced for the Little Karoo study area using the developed methods. This map will be interpreted in collaboration with Jan Vlok. Results will be validated through visual photo-interpretation and comparison with the field acquired ground truth.

## BNR Field Study (Objective 6)

A field trip to the BNR will be undertaken to develop familiarity with the area and ground truth sites. This field trip will also be used to evaluate the positional accuracy of the aerial imagery. While the pixel resolution of the aerial imagery is 0.5m, the positional accuracy (accuracy of orthorectification) may be of the order of 6m, which is typical for commercially available VHR imagery such as WorldView-2 (Satellite Imaging Corporation 2014). Accurate location of the 5x5m carbon stock ground truth plots in the aerial imagery will be problematic with this amount of positional variation. The ground truth plots are demarcated with metal stakes and danger tape but unfortunately the tape is not visible in the aerial imagery. If necessary, high resolution images of the demarcated ground truth plots will be captured in the field to facilitate the accurate location of the plots in the aerial imagery. This would be done by matching surrounding coarse-scale landscape and vegetation features. Field images will be captured using a remotely controlled GoPro camera, suspended from a helium balloon, to achieve a near vertical viewing angle for easier comparison to the aerial imagery.

## Carbon Stock Mapping (Objective 7)

A multivariate nonlinear regression approach will be adopted to model the relationship between TAGC and features derived from the aerial imagery. A comprehensive set of spectral features, texture features, vegetation indices and secondary measures (such as *P. afra* canopy cover) will be evaluated for their predictive ability. Given the limited number of 191 ground truth plots, it will be necessary to apply dimensionality reduction and feature selection techniques to reduce the full feature set to an informative minimum. A variety of popular regression models such as random forests and support vector machines will be compared based on their ability to predict TAGC from the derived features. The transferability of models between different habitat types and different levels of degradation will be investigated. Finally, a carbon stock map will be produced for the study area using the available map of habitat types (SANBI 2007) as ancillary information.

# LINKAGES OF STUDY TO DEPARTMENTAL PROGRAMMES

This research forms part of a larger research programme in the Department of Geography and Environmental Studies in the use of geographical information technologies (GIT) for sustainable land management decision support. It is also strongly linked to the “Carbon Stabilization Mechanisms in Spekboom Thicket Soils, Eastern Cape, South Africa” and “Thicket-wide Plot Experiment” projects being conducted by the Department of Soil Science.

REFERENCES

Baraldi, A, Durieux, L, Simonetti, D, Conchedda, G, Holecz, F & Blonda, P 2010. Automatic spectral-rule-based preliminary classification of radiometrically calibrated SPOT-4/-5/IRS, AVHRR/MSG, AATSR, IKONOS/QuickBird/OrbView/GeoEye, and DMC/SPOT-1/-2 imagery—Part I: System design and implementation. *IEEE Transactions on Geoscience and Remote Sensing* 48 (3): 1299–1325.

Baviaanskloof Mega-reserve Project 2006. *Baviaanskloof Mega-reserve background document for the strategic management plan*. Wilderness Foundation.

Bayer, A 2013. Methodological developments for mapping soil constituents using imaging spectroscopy. Doctoral dissertation. Potsdam: University of Potsdam, Department of Mathematics and Natural Sciences.

Chandelier, L & Martinoty, G 2009. A radiometric aerial triangulation for the equalization of digital aerial images and orthoimages. *Photogrammetric Engineering & Remote Sensing* 75 (2): 193–200.

Collings, S, Caccetta, P, Campbell, N & Wu, X 2011. Empirical models for radiometric calibration of digital aerial frame mosaics. *IEEE Transactions on Geoscience and Remote Sensing* 49 (7): 2573–2588.

Curran, P, Smedley, D, Thompson, P & Knight, AT 2012. Mapping restoration opportunity for collaborating with land managers in a carbon credit-funded restoration program in the Makana municipality, Eastern Cape, South Africa. *Restoration Ecology* 20 (1): 56–64.

Eisfelder, C, Kuenzer, C & Dech, S 2012. Derivation of biomass information for semi-arid areas using remote-sensing data. *International Journal of Remote Sensing* 33 (9): 2937–2984.

Fabricius, C, Burger, M & Hockey, PAR 2003. Comparing biodiversity between protected areas and adjacent rangeland in xeric succulent thicket, South Africa: arthropods and reptiles. *Journal of Applied Ecology* 40 (2): 392–403.

Forsyth, G, Vlok, J & Reyers, B 2008. *Retention and restoration of the biodiversity of the Little Karoo*. CSIR Report No CSIR/NRE/ECO/ER/2008/0118/C. CSIR.

Goetz, SJ, Baccini, A, Laporte, NT, Johns, T, Walker, W, Kellndorfer, J, Houghton, R a & Sun, M 2009. Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. *Carbon balance and management* 4: 2.

Guralnick, LJ & Ting, IP 1986. Seasonal response to drought and rewatering in Portulacaria afra (L.) Jacq. *Oecologia* 70: 85–91.

Hein, L, de Ridder, N, Hiernaux, P, Leemans, R, de Wit, A & Schaepman, M 2011. Desertification in the Sahel: Towards better accounting for ecosystem dynamics in the interpretation of remote sensing images. *Journal of Arid Environments* 75 (11): 1164–1172.

Honkavaara, E, Arbiol, R, Markelin, L, Martinez, L, Cramer, M, Bovet, S, Chandelier, L, Ilves, R, Klonus, S, Marshal, P, Schläpfer, D, Tabor, M, Thom, C & Veje, N 2009. Digital airborne photogrammetry—a new tool for quantitative remote sensing?—A state-of-the-art review on radiometric aspects of digital photogrammetric images. *Remote Sensing* 1 (3): 577–605.

Intergraph 2008. Digital mapping camera system [online]. Available from: http://www.geospace.co.za/pdf/DMC Brochure.pdf [Accessed September 4, 2014].

Jain, AK, Duin, RPW & Mao, J 2000. Statistical pattern recognition: a review. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 22 (1): 4–37.

Knight, AT, Cowling, RM, Boshoff, AF, Wilson, SL & Pierce, S 2011. Walking in STEP: Lessons for linking spatial prioritisations to implementation strategies. *Biological Conservation* 144 (1): 202–211.

Laliberte, AS, Goforth, M a., Steele, CM & Rango, A 2011. Multispectral remote sensing from unmanned aircraft: Image processing workflows and applications for rangeland environments. *Remote Sensing* 3 (11): 2529–2551.

Lechmere-Oertel, RG, Kerley, G, Mills, AJ & Cowling, RM 2008. Litter dynamics across browsing-induced fenceline contrasts in succulent thicket, South Africa. *South African Journal of Botany* 74 (4): 651–659.

Lelong, CCD, Burger, P, Jubelin, G, Roux, B, Labbé, S & Baret, F 2008. Assessment of unmanned aerial vehicles imagery for quantitative monitoring of wheat crop in small plots. *Sensors* 8 (5): 3557–3585.

López, DH, García, BF, Piqueras, JG & Guillermo, VA 2011. An approach to the radiometric aerotriangulation of photogrammetric images. *ISPRS Journal of Photogrammetry and Remote Sensing* 66 (6): 883–893.

Lu, D 2006. The potential and challenge of remote sensing based biomass estimation. *International Journal of Remote Sensing* 27 (7): 1297–1328.

Marais, C, Cowling, RM & Powell, M 2009. Establishing the platform for a carbon sequestration market in South Africa: The Working for Woodlands Subtropical Thicket Restoration Programme. In *XIII World Forestry Congress*, 1–13. Buenos Aires, Argentina.

Markelin, L, Honkavaara, E, Schläpfer, D, Bovet, S & Korpela, I 2012. Assessment of radiometric correction methods for ADS40 imagery. *Photogrammetrie - Fernerkundung - Geoinformation* 2012 (3): 251–266.

Mills, AJ, Blignaut, J, Cowling, RM, Knipe, A, Marais, C, Marais, S, Pierce, S, Powell, M, Sigwela, A & Skowno, A 2010. *Investing in sustainability. Restoring degraded thicket, creating jobs, capturing carbon and earning green credit.* Climate Action Partnership, Cape Town and Wilderness Foundation, Port Elizabeth.

Mills, AJ & Cowling, RM 2010. Below-ground carbon stocks in intact and transformed subtropical thicket landscapes in semi-arid South Africa. *Journal of Arid Environments* 74 (1): 93–100.

Mills, AJ & Cowling, RM 2006. Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa. *Restoration Ecology* 14 (1): 38–49.

Mills, AJ, Cowling, RM, Fey, M, Kerley, G, Donaldson, J, Sigwela, A, Skowno, A & Rundel, P 2005. Effects of goat pastoralism on ecosystem carbon storage in semiarid thicket, Eastern Cape, South Africa. *Austral Ecology* 30: 797–804.

Mills, AJ & Fey, M 2004. Transformation of thicket to savanna reduces soil quality in the Eastern Cape, South Africa. *Plant and Soil* 265 (1-2): 153–163.

Mills, AJ, Turpie, JK, Cowling, RM, Marais, C, Kerley, G, Richard, G, Sigwela, A & Powell, M 2007. Assessing costs, benefits, and feasibility of restoring natural capital in Subtropical Thicket in South Africa. In J. Aronson, S. Milton, & J. Blignaut (eds.) *Restoring Natural Capital: Science, Business and Practice (The Science and Practice of Ecological Restoration Series)*, 179–187. Washington DC: Island Press.

Mouton, J 2001. *How to succeed in your master’s and doctoral studies : a South African guide and resource book*. Pretoria: Van Schaik Publishers.

National Geo-spatial Information 2012. National aerial photography and imagery programme [online]. Department of Rural Development and Land Reform (DRDLR). Available from: http://www.ngi.gov.za/index.php/Image-tabs-home/national-aerial-photography-and-imagery-programme.html [Accessed May 22, 2012].

Pierce, S, Cowling, RM, Knight, AT, Lombard, AT, Rouget, M & Wolf, T 2005. Systematic conservation planning products for land-use planning: Interpretation for implementation. *Biological Conservation* 125 (4): 441–458.

Powell, M, Mills, AJ, Marais, C, Thicket, S, Project, R & Town, C 2005. Carbon sequestration and restoration: Challenges and opportunities in Subtropical Thicket. : 214–223.

Powell, MJ 2009. Restoration of degraded subtropical thickets in the Baviaanskloof Megareserve, South Africa. Master’s thesis. Grahamstown: Rhodes University, Department of Environmental Science.

Restoration Research Group 2012. Intact and degraded Spekboomveld [online]. Available from: http://www.r3g.co.za/spekboom.htm [Accessed May 15, 2012].

SANBI 2007. Baviaanskloof Mega-Reserve vegetation types [online]. Available from: http://bgis.sanbi.org/baviaanskloof/vegetation.asp [Accessed October 13, 2014].

Satellite Imaging Corporation 2014. WorldView-2 Satellite Sensor [online]. Available from: http://www.satimagingcorp.com/satellite-sensors/worldview-2/ [Accessed October 13, 2014].

Sigwela, A, Kerley, G, Mills, AJ & Cowling, RM 2009. The impact of browsing-induced degradation on the reproduction of subtropical thicket canopy shrubs and trees. *South African Journal of Botany* 75 (2): 262–267.

Statistics South Africa 2011. *Quarterly labour force survey quarter 1, 2011*. P0211. Pretoria: Statistics South Africa.

Stuart-Hill, G 1992. Effects of elephants and goats on the Kaffrarian succulent thicket of the eastern Cape, South Africa. *Journal of Applied Ecology* 29 (3): 699–710.

Suganuma, H, Abe, Y, Taniguchi, M, Tanouchi, H, Utsugi, H, Kojima, T & Yamada, K 2006. Stand biomass estimation method by canopy coverage for application to remote sensing in an arid area of Western Australia. *Forest Ecology and Management* 222 (1-3): 75–87.

Tax, DMJ & Juszcak, P 2003. Kernel whitening for one-class classification. *International Journal of Pattern Recognition and Artificial Intelligence* 17 (3): 333–347.

Thompson, M, Vlok, J, Rouget, M, Hoffman, MT & Cowling, RM 2009. Mapping grazing-induced degradation in a semi-arid environment: A rapid and cost effective approach for assessment and monitoring. *Environmental Management* 43: 585–596.

Turner, MD 2003. Methodological reflections on the use of remote sensing and geographic information science in human ecological research. *Human Ecology* 31 (2): 255–279.

Vlok, J, Cowling, RM & Wolf, T 2005. A vegetation map for the Little Karoo. Unpublished maps and report for a SKEP project supported by CEPF grant no 1064410304.

Vyver, ML, Cowling, RM, Campbell, EE & Difford, M 2012. Active restoration of woody canopy dominants in degraded South African semi-arid thicket is neither ecologically nor economically feasible. *Applied Vegetation Science* 15 (1): 26–34.

Zhang, L & Gruen, A 2006. Multi-image matching for DSM generation from IKONOS imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* 60 (3): 195–211.