ASSESSING AND EVALUATING THE PRODUCTIVITY OF LAVANDIN AND ROSEMARY USING SENTINEL-2 AND FIELD DATA: A CASE STUDY FOR BAVIAANSKLOOF, SOUTH AFRICA

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ABSTRACT

In the Baviaanskloof land productivity, soil fertility and biodiversity have decreased due to an extensive livestock overgrazing and unsustainable land management. To counteract these effects, multiple land restoration projects have been initiated in the area. The Grounded project with the collaboration of other stakeholders and local farmers have implemented a project of the sustainable agricultural business model in the study area. This aimed to generate a suficient income with the sustainable production of essential oil crops. To evaluate the contribution of the oil crops both to the health of the environment, and farmers' income, it is necessary to monitor the growing status and productivity of biomass of lavandin and rosemary. The main aim of this study was to explore and develop a good method for monitoring the biomass and production of rosemary and lavandin crops using field data, and Sentinel-2 derived vegetation indices.

The study used different methods such as the allometric equation and remote sensing. The allometric equations are developed using harvested individual plants of both rosemary and lavandin crops, which is a mathematical relationship between the canopy area and volume of different canopy shapes with the measured fresh and dry AGB. The best allometric equations were selected based on the highest R^2 and lower RMSE. Moreover, to develop the vegetation indices based AGB estimation model, this study assesses the relationship between the allometric equation based estimated AGB and remote sensing vegetation indices. So, six existing vegetation were compared to select the best model. The models for indices based AGB estimation were tested linear and multiple linear regression analysis. The best model was selected based on correlation coefficient, P-values, multicollinearity and R^2. Moreover, the spatiotemporal variation in the vegetation cover of the plots of the fields was identified based on the mean and standard deviation values of AGB and NDVI time series.

The result revealed that power regression model of the elliptical area is best allometric equation for dry AGB and essential oil estimation for rosemary and lavandin crops. The allometric equations showed a very good performance with R^2 of between 0.92 to 0. 95. The result of vegetation indices based AGB estimation, RERVI is the best predictor for AGB of rosemary and lavandin from the simple linear model. And the multiple linear regression analysis revealed that the NDVI with the soil cover percent and plant age for rosemary and RERVI with the soil cover percent for lavandin was selected to be the best predictor of AGB estimation. Generally, the accuracy of the estimated AGB was improved with the multiple linear models. The mean and standard values of AGB and NDVI time series profile has a potential to identify the spatial and temporal variability on the vegetation cover of the plots of the fields.

The allometric equation based AGB estimation is an accurate method for AGB estimation depending on the field measurement but does not apply to a large scale in terms of space and time. The remote sensing method of biomass estimation is applicable for large scale in space and time. Based on the result Sentinel-2 satellite multispectral image has a potential to monitor the biomass of rosemary and lavandin crops which can provide repeated measure through time. The red-edge band improved the accuracy of vegetation indices based AGB of the plots for both rosemary and lavandin crops.

***Keywords**: Rosemary; Lavandin; AGB; Allometric equation; Sentinel-2; Vegetation indices,*

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1. INTRODUCTION

1.1. Background and justification

In Africa agriculture constitutes the major part in the economy of the continent, which is absorbing 70% of the workforce, and accounts for about 30% of the gross domestic product (Chivasa et al., 2017). Sustainable agriculture is a farming system which aims to integrate a healthy environment, economic profitability, and social and economic equity (UC SAREP, 2007). The government of South Africa has established a policy of sustainable agricultural practices that comprise environmental (avoiding the exploitation of natural environment), economical (high-quality supply of farm products) and social (contribution to the well-being) aspects (Khwidzhili, 2017). In September 2015, the ministry of agriculture in Western Cape province hosted a large conference about climate change, in which it focussed on the contribution of climate change to food insecurity. And they realised that sustainable agriculture is one of the critical factors to fight against the climate change that improves the health of the environment and food security, in which contributes to increased production, reduced soil erosion, and enhanced the quality of water and soil health (SPEECH, 2015).

The Baviaanskloof is the crucial catchment area for agricultural activities and the Port Elizabeth water supply. But due to extensive livestock overgrazing and unsustainable land management, land productivity, soil fertility and biodiversity have decreased since the 1980s. To counteract these effects and secure the water supply for Port Elizabeth, multiple land restoration projects have been initiated such as Commonland, Living lands and Grounded (Commonland, 2017).

Parallel to the strategy of the enhancing the environment and food security, the Grounded project with the collaboration of Living lands, Commonland, the Coca-Cola African Foundation and local farmers have developed and implemented a project of the sustainable agricultural business model in the Baviaanskloof. The project motivates farmers to replace grazing animals (sheep and goats) from their farms by making an alternative income with a profitable and sustainable farming system of essential oil crops (lavandin and rosemary), parallel to that they also reintroduce native thicket species to improve soil quality and overall ecosystem health (Grounded, 2014a). These initiatives led the farmers to the recent planting of essential oil producing crops with the aim of restoring the landscape, minimising water shortages, and returning profit to the farmers.

Essential oil crops are perennials which are native to the Mediterranean region (Adam, 2006, Maganga, 2004) and can be easily grown in poor fertile, rocky, and sandy soil. They are considered as low impact agriculture because of their low demand for chemical fertiliser and pesticides (Maganga, 2004). Essential oils are produced by plants in variable quantities and extracted using distillation processes. They have many different uses both for the society and the environment, which is fully adaptable for change even by small-scale local farmers and in many cases, it grows environmentally friendly or organic techniques (Lichtfouse, 2009).

Lavandin (*Lavandula x intermedia*) is a hybrid of true lavender (*L. angustifolia Mill*) and spike lavender (*L. latifolia Med.*). Lavandin gives a higher yield than true lavender, making it more attractive for commercial farming but it is less expensive (Baydar & Erbaş, 2009). Lavandin is a long-life perennial crop that could be productive for about ten years and is an evergreen shrub. It is considered a crucial sustainable crop because it requires less fertiliser and pesticide application. Like most herbs, it has a few insect pests and few attacks fungal diseases and is originated around the Mediterranean in poor, rocky soils and mild coastal climates (Adam, 2006). It grows in well-drained soils such as sandy, sandy loam, or gravelly soils and grows well in low fertility soils PH between 6.5 to 7.5 (Maganga, 2004).

Rosemary (*Rosmarinus officinalis L.*) is an aromatic plant, which produces essential oil in leaves and branches (Das & Singh, 2012). Rosemary is a perennial woody evergreen herb and has beautiful needle-like leaves, native to the Mediterranean region. It can be used as fresh leaves or dried powder form. Its leaves can be used to prepare tea, essential oil, and liquid extract. Rosemary essential oil is commonly used in cosmetic, food and pharmaceutical industries (Takaki et al., 2008). Rosemary is a drought tolerant plant which grows in rocky to sandy soils, well drained with soil depths of about 0.2 meters and a soil PH of 4.5 to 8.7, has no serious pests or diseases (Maganga, 2004).

The motivation for growing essential oil crops in the Baviaanskloof is the need for a more sustainable agricultural business model for the land restoration project, to counteract land degradation on a large scale and generate sustainable income for the farmers living in this area. The opportunity of growing market demand and the construction of a processing plant for essential oil has also convinced the local farmers to move from traditional goat farming to cultivating lavandin and rosemary (Grounded, 2014a). The essential oils are extracted in an on-farm distillery constructed by the Baviaanskloof Development Company. Transporting the plant biomass outside the valley are costly and not economically viable (Grounded, 2014b). The cultivation of essential oil crop particularly lavandin and rosemary as low impact agriculture is implemented in the region. But, the productivity of the new farming system needs an assessment to understand the current conditions and benefits of the production system both to the farmers and the environment.

Sentinel-2 satellite data are useful for monitoring agricultural production, detection of land use and land cover type up to the pixel level, due to its high spatial and temporal resolution. According to Radoux et al. (2016), the variability of vegetation cover can be detected by the remotely sensed imagery of Sentinel-2, Spot-5 and Landsat-8. But the result revealed that Sentinel-2 performed the best and concluded that with the spatial resolution of 10 m and 20 m, Sentinel-2 is a promising sensor for detection of different landscape features.

Accurate and timely biomass or yield estimation is essential for the farmers to know the status of their business in which it plays a crucial role in making any improvement in the land management practice, the input used and the carbon balance estimates (Claverie et al., 2012). Agricultural production has been studied using remote sensing reflectance and vegetation indices for many years (Calvao & Pessoa, 2015). The benefits of remote sensing with high spatial, temporal and spectral resolution can be reproduced in Africa's heterogeneous agricultural landscapes without compromising the quality of the output (Chivasa et al., 2017). Vegetation is a crucial component of global ecosystems and plays an essential role in the infiltration of rainfall, reduction of runoff, and soil and water conservation in arid and semi-arid ecological systems (Sun et al., 2015).

Remote sensing data are widely used and proved to be a useful tool for monitoring crop production. In this way, several studies have been done regarding normalised difference vegetation index (NDVI) derived from remotely sensed data for yield estimation and crop condition or drought monitoring. For example, Mashaba et al. (2017) used remote sensing NDVI for crop monitoring, crop mapping and yield estimation. Besides, Belgiu & Csillik (2018) were also able to map the cropland and monitor the crop conditions using high spatial and temporal resolution Sentinel-2 image periodically and proved that phenological features, such as the maximum, minimum, mean and standard deviation values computed from the NDVI data, are relevant for classifying the vegetation of forest, grass and crop classes. Furthermore, as stated by Jianqiang et al. (2007), the application of NDVI is widely used in many research studies such as crop growth monitoring, crop yield estimation, crop mapping, vegetation phenology, vegetation classification and land use and land cover change and it found efficient. Besides, satellite-derived NDVI is used to assess the effect of climate condition on biomass and phenological pattern of vegetation and used initially to map vegetation distribution and productivity (Pettorelli et al., 2005).

The conceptual framework of the study area that showed all the activities and flow of information within the study is presented in Figure 1.1.

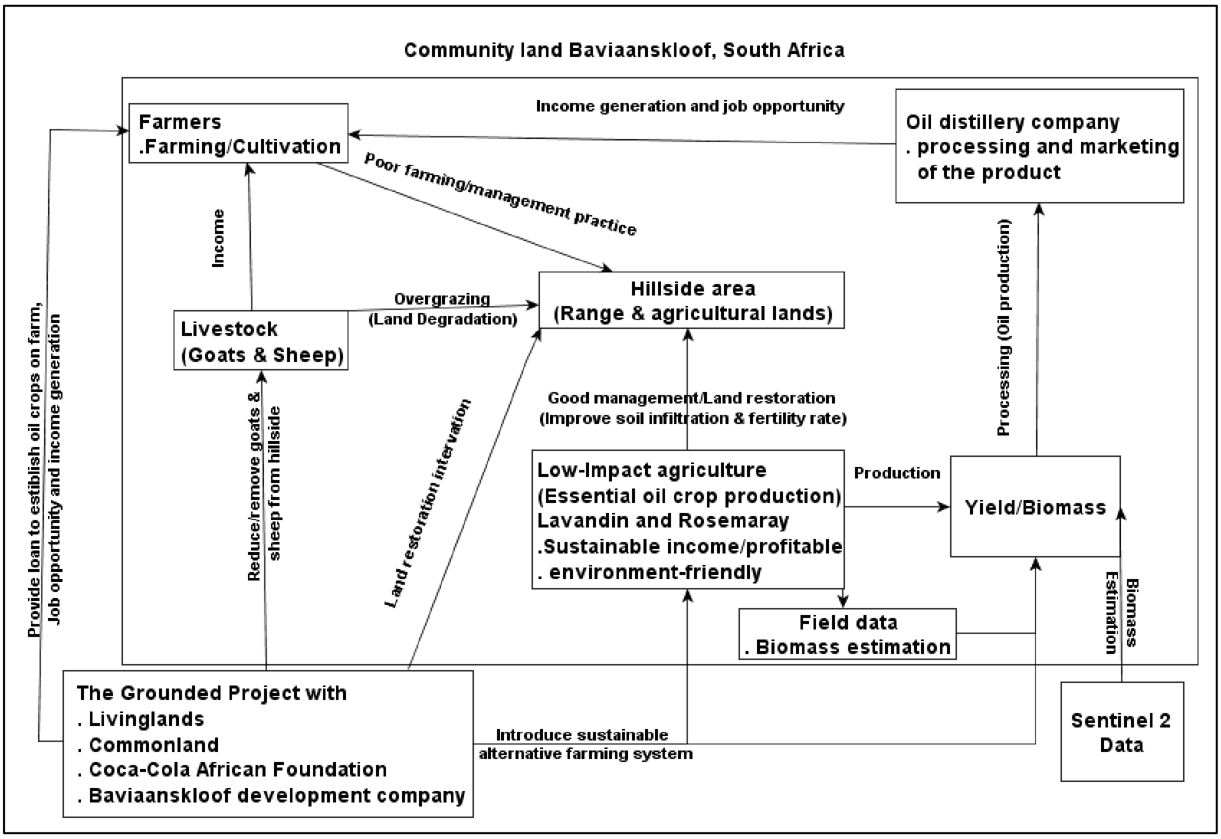

Figure 1-1. The conceptual framework of the study area

1.2. Research Problem

In the Baviaanskloof farmers aim to generate sufficient income with the sustainable production of essential oil crops (Grounded, 2014a). To evaluate the contribution of the oil crops both to the health of the environment, and farmers' income, it is necessary to monitor the growing status and productivity of biomass of lavandin and rosemary.

Biomass can be estimated based on a destructive (direct measurement) or non-destructive method, but the destructive method is not preferred, as it is costly and time-consuming (García et al., 2009). Field-based biomass estimation methods are direct and accurate, but they have a limitation regarding spatial and temporal sampling which cannot be applied to large scales both in space and time. Remote sensing is the only method for estimating biomass information at a wide range of spatial and temporal scale (García et al., 2009). Destructive method is a traditional technique and the most accurate way of collecting biomass data (Lu, 2006). To develop accurate aboveground biomass (AGB) estimation models and to evaluate the AGB estimation result, sufficient field measurements are required. This is the base for AGB estimation based on allometric equation and remote sensing.

Sentinel-2 data with its high spatial and temporal resolution provides new opportunities for global and regional agricultural monitoring such as crop conditions and yield prediction and monitor seasonal change (SINERGISE, 2017). According to Borgogno et al. (2017), NDVI is a practical and popular tool or an indicator for monitoring vegetation change both in time and space. Fung & Siu (2000), studied vegetation density using NDVI to monitor the spatial and temporal variation and vegetation health. Besides, Biswal et al. (2013), used Landsat NDVI to classify the vegetation density successfully and reported that NDVI is highly correlated with the biophysical parameters of the vegetation canopy such as, vegetation cover, and biomass. Moreover, Das & Singh (2012), studied biomass forest using field data and remotely sensed vegetation indices from Landsat TM image. The findings revealed that ratio vegetation index (RVI), Renormalized difference vegetation index (RDVI) and NDVI had shown the highest correlation with R^2 of 0.79, 0.76 and 0.75.

The study area does not have an information about the allometric equation and remote sensing data that can be used for monitoring the conditions of the crops and predict the yield before harvest. This is very helpful for the farmers for deciding what to do in fields regarding different management activities and getting some insights about production. Therefore, in this study, remotely sensed multitemporal vegetation indices derived from the Sentinel-2 image and field data were used to determine and assess the productivity (Biomass) and identify the spatiotemporal variation of vegetation cover of lavandin and rosemary within and between the fields. The result of the study could be relevant for the stakeholders and farmers to contribute to enhancing the environment and promoting sustainable agriculture and used as a base for further study of lavandin and rosemary in Baviaanskloof.

1.3. Research Objective

The main objective of this study is to estimate the biomass of lavandin and rosemary and detect the spatiotemporal variation within and between the crop fields using Sentinel-2 multitemporal vegetation indices and field data. To achieve this objective, four specific objectives and research questions are defined: -

Table 1-1. Objectives and Research questions

Specific objective	Research question (RQ)
1. To estimate the standing biomass and yield of lavandin and rosemary.	1.1. What is the relationship between crop dimensions and measured aboveground biomass? 1.2. What part of the total biomass is harvestable?
2. To evaluate the relationship between the allometric equation based above-ground biomass (AGB) and Sentinel-2 vegetation indices data?	2.1. What is the relation between AGB based on canopy size and vegetation indices remotely sensed data? 2.2. How does herb cover influence the vegetation indices-based AGB estimates?
3. To identify or detect the spatial and temporal variability in vegetation cover of lavandin and rosemary using multitemporal vegetation indices.	3.1. What spatial and temporal patterns in the VI-based estimated AGB are present within and between the fields? 3.2. How does the vegetation indices profile reflect the growth and harvesting of the crops?

To answer these research questions, the following research hypothesis was developed.

1.1. H_0: There is no significant relationship between crop dimensions and biomass.
H_1: There is a significant relationship between crop dimensions and biomass.

2.1. H_0: There is a significant relationship between the estimated AGB and vegetation indices.
H_1: There is a significant relationship between the estimated aboveground biomass and vegetation indices.

2.2. H_0: There is no linear relationship between herb cover and vegetation indices.
H_1: There is a linear relationship between herb cover and vegetation indices.

3.1. H_0: There is no relationship between the vegetation indices time series and the spatiotemporal pattern of the crops within and between plots of the fields.
H_1: There is a relationship between the vegetation indices time series and the spatiotemporal pattern of the crops within and between plots of the fields.

2. STUDY AREA AND METHODS

2.1. Study Area

The study was conducted in the Baviaanskloof (Valley of Baboons) area located in the Willowmore district, Eastern Cape province of South Africa see Figure 2.1. It covers about 200 kilometres of pristine, rugged, mountainous terrain that lies between the two parallel mountain ranges of Kouga to the south and Winterhoek to the north (Scheltema & Haupt, 2015). It lies between 33° 38' 11.6" S, and 24° 27' 2.3" E. The Baviaanskloof catchment is a vital catchment area for the Port Elizabeth water supply which is 120 km far (Commonland, 2017).

The topography of Baviaanskloof has a great influence on the rainfall pattern in which the lower parts get an average annual rainfall less than 250 mm while the higher altitude gets about 800 mm. The average annual minimum and maximum temperature of the area is 5 C° and 32 C° (Hattingh, 2011).

The first farm in Baviaanskloof was started under the system of quitrent in the early 1800s. Farms are extended east-west along the rivers of Baviaans and Kouga (Scheltema & Haupt, 2015). The main farming activity in the area was livestock for a century ago. The farmers are concentrating on the production of the essential oil crops of lavandin and rosemary. About 50 hectares are currently under cultivation which targeted the sustainable land management activities to achieve the aim of the project that has been done parallel with the land restoration activities. The farmers were starting planting essential oil crops since November 2015. Currently, they are commercialized on selling of raw dry leave biomass and essential oils of the rosemary both locally and internationally. In Baviaanskloof, most of the crops field have the same age. Additionally, they grow a cover crops for sustainable agricultural practice to improve the infiltration rate and fertility condition of the soil.

The currently the rosemary was in good condition which cultivated under the drip and pivot centre irrigation system. The rosemary under drip irrigation was better in terms of plant density which can push to high productivity. The lavandin crop was cultivated under drip irrigation system, but it was not in good condition in general. This was due to some pest attack such as nematodes. Some of the fields were fully damaged and were preparing for other use.

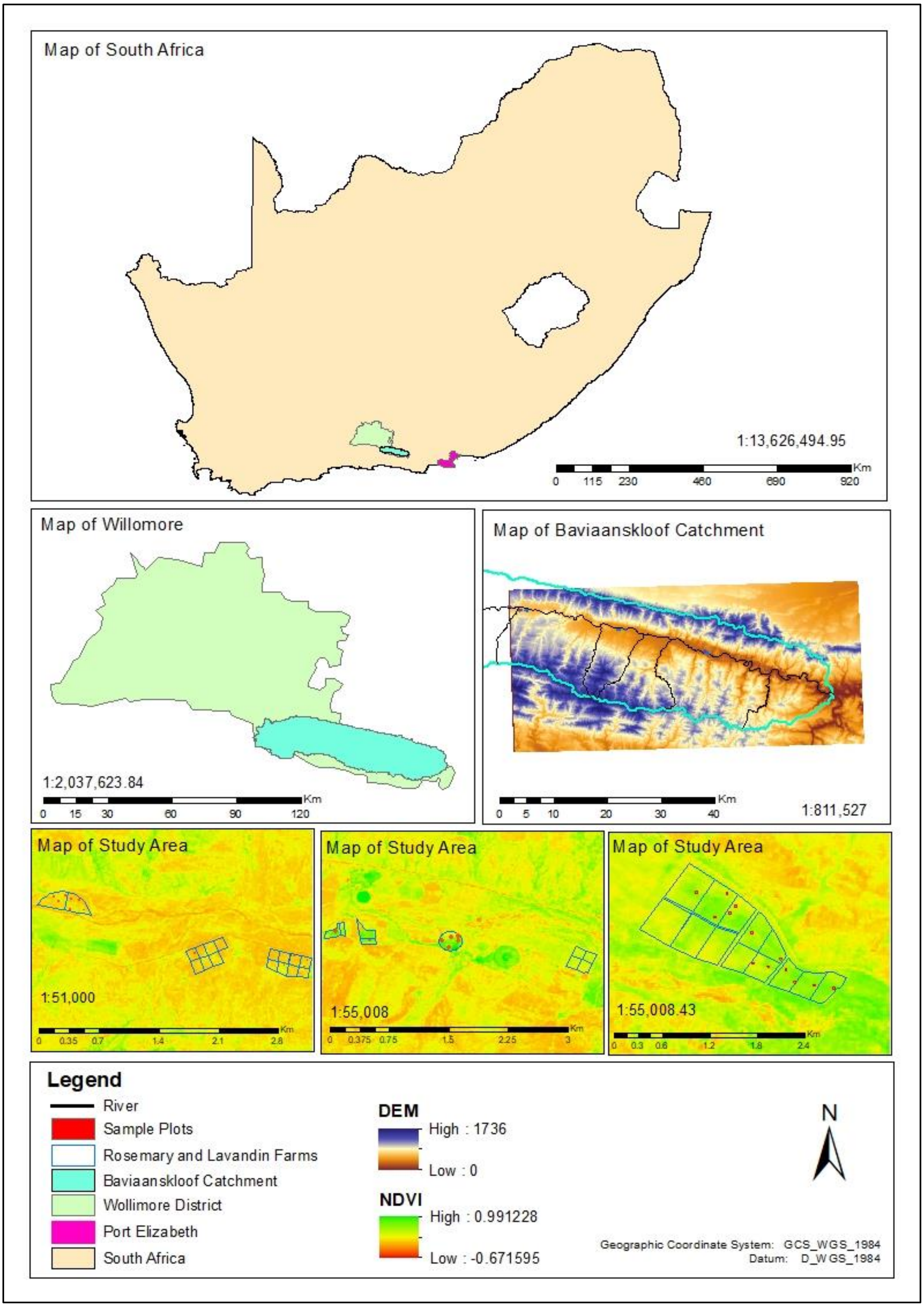

Figure 2-1. Location of the study area, Baviaanskloof catchment, the digital elevation model of Baviaanskloof catchment, the vegetation indices map of the crop fields, and the rivers.

2.2. Methods

The methodology of this study breaks down into five steps:

Step 1: In this step, allometric equations were developed from the harvested and dried individual lavandin and rosemary plant.

Step 2: For selected field samples measurement of the canopy diameter and height of each plant within the plot were taken. These parameters were used to compute the canopy volume and area of different geometric shape which would apply to estimate AGB of lavandin and rosemary using the allometric equation developed in step 1. Then the harvestable biomass was estimated from the total dry AGB based on the conversion factor.

Step 3: In this step, the satellite images of Sentinel-2 were used to compute the six vegetation indices. The vegetation indices maps were used to estimate and create a relationship between the AGB and the values of the vegetation indices.

Step 4: The vegetation indices were then analysed by assessing its relationship with the estimated AGB using linear and multiple linear regression model.

Step 5. Vegetation indices based AGB was estimated based on the model developed in step 4.

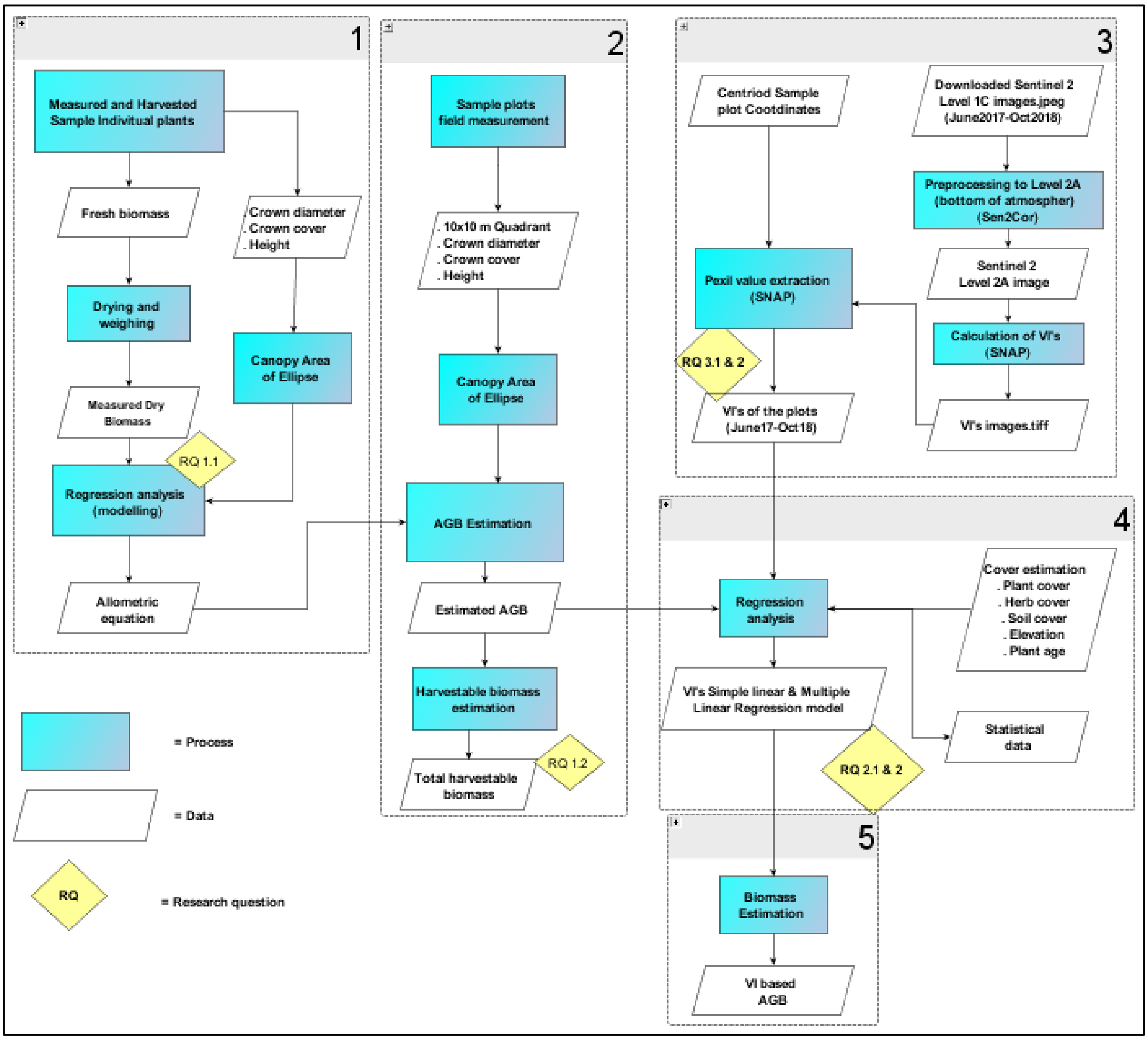

Figure 2-2. Flow chart of the research method

2.2.1. Estimate the standing biomass and yield of lavandin and rosemary.

In this section, the method for allometric equation development which used to estimate the measured AGB based on the crop dimensions and the harvestable AGB was done.

2.2.1.1. Developing the allometric equation and estimating AGB using field data

To estimate the standing biomass, the field data were collected from September 22 to October 12, 2018. A total of 30 individual plants were harvested. To develop the allometric equation for rosemary and lavandin in the study area, the harvested 18 rosemary and 12 lavandin see Figure 2.3. The plants were dried to a constant weight by in the sunlight for six days to reach a stable and consistent moisture content across all the samples see Figure 2.4 and Appendix 1 and 2. An allometric equation is a statistical model used to measure the biomass based on the biometric characteristics such as height or diameter, which are non-destructive and easy to estimate biomass of trees and shrubs (Maulana, 2014).

Destructive methods for estimating aboveground biomass (AGB) are the most accurate and simple technique in which direct harvesting and weighing of different trees or shrubs have been done (García et al., 2009, Roxburgh et al., 2015). However, it is expensive, time-consuming and cannot apply to a large area(García et al., 2009). Since there is no allometric equation developed for the rosemary and lavandin, 18 rosemary and 12 lavandin plants were harvested and weighed. The plants were selected randomly from all range of crop size (big, medium and small). To select the best allometric equation different linear and nonlinear regression analysis were tested for different geometric shapes (conical, cylindrical, ellipse and circular) for both crops. So, based on the coefficients of determinant and root mean square error (RMSE), the geometric shape that best fitted to the collected samples of the two-shrub species was selected. The allometric equations were developed as the mathematical relation between the canopy area and volume of the selected canopy geometric shape derived from the measured canopy diameter (2 perpendicular diameters) and height and the measured fresh and dry AGB to estimate the dry biomass and essential oil. The formula used to calculate the elliptical canopy volume ($\mathbf{V=3/4*\pi r_1 r_2 h}$) and canopy area ($\mathbf{A = \pi r_1 r_2}$). Where:
V= Canopy volume in cm^3; A= Canopy area in cm^2; r_1 = canopy radius one in cm; r_2 = Canopy radius two in cm & h = canopy height in cm
In the selection of the best allometric equation the importance of object-based, cover estimation on the field and relation with the remote sensing information which was captured from above were considered. Furthermore, the relationship between the average diameter and height for both crop plants were also tested with the dry biomass.
To develop the allometric equation the following steps were taken:

1. 18 rosemary and 12 lavandin plants were harvested
2. The harvested plants were selected from the different range in size
3. The two perpendicular canopy diameters (D_1, & D_2) and the height of the crop plants were measured using a measuring tape, and the weight of fresh biomass was measured using the digital scale.
4. Then, the harvested individual was dried at the temperature of above 31 ^{0}C in the sun in an open space for the whole day for six days until it reached a constant weight. A digital scale with an accuracy of 0.1 gram was used for weighing the biomass, see in Figure 2.5. The dry biomass of the harvested plants was separated as total dry biomass (harvestable and non-harvestable) and harvestable dry biomass (woody and dry leave biomass). See the details of the weight of the dry biomass for each day in Appendix 1 and 2.
5. This step uses the total and harvestable dry to estimate the conversion factor of total dry biomass to harvestable dry biomass which was used to estimate the harvestable dry biomass.

6. Here the total and harvestable fresh biomass were used to calculate the conversion factor of total fresh to harvestable fresh biomass that used to estimate the essential oil. Here the conversion factor was calculated from the ratio of harvestable fresh to total fresh biomass, so that essential oil is 0.7 % (DEVCO, 2018) of the total harvestable biomass in the study area.
7. In this step, the total fresh and dry biomass were used to develop the allometric equation and estimate the dry biomass and select the best predictor allometric equations. Moreover, the selected models were used to estimate the dry biomass based on the plant dimensions to cross-validate the accuracy between the measured and estimated based on the allometric equations.

Statistical analyses were done to develop an allometric equation from the measured dry biomass with the parameter of canopy volume and area derived from the measured canopy diameter and height of the crop plants. And the best-selected regression equation is used to estimate AGB in the non-destructive method. The best allometric equation was chosen based on the highest coefficient of determination (R^2), and the lowest root means square error (**RMSE**). Moreover, the bias that measures the tendency of the estimated AGB based on the allometric equation from the measured value of AGB was tested. Bias test tells that the estimated value is either underestimated, overestimated or same with the measured value of AGB. The perfect value of bias is 1. The formula used to calculate the bias is:

$Bias = \sum_1^n \frac{Estimated\ value}{n} / \sum_1^n \frac{Measured\ value}{n}$ Where: n is the number of observations.

Figure 2-3. Measuring and harvesting the harvestable and non-harvestable biomass of rosemary.

Figure 2-4 Drying the biomass of lavandin and rosemary in the sun light.

Figure 2-5. Weighing the woody and dry leaves biomass of rosemary using a digital scale.

2.2.1.2. Estimating harvestable dry biomass

Based on the information from the farmers and the specification of the harvesting machine the harvestable part of the crop plant dimensions is 20 cm above the ground level from the total crop plant size or height specifically for rosemary. Therefore, the harvestable part was measured and dried separately, and the conversion factor from total dry biomass to harvestable biomass was computed. So, the harvestable dry biomass was estimated both as the proportion of total dry biomass and the allometric equation developed for it. The farmers in Baviaanskloof used the harvestable AGB or yield as dry leaf and essential oil. The dry leave can be estimated as a proportion of the harvestable dry biomass by calculating the conversion factor from the measured dry Harvestable AGB. While the essential oil can estimate from the harvestable fresh AGB.

The essential oil was produced from the processing of the harvestable fresh biomass. So, a separate allometric equation was developed for the estimation of essential oil of lavandin and rosemary, in the same way with the allometric equation of the dry biomass. Therefore, the allometric equation for the estimation of essential oil of lavandin and rosemary was developed as the mathematical relation of measured total fresh biomass and the parameter of canopy area and volume of the crop plants.

2.2.2. Evaluating the relationship between the estimated essential oil crop AGB and Sentinel-2 vegetation indices data

This section showed the method for the estimation of AGB based on the developed allometric equations, the calculation of vegetation indices derived from Sentinel-2 images and the relationship between the allometric equation based estimated AGB and the vegetation indices had been done respectively.

2.2.2.1. Biomass estimation based on allometric equation

To estimate AGB using a non-destructive method, a survey of the study area was done with the establishment of 100-m² plots in each farm. A Garmin 30X- GPS was used to delineate the sample plots, in which the locations were established with the reference of Sentinel-2 satellite image. Here 32 sample plots of 10x10 meter from 7 fields (A1, A2, B and C for rosemary and A, B1 and B2 for lavandin) were used, see Figure 2.6. In each farm, a minimum of four plots from the matured crops of rosemary and lavandin based on the size of the farm were sampled. The plots were selected based on the NDVI value or vegetation density, which was detected before fieldwork. The sample plot location was stratified as high, medium and low NDVI values to capture the full range of NDVI values in the fields. To apply the allometric equation to estimate AGB, in each plot the two perpendicular canopy diameters and height of all crop plants were measured.

The general steps to estimate the AGB was as follows:

1. Selecting 4 sample plots from all seven essential oil fields.
2. Counting all the plants in each sample plot and measure the two perpendicular canopy diameters and height of the crop plant.
3. Estimation of total and harvestable AGB using the selected best allometric equation.
4. Upscaling the estimated AGB of the plots to per hectare and farm level.

Figure 2-6. The sample plot design on the rosemary field.

2.2.2.2. Deriving Vegetation Induces from Sentinel-2 Optical Satellite Image

Vegetation indices have been developed to relate the reflectance from the leaves or canopy to leaf and canopy characteristics (Hatfield et al., 2008). They are the mathematical combination of spectral bands of visible, near-infrared and shortwave infrared. Healthy vegetation absorbs most of the visible wavelengths that it receives and will reflect a large proportion of the near-infrared light, whereas poor condition vegetation, will reflect more visible wavelength light and less near-infra-red light (Mayer & Kylling, 2005), see Figure 4.4.

Sentinel-2A is a multispectral satellite sensor launched June 2015, under the European Copernicus programme that provides a quality image. The Sentinel-2 multispectral instrument measures the earth's reflected radiance in 13 spectral bands in the visible, near-infrared and short-wave infrared (ESA, 2019) see

Table 2.1. Sentinel-2 data is appropriate to see very early change in plant health due to high temporal, spatial resolution and three red-edge bands which makes it powerful for agricultural application in monitoring the changes in agricultural production and productivity (SINERGISE, 2017, European Space Agency, 2019).

Table 2-1. The spectral bands of Sentinel-2 sensors (S2A & S2B) (European Space Agency, 2019)

Band name	Resolution (m)	Central wavelength (nm)	Band width (nm)	Purpose
B01	60	443	20	Aerosol detection
B02	10	490	65	Blue
B03	10	560	35	Green
B04	10	665	30	Red
B05	20	705	15	Vegetation classification
B06	20	740	15	Vegetation classification
B07	20	783	20	Vegetation classification
B08	10	842	115	Near infrared
B08A	20	865	20	Vegetation classification
B09	60	945	20	Water vapour
B10	60	1375	30	Cirrus
B11	20	1610	90	Snow / ice / cloud discrimination
B12	20	2190	180	Snow / ice / cloud discrimination

The vegetation indices were calculated from Sentinel-2 image (S2A and S2B) spectral bands using the SNAP software for the period June 2017 to October 2018. All the vegetation indices images were saved in the raster (GeoTiff) format. The vegetation indices were selected based on their performance on the biomass estimation in the previous studies (Jin, Ye, Zheng, Fan, & Lin, 2016), six vegetation indices were selected. The normalized difference vegetation index (NDVI); the ratio vegetation index (RVI); the soil adjusted vegetation index (SAVI); the modified soil adjusted vegetation index (MSAVI); the red-edge normalized difference vegetation index (RENDVI); and, the red-edge ratio vegetation index (RERVI). NDVI and RVI are common and widely used for biomass estimation and shown a significant relationship in several studies (Das & Singh, 2012). But they are strongly affected by the soil background (Huete, 1988). To compensate for the soil background effect, two vegetation of SAVI and MSAVI were selected for this study. Moreover, NDVI and RVI can saturate with moderate to high vegetation density (Haboudane, 2003), so RENDVI and RERVI, which are not affected by saturation were used to test the relationship with above-ground biomass (AGB). Red-edge vegetation index is developed and becoming interesting due to the saturation character of the common vegetation indices to the moderate to high vegetation cover (Delegido et al., 2013). The red edge vegetation indices for this study were calculated in the same way with the above vegetation indices, but it uses band 6 (750 nm) for the red and band 8 for the NIR instead of band 4 and 8. Red-edge is a steeply sloped region of the vegetation reflectance curve caused by the transition of chlorophyll absorption and near-infrared leaf scattering (Ho, 2009). The position of the red-edge is presented in Figure 2.7.

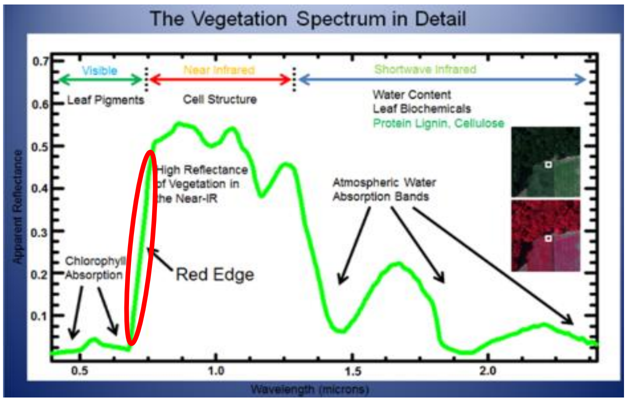

Figure 2-7. The position of Red-edge along the electromagnetic spectrum (Ho, 2009).

Table 2-2. Vegetation indices calculation for Sentinel-2

VI	Equation	Explanation of symbols	Explanation	Author of the index
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$	**Where:** NIR is spectral band 8 with a wavelength of 842 nm, and red is the spectral band of 4 with a wavelength of 665 nm.	Common and most popular for biomass estimation	(Rouse et al., 1974)
Ratio Vegetation Index (RVI)	$RVI = \frac{NIR}{Red}$	**Where:** NIR is spectral band 8, and red is the spectral band 4	Common and most popular for vegetation monitoring and biomass estimation	(Jordan, 1969)
Soil Adjusted Vegetation Index (SAVI)	$SAVI = \frac{(NIR - Red) * (1 + L)}{(NIR + Red + L)}$	**Where:** NIR is band 8 & R is band 4 **L** = 0.5 account first-order soil background variation or soil brightness correction factor.	Minimize the effect of soil background on the vegetation signal and effective at low vegetation density	(Huete, 1988)
Modified Soil Adjusted Vegetation Index (MSAVI)	$MSAVI = \frac{(NIR - Red) * (1 + L)}{(NIR + Red + L)}$	**Where: L = the soil line slope** (derived using the product of NDVI and weighted difference vegetation index (WDVI)	Minimize the effect of soil background on the vegetation, but resulting in higher sensitivity to vegetation change	(Qi, Chehbouni, Huete, Kerr, & Sorooshian, 1994)
Red-edge Normalized Difference Vegetation Index (RENDVI)	$RENDVI = \frac{(NIR - Red\ edge)}{(NIR + Red\ edge)}$	**Where:** NIR is spectral band 8 with a wavelength of 842, and the red edge is the spectral band of 6 with a wavelength of 740 nm.	Effective for the moderate and high vegetation cover biomass estimation.	(Delegido et al., 2013)
Red-edge Ratio Vegetation Index (RERVI)	$RERVI = \frac{NIR}{Red\ edge}$	**Where:** NIR is spectral band 8 and 11 with a wavelength of 842 & 1610, and the red edge is the spectral band of 6 with the wavelength of 740 nm.	Useful for the moderate and high vegetation cover biomass estimation	Delegido et al., (2013)

The pixel values of the vegetation indices of all the plots were extracted from the vegetation indices map using the centroid X and Y coordinates of the plots in SNAP software. The values of the vegetation indices were the mean value of the 3x3 windows (9 pixels) see Figure 2.7. This is due to the accuracy of the GPS used which were shown an error of about 8 meters.

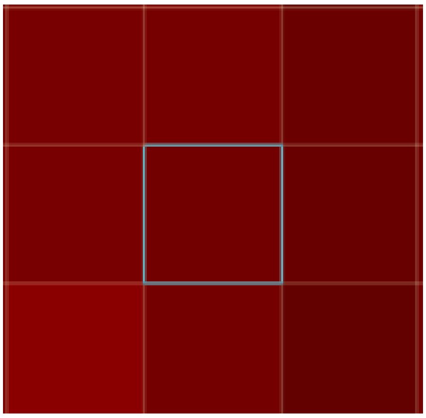

Figure 2-8. The pixel value for the vegetation index which shows the centre with blue line is the sample plot surrounded by 3x3 pixels of 10 m spatial resolution.

So, mapping biomass and calculation of the vegetation indices comprises the following steps:

1. Downloading 17 Sentinel 2 level 1C images. The Sentinel-2 optical satellite images were downloaded for June 2017 to October 2018 in which one cloud-free image per month was used. The satellite images for the study area were downloaded and collected from the website of Copernicus Open Assess Hub (http://scihub.copernicus.eu/) which is initiated by the European Space Agency (ESA). The product is available as level 1C (Top of Atmosphere Reflectance), organised in ortho-rectified tiles of 100 x 100 km^2 (UTM WGS84 projections). The imagery of each band is in a separate JPEG2000 file (ESA, 2018).
2. Pre-processing of Level 1C top of atmospheric reflectance (TOA) input data were done to create level 2A which is bottom of atmospheric reflectance (BOA) in the format of JPEG2000. The level-2A images were generated using the standalone version of the Sen2Cor processor (ESA, 2018). And all the bands were resampled to a spatial resolution of 10 m to get the same spatial resolution.
3. The processed level 2A images were used to generate the vegetation indices map. The values of the vegetation indices were calculated from the visible wavelength (Red), red edge, near-infra-red (NIR) and short wave near-infra-red (SWIR) wavelengths using SNAP software. All the vegetation indices maps were exported in the raster (GeoTiff) format.
4. Extract the pixel value of each vegetation index for the plots of rosemary and lavandin using SNAP software.
5. The statistical summary and the temporal profile were done to analyse the result.

2.2.2.3. To establish the relationship between the estimated aboveground biomass (AGB) and vegetation indices

A remote sensing method for agricultural monitoring provided a frequent measure from the field without a destructive sampling of the crop (Hatfield & Prueger, 2010). Vegetation indices derived from remote sensing image such as NDVI is useful for agricultural monitoring and to estimate biomass density (Barbosa et al., 1999) and shows significant correlation with above-ground biomass (Das & Singh, 2012)

To determine biomass estimation based on the remote sensing information, statistical analysis was done to compute the relationship between the estimate AGB and vegetation indices. Simple linear and multiple linear regression analyses were tested to assess the relation of AGB and six vegetation indices. The goodness of the model was evaluated based on the coefficient of the determinant (R^2), correlation coefficient, level of significance and multicollinearity (VIF) measures between all the variables. Additionally, the crop fields were dominated by green herbs and bare soil in which it affects the reflectance value of the vegetation index. So, to accommodate the effects of other vegetation and bare soil on values of vegetation indices, we considered the following factors in each sample plot:

1. Crop plant cover %
2. Herb cover %
3. Bare soil cover %
4. Elevation
5. Plant age

The crop cover percentage estimation was done based on the elliptical canopy area covered by the rosemary and lavandin plants. The crops are planted in the row-wise, in which there was a gap or open space of about 160 centimetres between the rows and 40 cm between the crop plants within the rows on average. The measure for the cover estimate was used from a distance between the rows of canopy edges of the crop plants, in which five measurements were taken randomly from each plot to estimate the proportion of herb and soil cover between the rows. The area of each plot is 100 m^2. So, the area covered by the green herb and bare soil is the difference between the total area of the plot and the entire canopy area of the crop plants covered in each plot. The herb cover has great influence on the values of the vegetation indices. Therefore, to test the influence of herb cover on the estimated AGB which was computed based on the vegetation indices, the proportion (partial R^2) of that variable needs to calculate on the model from the ANOVA analysis table. The formula to calculate partial R^2 is:

$$\text{Partial R2} = \frac{\text{SSR(with)} - \text{SSR(without)}}{\text{SSE(without)}}$$

Where: SSR is sum square of the model; SSE is sum square of the residual

Statistical analysis using R software was carried out to compute the following:
1. Linear and nonlinear relationship between vegetation indices and estimated AGB.
2. Multiple linear relationships between vegetation indices and estimated AGB.
3. Evaluation and selection of the best model for AGB estimation.
4. Estimation of AGB based on the model developed with the vegetation indices.

The statistical analyses were done using R and Microsoft Excel.

2.2.3. Identifying the spatial and temporal variability in vegetation cover of lavandin and rosemary using multitemporal vegetation indices

Remote sensed NDVI data was used to monitor and evaluate the spatial and temporal variation in the vegetation density of different landscape features (Fung & Siu, 2000). Luan et al. (2018) used to study the spatial and temporal variation of vegetation cover using multitemporal mean NDVI. To identify the spatial and temporal variation in vegetation cover within and between the plot of rosemary and lavandin fields the values of vegetation indices based AGB and temporal values of vegetation indices were used.

The spatial variation of the crop vegetation cover was characterized based on summary statistics of the mean and standard deviation of vegetation indices based AGB values for lavandin and rosemary fields. The mean and standard deviation values could show the variation within and between the sample plots of rosemary and lavandin fields. Besides the significance level of the spatial variation between the plots of the farms was tested using an ANOVA single factor.

The temporal variation was done based temporal profile of the NDVI time series in which the mean value was assigned to each pixel of the plots for the period of June 2017 to October 2018. That could show the variability of the crop vegetation cover over time. Moreover, it enabled to demonstrate the crop growth trend and harvesting period of the crops, even though most of the crop fields were not harvested yet and dominated by another green herb cover.

3. RESULTS

3.1. Estimating the standing biomass and yield of lavandin and rosemary.

3.1.1. Estimating aboveground biomass (AGB) and yield using the measured field data

The average diameter and height of the individual harvested plants of rosemary ranged from 16 to 79 and 20 to 96 cm respectively, with a dry weight ranged from 11.3 to 1,434 grams, see the detail in Table 3.1 and Appendix 3. At the same time, the average diameter and height of the lavandin ranged from 18.5 to 58, and 12 to 23 cm respectively, with a dry weight ranged from 30.4 to 668 grams, see in Table 3.2 and Appendix 4. Furthermore, the predictor variables of diameter and height showed a good relationship with the dry biomass of rosemary and lavandin which shown by the coefficient of the determinant (R^2) of 0.93 and 0.85 and 0.94 and 0.78 with the power regression model for diameter and height respectively, see Figure 3.1 and 3.2.

The allometric equations were similar for all canopy shape with the parameters of volume and area. The best models evaluated based on R^2 and RMSE were developed from the relationship between the elliptical shape of the canopy area and dry biomass. Therefore, the power regression model was the best model used to estimate the AGB for both lavandin and rosemary with the canopy area see Table 3.3. Based on the measured AGB, the total dry harvestable biomass of rosemary was 50 % of the total dry AGB on average. Additionally, the harvestable dry biomass was also estimated based on the allometric equation, see Table 3.5. The dry leave biomass of rosemary was 61% of the harvestable dry biomass on average see the detail in Appendix 3. Based on the measured AGB, the total dry AGB is 46 % of the total fresh AGB of lavandin.

Table 3-1 Measured total fresh and dry AGB, canopy diameter, height, volume and area of rosemary

S.no	Average Diameter (cm)	Height (cm)	Canopy Volume of Ellipse (cm^3)	Canopy Area of Ellipse (cm^2)	Total Fresh AGB (g)	Total Dry AGB (g)	Harvestable fresh AGB (g)	Harvestable dry AGB (g)
Average	43.2	52.1	145,354.4	1,662.5	1,022.4	424.9	657.2	244.9
Minimum	16	20	5,342.9	200.4	37.1	11.3	0	0
Maximum	79	96	621,229.7	4,853.4	3,406.7	1,434	2,458.6	980.1
SD	16.6	21.7	161,581.9	1,223.2	1,002.5	429.3	695.6	274.1

Table 3-2. Measured total fresh and dry AGB, canopy diameter, height, volume and area of Lavandin

S.no	Average Diameter (cm)	Height (cm)	Canopy Volume of the ellipse (cm^3)	Canopy Area of the ellipse (cm^2)	Total Fresh Biomass (g)	Total Dry Biomass (g)
Average	35.33	17.3	29,029.3	1,101.2	449.9	212.4
minimum	18.5	13	4630.5	267.1	64.1	30.4
Maximum	58	23	79875.7	2604.6	1342.5	668
SD	13.3	4.1	26,037.8	783.7	375.8	187.8

3.1.2. The relationship between crop dimensions and measured dry biomass

The allometric equations that best predicted the standing biomass of lavandin and rosemary are presented in Tables 3.3, 3.4, 3.5 and 3.6 and see the scatterplot of the allometric equations in Appendix 5. **Where:**
Y = Predicted dry AGB in grams; A= Elliptical Canopy Area in cm^2; V= Elliptical Canopy Volume in cm^3; HAGB = Harvestable above-ground biomass in grams; FAGB = Total fresh above-ground biomass in grams; R^2= Coefficient of determination; N = Number of samples; RMSE= Root mean square error

Table 3-3 Allometric equation of dry AGB, Elliptical Area in cm2 and dry AGB in gram(g)

Species	Equation	R^2	RMSE (g)	P-value	N
Lavandin	$Y = 0.0243\ A^{1.2824}$	0.934	0.3	<0.001	12
Rosemary	$Y = 0.0055\ A^{1.4934}$	0.925	23.6	<0.001	18

Table 3-4. Allometric equation of dry AGB, Elliptical Volume in cm^3 and dry AGB in gram(g)

Species	Equation	R^2	RMSE (g)	P-value	N
Lavandin	$Y = 0.0079V^{0.992}$	0.923	1.2	<0.001	12
Rosemary	$Y = 0.0025V^{1.0122}$	0.946	28.3	<0.001	18

Table 3-5. The allometric equation of harvestable dry AGB, Elliptical canopy area in cm^2 and harvestable dry AGB in grams(g)

Species	Equation	R^2	RMSE (g)	P-value	N
Rosemary	$HAGB = 0.22*A - 119.09$	0.954	22.2	<0.001	18

The best allometric equation for the estimation of essential oil of lavandin and rosemary is developed as the mathematical relation of measured total fresh biomass and the elliptical canopy area of the crop plant see in table 3.6.

Table 3-6. Fresh AGB allometric equation, Elliptical Area in cm^2 and Fresh AGB in grams (g)

Crop Plant	Equation	R2	RMSE (g)	P-value	N
Lavandin	$FAGB = 0.0748A^{1.2325}$	0.937		<0.001	12
Rosemary	$FAGB = 0.0261\ A^{1.4067}$	0.949		<0.001	18

The crop dimensions of average diameter and height for rosemary and lavandin show a good relationship with the measured dry biomass. As a result, the average diameter performs a better power regression model with the measured dry biomass for both crops. See Figures 3.1 and 3.2

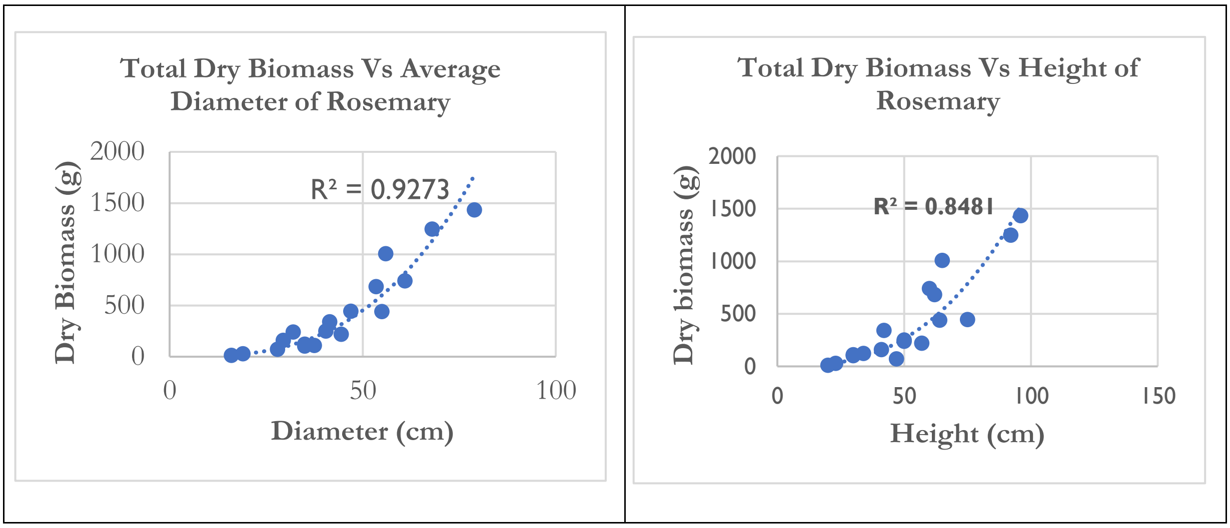

Figure 3-1. The relation of measured dry biomass of rosemary with its corresponding average diameter and height.

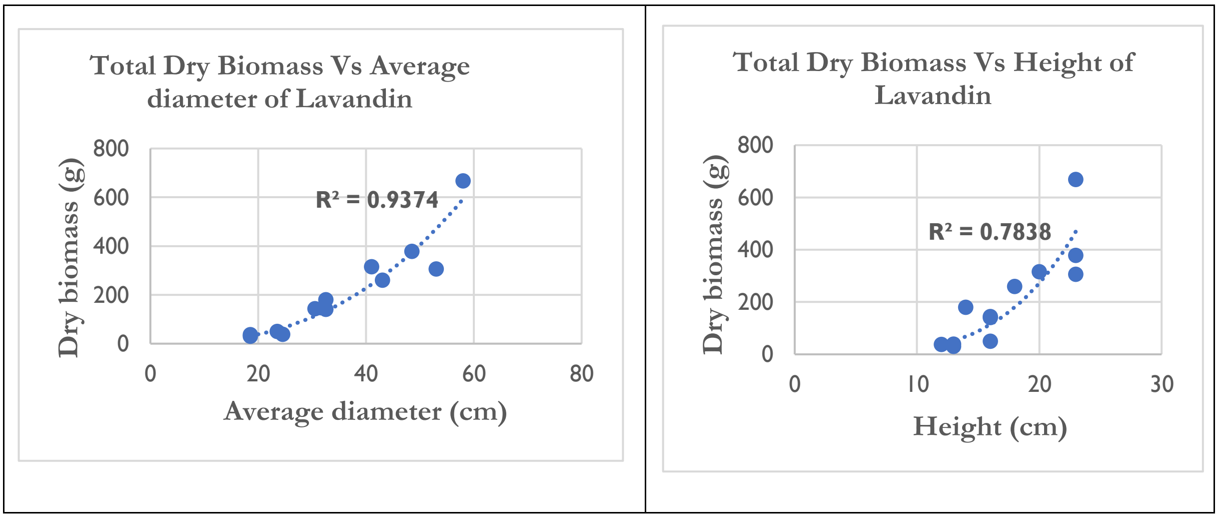

Figure 3-2. The relation of measured dry biomass of lavandin with its corresponding average diameter and height.

AGB of the measured pants was also estimated based on the allometric equation which ranged from 15 to 1,758 grams with an average of 418 grams per plant and showed a standard deviation of 463 grams; it is presented in Figure 3.3 and Appendix 3. The bias between the estimated and measured dry AGB was tested, to check the tendency of estimated AGB from the measured value. That showed either the estimated value is underestimated, overestimated or the same in comparison to the measured value. So, the result reals that the bias is 1.001 which is almost 1, which indicated that the measured and estimated AGB is about the same in general for the rosemary.

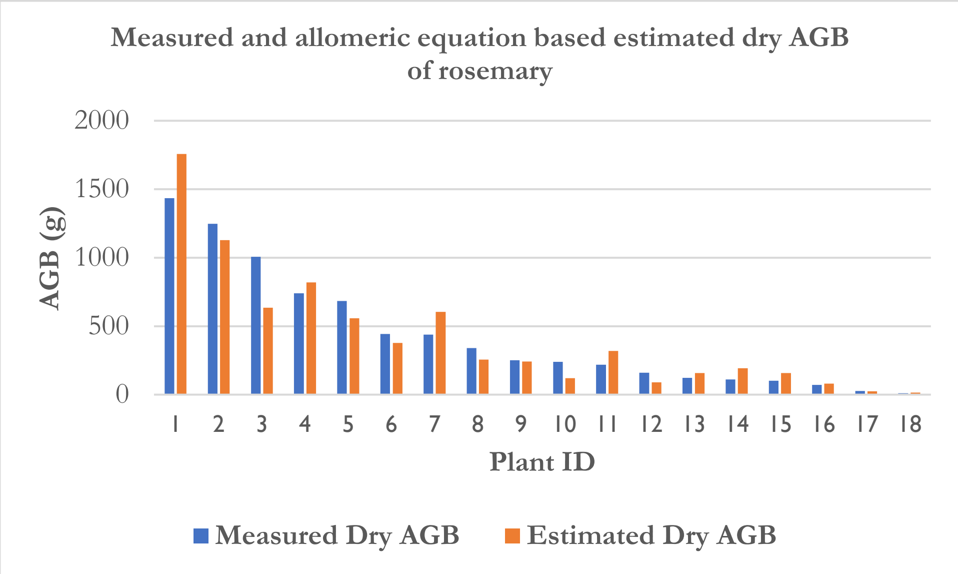

Figure 3-3. The relationship between the measured and allometric based estimated dry biomass of rosemary

The estimated AGB based on the allometric equation ranged from 31.5 to 583.4 grams with an average of 209 grams per plant and showed a standard deviation of 183 grams, see in Figure 3.1 and Appendix 4. The bias between the estimated and measured dry AGB was tested. So, the result reals that the bias is 0.99 which is less than one, which indicated that the estimated AGB show a small underestimation for the lavandin.

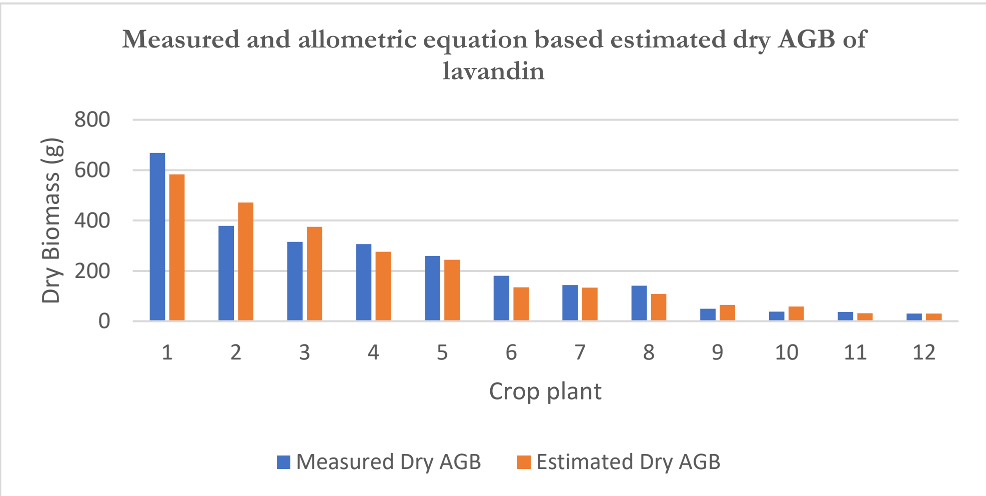

Figure 3-4. The relation between the measured and allometric based estimated dry biomass of lavandin.

3.1.3. Estimating the harvestable dry AGB of the measured crop plants

The farmers in the Baviaanskloof have commercialised the production of essential oil crops both in the form of essential oil and dry leave from the harvestable part of the plant specifically rosemary. The dry leave was obtained from the harvested plant of rosemary. This study is only concentrating on the rosemary crop for harvestable biomass estimation because lavandin was not reached on the harvesting stage during the fieldwork in which the harvesting period is between December and January. So, it was not possible to estimate the harvestable part of the lavandin at that time.

Based on the measured and harvested aboveground biomass of the crop plant, the harvestable part (yield) of rosemary is 0.50 of the total dry AGB on average which is presented in Table 3.7 and Appendix 3. Two plants had not reached on the harvesting stage but considered in the estimation of the harvestable biomass. The average conversion factor of 16 plants is increased to 0.56 per individual plant in which it could not show the total AGB of the crop plants within the plots and the farms in general. Moreover, based on the information from the farmers and the manager of an essential oil processing company, the farmers are also selling the products as essential oil and a dry leave for the users specifically for the rosemary. So, taking the measured and harvested plant biomass as a base, the dry leaves were 0.61 of the total harvestable dry biomasses on average see Table 3.7.

Table 3-7. Measured total, harvestable and dry leaves AGB of rosemary and the average conversion factor of 18 plants.

S.no	Measured Total Dry AGB (g)	Measured Harvestable Dry AGB (g)	Harvestable to Total ratio	Measured dry leaves (g)	Dry leave to Harvestable ratio
Average	424.9	244.9	0.50	152.1	0.61
Minimum	11.3	0	0	0	0
Maximum	1434	980.1	0.69	529.9	0.87
SD	417.2	266.4	0.20	151.0	0.23

Where: SD is the standard deviation

Moreover, based on the measured biomass, the harvestable fresh biomass of rosemary is 0.56 of the total fresh biomasses on the average per plant. Furthermore, according to the manager of the oil processing company (DEVCO, Sept 2018), the production of essential oil is 0.7 % and 1.6 % of the total fresh harvestable biomass of rosemary and lavandin on average respectively. Therefore, the estimated essential oil that could be produced from the harvested crop plant of rosemary is 4.6 grams per plants on average for further detail see Table 3.8 and Appendix 3.

Table 3-8. Summary statistics per individual plat of estimated essential oil from the measured and estimated fresh biomass of rosemary.

Parameter	Measured Total Fresh AGB (g)	Measured harvestable fresh biomass (g)	Harvestable to total AGB	Estimates total fresh biomass (g)	Estimated harvestable fresh Biomass (g)	Essential Oil from measured (g)	Essential Oil from Estimated (g)
Average	1,022.4	657.2	0.56	1,007.7	564.3	4.6	4.0
Minimum	37.1	0.0	0.0	45.1	25.3	0.0	0.2
Maximum	3,406.7	2,458.6	0.7	3,997.6	2,238.6	17.2	15.7
SD	1,002.5	695.6	0.22	1,024.6	573.8	4.9	4.0

3.2. Evaluating the relationship between the estimated above-ground biomass and Sentinel 2 vegetation indices data

This section included the results of estimated AGB, and yield based on allometric equation both at plot and farm level, the calculated vegetation indices values and the relationship between allometric equation based AGB and the vegetation indices.

3.2.1. Above-ground biomass (AGB) estimation based on allometric equations

The total AGB of the 32 sample plots was estimated based on the allometric equation developed from the harvested dry biomass with the elliptical canopy area of both rosemary and lavandin. The sample plots were 22 plots for rosemary and 10 for lavandin. Out of the total 32 sample plots, 27 sample plots were used to determine the relation between the estimated AGB and the vegetation indices. This was because the plants of those fields were in the young stage and fully dominated by another green herb cover.

The dry AGB of the plots were estimated based on the allometric equation for individual crop plants within the sample plots and aggregated to the plot level. Moreover, the estimated total AGB, harvestable AGB, dry leave and essential oil of the plots were upscaled to per hectare, and farm level sees Tables 3.10, 3.11 and 3.12 and Figure 3.6. Therefore, the summary of the estimated dry AGB of rosemary for the plot is shown in Table 3.9 and the detail in Appendix 6.

Table 3-9. Estimated total and harvestable fresh and dry AGB of rosemary

Parameters	Number of plants per plots	Total dry AGB (kg/plot)	Harvestable fresh AGB (kg/plot)	Allometric equation based harvestable dry AGB (kg/plot)	Harvestable dry AGB as % of total AGB (kg/plot)
Average	120	38.4	93.49	21.62	19.2
Minimum	57	6.88	10.18	-0.1	3.44
Maximum	210	146.37	188.75	81.32	73.19
SD	46	31.6	72.99	19.10	15.8

The estimated AGB of the plots of rosemary was upscaled to the hectare level, and then it aggregated to the farm level of each farmer see in Tables 3.10.

Table 3-10. Upscaling total dry AGB, harvestable AGB and dry leave of rosemary from plot level to per hectare and farm level

Farm ID	Number of plots	Area (ha)	Average number of plants per ha	Average AGB (kg/plot)	Average AGB (kg/ha)	Average Harvestable AGB (kg/ha)	Average dry Leave (kg/ha)	Average Essential oil (kg/ha)	Average AGB (kg/farm)
$A1_R$	5	4.68	11,800	28.99	2,899	1,449.50	884.5	57.7	13,567.3
$A2_R$	2	3.2	13,700	16.26	1,626	813.00	495.9	27.6	5,203.2
B_R	8	10.70	16,200	60.70	6,070	3,035.00	1,851.4	16.8	64,949
C_R	7	5.70	7,100	25.85	2,585	1,292.50	788.7	24.7	14,734.5
Average	**22**	**24**	**12,000**	**38.4**	**3,840**	**1,920**	**1,171.2**	**36.5**	**24,613.5**
SD			**3,848**	**31.6**	**3,160**	**1,580**	**963.8**	**28.6**	**27,223.3**

The harvestable dry AGB is 0.50 of the total dry AGB, which is presented in Table 3.7. The standard deviation between the plots of the rosemary farms was higher; this was due to the age difference of the crop plants especially farm A2 is a very young plant of rosemary field. Besides, the dry leaves of rosemary were 0.61 of the harvestable dry AGB on average see Table 3.7. Therefore, the average estimated dry leave was 10.1 kg/plot which ranged from a minimum of 7.9 kg/plot in farm C to a maximum of 18.5 kg/plot in farm

B on average. Therefore, based on the average estimated dry leave biomass per plot, the average dry leaves of per Hectare was computed see Table 3.10 and Appendix 7.

Additionally, for the estimation of essential oil, the harvestable fresh AGB of rosemary is 0.56 of the total fresh AGB on average per plant see Table 3.8 and Appendix 3. The estimated essential oil of rosemary was 0.4 kg per plot on average with the standard deviation of 0.3 kg between the plots, which ranged from a minimum of 0.07 kg to a maximum of 1.32 kg see in Appendix 6. The estimated essential oil of the plots was upscaled to per hectare level and aggregated to the farm level see in Figure 3.5 and Appendix 7.

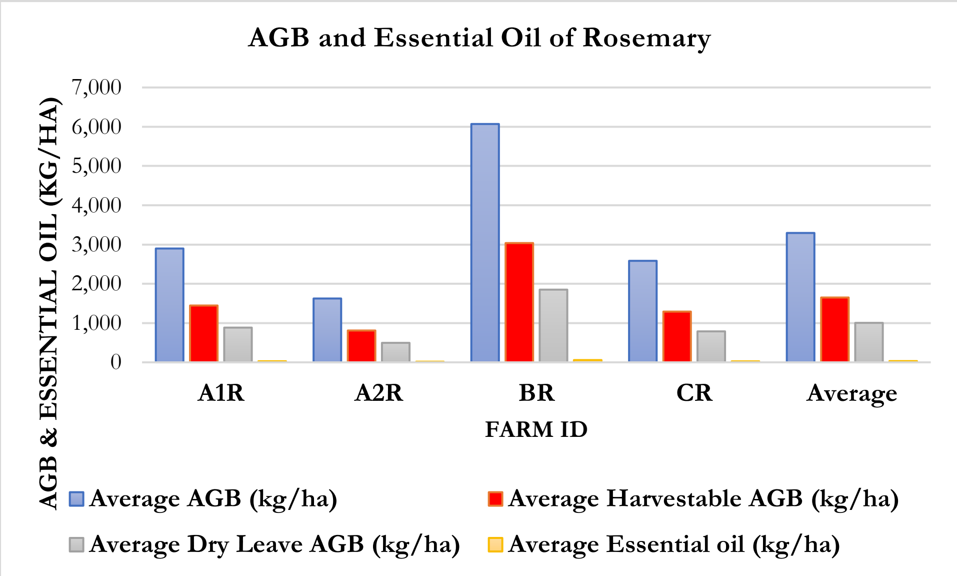

Figure 3-5. Comparison of total AGB and the yield of rosemary farms as total harvestable dry AGB, dry leaf and essential oil per hectare.

The summary of the estimated total AGB of lavandin per plot and the upscaling to per hectare and farm level was presented in Table 3.11. See the detail in appendix 8. The overall average dry biomass of lavandin is 16.5 kg per plot which ranged from a minimum of 2.4 kg to a maximum of 48 kg per plot, see Appendix 9. The big difference in the values of AGB is due to the difference in age of the lavandin crops.

Table 3-11. Upscaling total AGB of lavandin plots to per hectare and farm level

Farm ID	Number of plots	Area (ha)	Average number of plants/plots	Average AGB (kg/plot)	Average AGB (kg/ha)	Total AGB (kg/farm)
A_L	5	10.1	139	12.4	1,236	12,483.6
$B1_L$	4	6.3	73	25.3	2,528	15,926.4
$B2_L$	1	5.8	153	2.4	243	1,409.4
Average			**114**	**16.5**	**1,650**	**9,939.8**
SD			**40**	**13.2**	**1,320**	**7,585.4**

3.2.2. Calculation of vegetation indices from Sentinel-2 image

The spectral reflectance of a crop or plant canopy is a combination of the reflectance of the crop, other green vegetation and soil background (Rondeaux et al., 1996). So, the pixel value of the vegetation indices for the crop plants of rosemary and lavandin were strongly affected by the cover crops (green herbs) and the soil background in each plot and all the fields in general. The values of all the indices, dry AGB, the cover percentage of soil and herb, elevation and plant age were given in Table 3.16 and Table 3.17 for the rosemary and lavandin respectively.

Table 3-12. Estimated AGB (kg), VI's, herb cover (%) and Bare soil cover (%) of the mature rosemary.

Plotid	AGB (kg)	NDVI	RVI	SAVI	MSAVI	RENDVI	RERVI	Herb Cover %	Soil Cover %	Elevation (m)	Age(months)
A1	22.6	0.45	2.69	0.31	0.27	0.28	1.80	42.65	46.1	452	29
A2	23.5	0.65	4.83	0.43	0.38	0.40	2.34	67.92	20	453	29
A3	23	0.37	2.21	0.26	0.23	0.25	1.65	35.13	53.6	455	29
A4	6.9	0.44	2.60	0.30	0.27	0.27	1.75	53.11	42.3	465	29
A5	69	0.56	3.54	0.38	0.34	0.34	2.06	47.67	29.1	455	29
B1	40.1	0.55	3.49	0.38	0.35	0.39	2.30	29.38	50.2	351	25
B2	33.2	0.59	3.97	0.41	0.37	0.41	2.38	28.39	52.8	347	25
B4	65.9	0.41	2.42	0.29	0.26	0.29	1.84	29.14	44.7	355	25
B5	40.8	0.57	3.68	0.39	0.35	0.40	2.35	36.21	43	348	25
B6	55.1	0.62	4.24	0.42	0.38	0.43	2.53	44.14	29.8	349	25
B7	146.4	0.68	5.23	0.48	0.44	0.47	2.77	36.6	19.1	335	25
B8	89.2	0.61	4.12	0.42	0.38	0.43	2.53	37.98	25.7	348	25
C1	34.7	0.21	1.54	0.16	0.15	0.15	1.35	21.05	66.7	627	29
C2	27.2	0.31	1.89	0.20	0.18	0.17	1.41	28.73	60.3	626	29
C3	34.3	0.28	1.77	0.21	0.18	0.17	1.41	32.36	54.8	620	29
C4	23.8	0.19	1.46	0.14	0.13	0.11	1.24	25.59	63.4	627	29
C5	15.7	0.25	1.66	0.17	0.15	0.16	1.37	36.43	55.86	625	29
C6	28.9	0.30	1.86	0.19	0.16	0.18	1.45	32.19	54.9	626	29
C7	16.5	0.20	1.49	0.15	0.13	0.12	1.27	33.81	57.9	623	29
Average	**41.9**	**0.43**	**2.88**	**0.30**	**0.27**	**0.29**	**1.88**	**36.76**	**45.8**	**478.3**	**28**
SD	**31.8**	**0.16**	**1.18**	**0.11**	**0.10**	**0.12**	**0.50**	**10.6**	**14.2**	**123.1**	**2**

Table 3-13. Estimated AGB (kg), VI's, herb cover (%) and Bare soil cover (%) of the mature lavandin.

plotid	AGB (kg)	NDVI	SAVI	MSAVI	RVI	RENDVI	RERVI	Herb Cover %	Soil Cover %	Elevation (m)	Age (months)
A11	19.2	0.42	0.27	0.24	2.46	0.22	1.56	32.73	55.15	347	19
A12	15.4	0.52	0.35	0.31	3.14	0.09	1.21	40.72	49.47	352	19
A13	5.5	0.63	0.45	0.41	4.39	-0.07	0.86	55.85	40.27	348	19
A14	11.5	0.46	0.33	0.30	2.73	0.10	1.23	40.95	51.19	350	19
A15	10.2	0.58	0.40	0.36	3.87	0.01	1.03	48.21	45.13	352	19
B11	15.8	0.19	0.15	0.13	1.46	0.19	1.47	29.78	61.62	603	37
B12	27.9	0.21	0.16	0.15	1.52	0.17	1.41	29.29	56.75	603	37
B13	48.0	0.32	0.21	0.18	1.93	0.22	1.56	56.67	22.84	602	37
B15	9.4	0.29	0.21	0.19	1.81	0.15	1.36	48.5	46.25	603	37
Average	**18.1**	**0.40**	**0.28**	**0.25**	**2.59**	**0.12**	**1.30**	**43.85**	**46.22**	**462.22**	**27.00**
SD	**13.0**	**0.16**	**0.11**	**0.10**	**1.04**	**0.10**	**0.24**	**8.48**	**6.12**	**133.33**	**9.49**

The value of the indices and AGB of all the plots of lavandin were different throughout all the farms.

3.2.3. The relationship between the Allometric equation based AGB and vegetation indices

To explore the relationship between biomass the vegetation indices, a regression analysis was performed between biomass and six vegetation indices. The relationship between the allometric equation based AGB and the pixel values of the vegetation indices was calculated with different types of regression analysis to develop the best model used to predict the AGB rosemary and lavandin in the study area.

The simple linear regression analysis between the estimated AGB and value of vegetation indices of the rosemary plots was done and given below in Tables 3.17 and see the detail of the scatterplots in appendix 9.

Table 3-14. Linear regression analysis (Equation, R^2 & P-value) performed between the VI's and AGB for the rosemary

VI	**Equation**	**R^2**	**P-value**
NDVI	$AGB = 110.28 \times NDVI - 5.81$	0.32	P<0.01
RVI	$AGB = 16.8 \times RVI - 6.4$	0.39	P<0.01
SAVI	$AGB = 173.24 \times SAVI - 10$	0.36	P<0.01
MSAVI	$AGB = 193 \times MSAVI - 9.87$	0.37	P<0.01
RENDVI	$AGB = 162 \times RENDVI - 4.3$	0.38	P<0.01
RERVI	$AGB = 42.45 \times RERVI - 37.8$	0.43	P<0.01

Though the R^2 for the linear regression model between the estimated AGB and the vegetation indices for the plots of rosemary was not high which was between 0.32 and 0.43, it is statistically significant at the confidence interval of 95 % in which p-value is less than 0.05. The RERVI performs a better linear relationship with AGB in compare to the other vegetation indices, see Figure 3.5 which was followed by RVI Table 3.17.

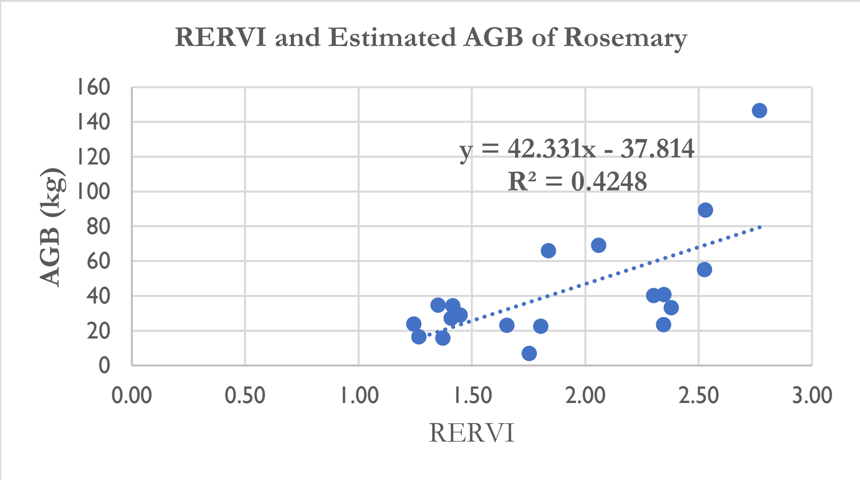

Figure 3-6. A linear relationship between the RERVI and the estimated AGB of rosemary.

The simple linear regression between the estimated dry AGB and the vegetation indices for each plot was not good, as a result, a multiple linear regression was done by considering the parameters of green herb and soil cover %, elevation and the plants age in the relationship. The estimated dry AGB, vegetation indices, the cover estimation of the plots, elevation and age of the plant is given in Tables 3.15 and 3.16 for rosemary and lavandin respectively.

The correlation and scatterplot matrix for the multiple linear models of rosemary was done to test the strength of the relationship between the variables. As presented in Appendix 11 and 12, the herb cover shows a weak positive linear relationship with all the explanatory variables, but very weak negative relationship with dry AGB. All the vegetation indices were shown a good relationship with the dry AGB, soil cover %, plant age and elevation with a correlation coefficient of greater than 0.5. But they have shown a weak positive relationship with herb cover percent.

The multiple linear regression model of the AGB estimation was determined as a function the vegetation indices, green herb cover percent, bare soil cover percent, elevation and the plant age for. The multiple linear regression analysis has been done with all the vegetation indices see Table 3.19 and the details of the analyses in Appendix 11. Therefore, based on the correlation coefficient, significance level (P-value) and multicollinearity (VIF) between the variables, herb cover percent and elevation were removed from the model. As a result, the best multiple linear regression model for AGB estimation of rosemary is NDVI with the soil cover percent and the plant age. The model with NDVI has a lower VIF in comparison to the other indices which indicated that there was no severe multicollinearity between the explanatory variables and perform a higher coefficient of determination see Table 3.19. Moreover, the model with NDVI has a lower standard error of 20 kg.

Table 3-15. Multiple linear regression analysis (Equation, R^2 & P-value) performed between the AGB and VIs, Soil cover % and plant age for the rosemary

VI	Equation	Adj.R^2	P-value	N
NDVI	$AGB = 452.7 - 113.6 \times NDVI - 2.3 \times \text{Soil cover \%} - 9.3 \times Age$	0.60	<0.001	19
RVI	$AGB = 368.4 - 9.3 \times RVI - 1.9 \times \text{Soil cover \%} - 7.7 \times Age$	0.54	<0.01	19
SAVI	$AGB = 448.5 - 157.6 \times SAVI - 2.2 \times \text{Soil cover \%} - 9.4 \times Age$	0.58	<0.001	19
MSAVI	$AGB = 439 - 162.5 \times MSAVI - 2.1 \times \text{Soil cover \%} \times 9.3 \times Age$	0.57	<0.01	19
RENDVI	$AGB = 495.1 - 168.8 \times RENDVI - 2.2 \times \text{Soil cover \%} - 11 \times Age$	0.59	<0.001	19
RERVI	$AGB = 483.5 - 34 \times RERVI - 2.1 \times \text{Soil cover \%} - 10.3 \times Age$	0.56	<0.01	19

Although, the relationship between the dry AGB and the vegetation indices, soil cover % and plant age are not high (R^2 < 60 %), they are statistically significant at the confidence interval of 95 %. Therefore, the best model selected and used to estimate the AGB of rosemary is for NDVI.

The estimated AGB based on the vegetation index shows a deviation from the AGB based on the allometric equation. This was due to the low accuracy between the AGB and NDVI which reveals R^2 of 0.60. There was an underestimation and overestimates between the AGB of the plots. But the overall average is nearly the same. To check the tendency of the estimated AGB based on the NDVI from the allometric equation based AGB, a bias test was computed. Therefore, the result revealed a bias about 1.01 which indicated that there was a small overestimation in the NDVI based AGB. The scatterplot of the relationship is given in Figure 3.9 below.

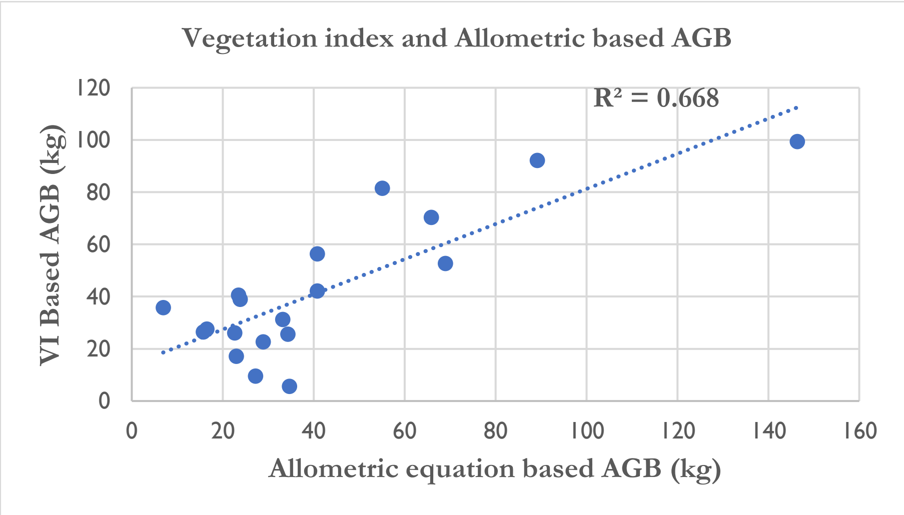

Figure 3-7. The relationship between vegetation index and allometric equation based AGB of rosemary.

The simple linear regression analysis between the estimated AGB and vegetation indices of the lavandin is given below in Table 3.17 and the detail of the scatterplots in appendix 10.

Table 3-16. Linear regression analysis (Equation, R^2 & P-value) performed between the vegetation indices and AGB for the lavandin

Indices	Equation	R2	P-value
NDVI	AGB = 33.48 − 38.42 × NDVI	0.23	P=0.19
RVI	AGB = 34.9 − 6.5 × RVI	0.27	P=0.15
SAVI	AGB = 36.4 − 65.1 × SAVI	0.29	P=0.14
MSAVI	AGB = 36.7 − 73.8 × MSAVI	0.31	P=0.13
RENDVI	AGB = 85.4×RENDVI −7.9	0.42	P=0.06
RERVI	AGB = 36.2 × RERVI − 28.9	0.45	P<0.05

At the confidence interval 95 % the P-value>0.05 see Table 3.22. So, the result indicated that there was no linear relationship between the dry AGB of lavandin and most of the vegetation indices except with the RERVI. But the relationship between the dry AGB of lavandin and Red-edge ratio vegetation index is significant. Therefore, only the RERVI shows a significant relationship with the AGB of lavandin for the linear regression model at 95 % confidence interval.

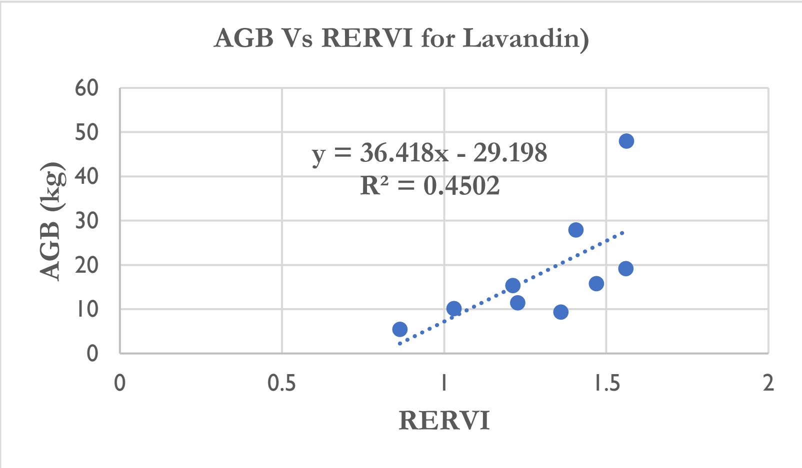

Figure 3-8. The relationship between RERVI and allometric based AGB of lavandin

The multiple linear regression analyses for AGB estimation of lavandin is as follow ;
All the vegetation indices show a negative correlation with AGB of lavandin except the red-edge indices. The NDVI was showed a weaker correlation with AGB. Moreover, herb cover was showed a very low correlation with AGB which is below 0.1 see in Appendix 14.

The multiple linear regression model of the AGB estimation was determined as a function the vegetation indices, green herb cover percent, bare soil cover percent, elevation and the plant age for all the vegetation indices. The multiple linear regression analyses have been done with all the vegetation indices. See the details of the models in appendix 12. Therefore, based on the significance level the model, correlation, VIF and coefficient of determination, the best multiple linear regression model for the estimation of AGB of lavandin was RERVI which is given in Table 3.18. Therefore, the best model for lavandin biomass estimation is performed as a function of RERVI and the soil cover percent.

Table 3-17. Multiple linear regression analysis (Equation, R^2 & P-value) performed between the vegetation indices and AGB for the lavandin

Indices	Equation	Adj.R^2	P-value	N
NDVI	$AGB = 77.2 - 54.5 \times NDVI - 0.8 \times \text{Soil cover } \%$	0.54	<0.05	9
RVI	$AGB = 76.9 - 8.6 \times RVI - 0.8 \times \text{Soil cover } \%$	0.59	<0.05	9
SAVI	$AGB = 78 - 83.8 \times SAVI - 0.8 \times \text{Soil cover } \%$	0.59	<0.05	9
MSAVI	$AGB = 77.4 - 92.7 \times MSAVI - 0.8 \times \text{Soil cover } \%$	0.61	<0.05	9
RENDVI	$AGB = 96 \times RENDVI - 0.7 \times \text{Soil cover } \% + 38.3$	0.68	<0.05	9
RERVI	$AGB = 39.4 \times RERVI - 0.7 \times \text{Soil cover } \% - 2.1$	0.69	<0.05	9

The AGB of the lavandin was estimated based on the model derived from RERVI and soil cover percent of the plots. Because the model with RERVI has low multicollinearity with the explanatory variables and has a higher coefficient of determination (R^2) in comparison to the other indices followed by RENDVI. Moreover, it also showed a lower standard error of about 7.7 kg. So, the best model selected to estimate the AGB of lavandin is for RERVI. Furthermore, AGB based on the RERVI was underestimated in compare to the allometric equation based AGB. As a result, the average AGB was reduced due to underestimation in most AGB of the plots see in Figure 3.9. Therefore, bias test was done which is 0.87 which indicated that the RERVI based AGB is underestimated.

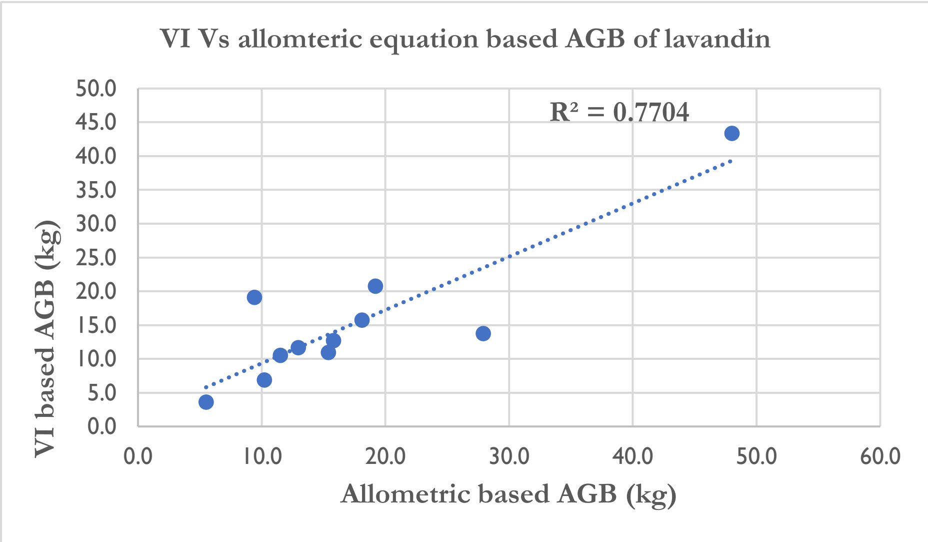

Figure 3-9. The relationship between the allometric and vegetation index based AGB of lavandin

The average vegetation indices based estimated AGB of lavandin is 18.31 kg/plot and 1831 kg/ha with a standard deviation of 9kg and 902 kg respectively. It ranges from a minimum of 11.9 kg/plot in farm A to a maximum of 24.7 kg in farm B. The estimated AGB of rosemary is much higher than AGB of lavandin. The average AGB of rosemary is 4,190 kg/ha while the average AGB of lavandin is 1831 kg/ha.

Herb cover influences the values of vegetation indices directly, and as such affected vegetation indices based AGB of rosemary and lavandin, even though it was removed from the model due to the correlation and multicollinearity effect with the other variables of the model. So, to test the influence of herb cover on the estimated AGB which was computed based on the vegetation indices, it should calculate the proportion (partial R^2) of herb cover on the model.

Therefore, the influence of herb cover on the NDVI-based estimated AGB of rosemary and lavandin is determined based on the analysis of variance table (ANOVA) for a model with herb cover and without herb cover. The result revealed a partial R^2 of 0.23 and see in Appendix 13. Therefore, holding the NDVI value constant 23 % of the variation in the models is explained by the explanatory variable of herb cover. So, removing the parameter of herb cover from the model causes the coefficient of determination to be dropped from 0.48 to 0.39, from this we can understand that herb cover influences the estimated AGB of rosemary which was computed based on the vegetation indices. In general, 9 % of the variation in the estimated AGB was explained by the parameter of herb cover.

3.3. Identifying the spatial and temporal variability in vegetation cover of lavandin and rosemary using multitemporal vegetation indices

The spatial variation of the plots within and between the fields were shown both from the NDVI map, and the mean, maximum, minimum and standard deviation values of NDVI and AGB for the plots in different fields or farms see Table 3.19 and 3.20 and Figure 3.10. And the temporal variation of the plots was shown from the multitemporal NDVI values presented in Figures 3.11, 3.13, and 3.14.

3.3.1. Spatial Variation of the vegetation cover within and between the plots and farms

The spatial variation of the vegetation cover of the plots was evaluated based on the NDVI map, the mean and standard deviation of the AGB within and between the plots and farms for October 7, 2018.

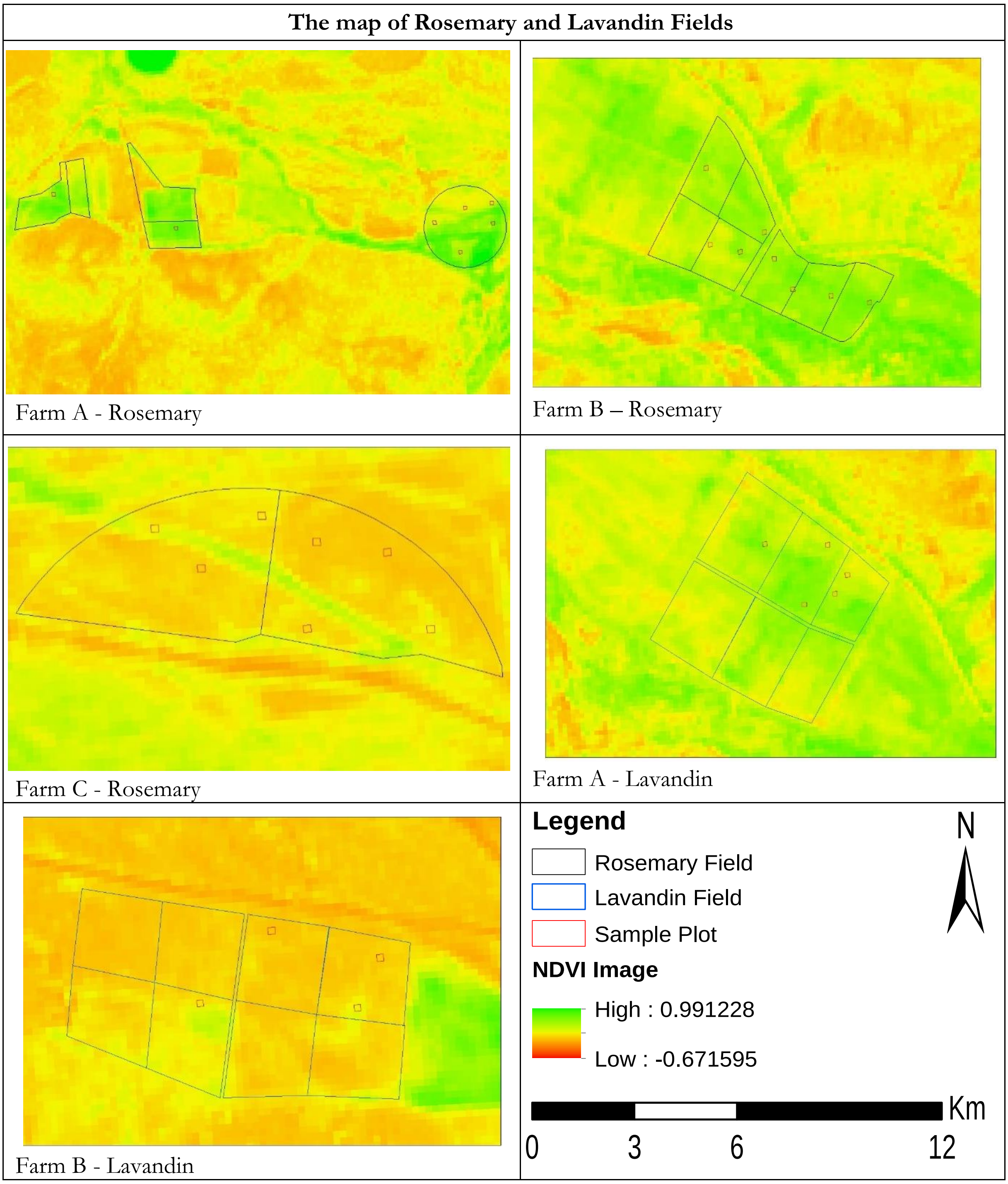

Figure 3-10. The vegetation indices maps of the lavandin and rosemary field for October 7, 2018.

The spatial variation in AGB of rosemary is the highest in farm B_R within the plots in comparison to other farms. The standard deviation is also higher in farm B_R which is about 41 kg/plot and lowers in farm C_R

which is about 8 kg/plot within the plots of the same farms, see Table 3.19. While the variation in the AGB of lavandin is higher in farm B_L which ranges from 9.6 to 48 kg/plot that shows a deviation of 17 kg/plot within the plots see in Table 3.20.

Table 3-18. The spatial variation of NDVI based AGB of rosemary within and between the farms

Farm ID	AGB of Rosemary (kg/plot)			
	Average	Maximum	Minimum	Standard deviation
A_R	29.0	69.0	6.9	23.4
B_R	67.3	146.4	33.2	39.8
C_R	25.9	34.7	15.7	7.7
Average	**40.7**	**83.4**	**18.6**	**23.6**
SD	**23.1**	**57.2**	**13.4**	**16.1**

Table 3-19. The spatial variation of NDVI based AGB of lavandin within and between the farms

Farm ID	**AGB of Lavandin (kg/plot)**			
	Average	**Maximum**	**Minimum**	**Standard deviation**
A_L	12.36	19.2	5.5	5.2
B_L	25.3	48	9.6	17
Average	**18.8**	**33.6**	**7.6**	**11.1**
SD	**9.1**	**20.4**	**2.9**	**8.3**

The significance level of the spatial variation between the farms was tested using an ANOVA single factor. The spatial variation between the mean values of the plots of the farms for rosemary and lavandin is statistically significant at the confidence interval of 95 % in which p-value is less than 0.05. Moreover, F critical (2.795) is less than F calculated (4.844), which implied that there was a significant difference in the variation of AGB between the plots of the farms see Table 3.21.

Table 3-20. ANOVA table for the significance measure of spatial variation of the farms of rosemary and lavandin.

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	10966.961	4	2741.740	4.844	0.0055	2.795
Within Groups	13016.810	23	565.948			
Total	23983.773	27				

3.3.2. Temporal variation within and between the plots of rosemary and lavandin

Farm C which was indicated by the black lines was harvested during the field work on October 01, 2018. As shown in the NDVI time series profile above, there is only a small decline in the profile from September to October even though it was harvested. This was due to the leftover, which the harvesting machine was left 20 cm of the biomass from the ground while it harvested. Additionally, the green herb is also still there after harvesting due to the irrigation system. See the difference in Figure 3.12 below that shown the harvested and non-harvested crop plant. As observed in Figure 3.11 farm B which was indicated by the green line was harvested in December 2017, which shown a decline in the mean NDVI profile, then started to increase steadily. At the same time, farm-A shows an increase in mean NDVI value with time, but farm C was not showing a major change in the mean NDVI value except for the period January to May 2018. In general, regardless of the effect of the annual green herbs on the field, there is an increase in vegetation density of the crop plant with time. As shown in Figure 3.15, the precipitation in the study area was higher in February, March, April and September in which it was reflected in the temporal NDVI profile of the fields of A and B. This contributed to the rapid growth of green vegetation in the fields which was increasing the NDVI values. Moreover, the standard deviation of the NDVI time series values of plots of the farms showed the spatial and temporal variability of the vegetation density through time between and within the farms.

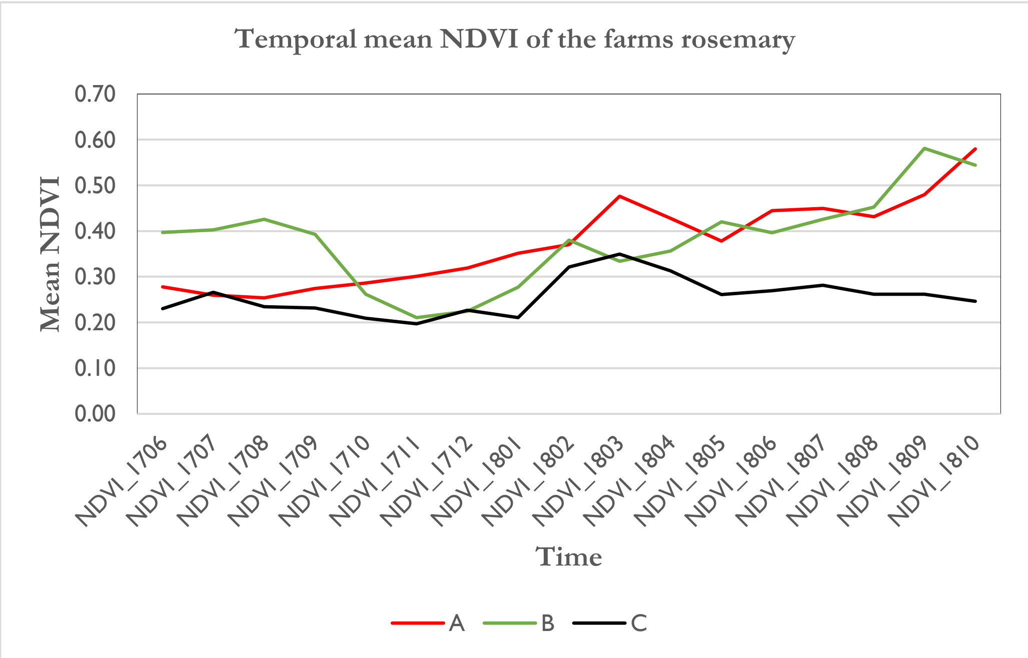

Figure 3-11. Mean NDVI temporal profile for the rosemary farms

Figure 3-12. Rosemary field harvested on October 01, 2018

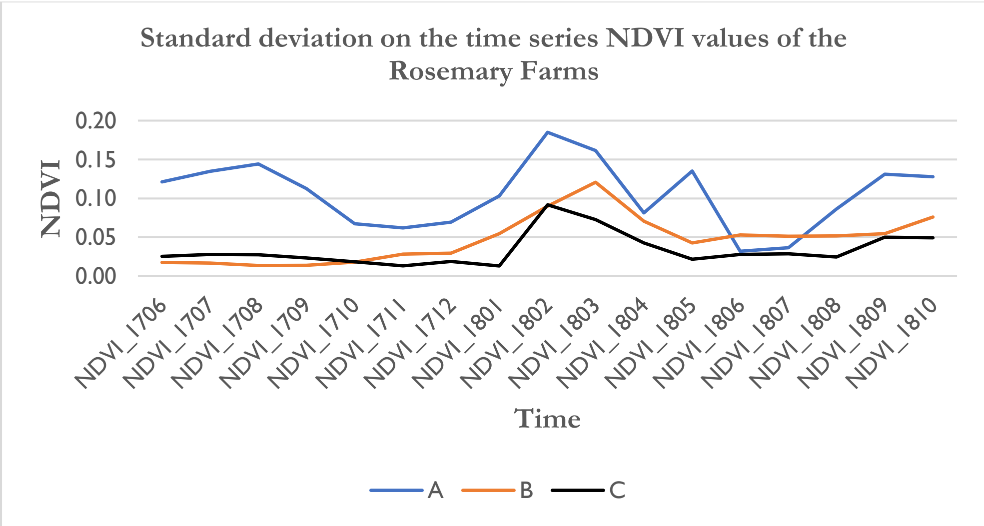

Figure 3-13. The standard deviation of NDVI temporal profile of the plots for the rosemary farms

The sharp increase and decrease on the mean NDVI profile especially in farm A of the lavandin field, which indicated by the green line is the growth of the annual green herbs in the field which was due to high precipitation and the irrigation system and then started to decline sharply since they have a short life span.

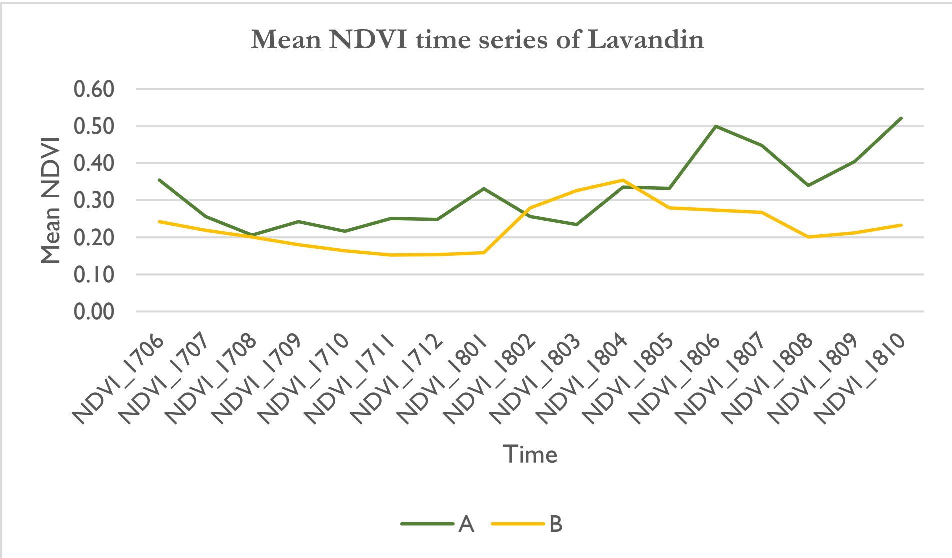

Figure 3-14. Mean NDVI temporal profile for the lavandin farms

The temporal trend of or profile of NDVI of the fields of rosemary and lavandin are affected by the trend of the rainfall distribution in the study area. The rainfall trend of Baviaanskloof is presented in Figure 3.19. The blue colour showed the value of precipitation for each month.

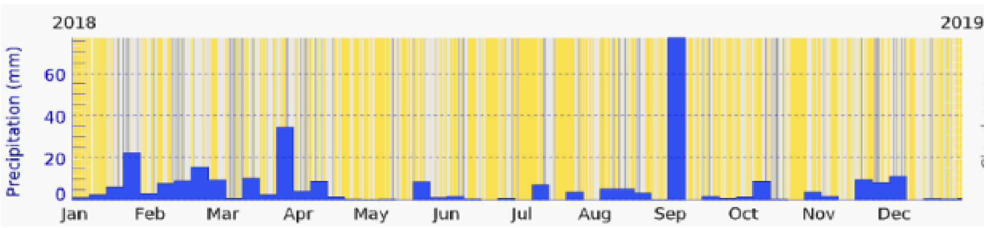

Figure 3-15. The trend of precipitation (rainfall) of the months in Baviaanskloof (Meteoblue, 2019)

4. DISCUSSION

4.1. Aboveground biomass estimation

Allometric equations for estimation of above-ground biomass specifically for the herbaceous perennial shrubs of rosemary and lavandin are not available in the literature. Since there was no allometric equation developed to estimate the AGB of rosemary and lavandin, the allometric equations were developed for AGB and yield estimation of both crops. Additionally, the biometric measurement of the variables such as two perpendicular canopy diameter, height and canopy area of each plant has been measured. This was used to validate the model that has been developed using the dry biomass and the canopy area of the ellipse geometrical shape of the plant. The selected allomeric equations showed a good relationship with R^2 of 0.92 to 0.95 for both rosemary and lavandin crops.

Diameter and height are a strong predictor of AGB estimation for the species-specific allometric model of the shrubs (Ali et al., 2015). Castro & Freitas,(2009) studied above-ground biomass and productivity of two Lavandula shrub species in different land use categories and developed an allometric power equation using six individual harvested plants. They developed an allometric equation from the inverted conical geometric shape of the plant (canopy area and dry biomass) and got the coefficient of determination (R^2) of 0.889 and 0.960 which is comparable with the result of this study with R^2 of 0.934 for the lavandin and 0.925 for rosemary.

Rao et al., (2016), reported the best power relationship between the diameter and AGB with an R^2 of 0.97 which was conducted in the semi-arid of Southern India. This is comparable with the result obtained in the study, which the crop dimensions of diameter showed a very good power relationship with the measured dry AGB of rosemary and lavandin. It performs R^2 of 0.93 and 0.97.

The estimated AGB of lavandin of this study is ranging from a minimum of 0.02 kgm^{-2} for the younger crop plant of farm B_1 to a maximum of 0.25 kgm^{-2} in farm B_2. This result is lower in comparison to the study that has been conducted by Castro & Freitas,(2009) in Montado, Portugal. The achieved estimated AGB was ranging from 0.20 to 1.17 kgm^{-2} for different shrubs, but this result was done in different land use categories in combination with the two Lavandula and other shrubs at different age level. Besides, it was comparable with the estimated AGB of rosemary which ranged from 0.07 kgm^{-2} in farm A1 and 1.46 kgm^{-2} in farm B.

According to the report from Wikfarmer, (2017), the average dry yield of rosemary is 6.7 tons per hectare which higher than the result achieved in this study, which is 3.8 tons per hectare. But it is comparable with the average yield of rosemary (AGB) on farm B which comprises 6.07 tons per hectare. Moreover, they reported that the average yield of dried leaf is 2.5 tons per hectare, in which it is higher than the result achieved in this study 1.17 tons/ha, but it is nearly comparable with the average yield of dried leaf on farm the farm B_R which is about 1.9 tons/ha. They also reported that the average yield of essential oil is estimated close to 0.3 % of the fresh harvestable biomass, which gives the expected yield of 24 kg/ha of essential oil. They used a lower percentage than this study (0.7 %) which revealed an estimated yield of essential oil to be 36.5 kg/ha. Keep in mind that the result from the report was considered the average annual yield, health matured plant (older than three years), which was managed by professional growers. These helped them to produce high quantity of essential oil per hectare using a lower conversion factor of 0.03 %.

Moreover, Mishra et al. (2009) studied the productivity of rosemary in relation to the plant spacing between and within the rows. The study demonstrated three different spacing for two years. The result reveals the maximum yield was 100 & 84 grams per plant for the higher spacings for the two years respectively. The wider spacings motivated the plant to get the chance of spreading and growth, resulting in an increase in the yield of the plants. However, the total herbage yield per hectare was lower in the wider planting spacings due to the accommodation of a small number of plants in one hectare of land. The result from the report is very low in comparison to the result obtained from this study, which comprises 425 grams per plant. But the study from the report was conducted in the rainfed cultivation system.

The study by Mishra et al. (2009) reported that the herbage yield of rosemary was the main source of essential oil. The average essential oil obtained per hectare was 44.1 kg and 24.4 kg for the lower and medium spacings respectively. This result was comparable with this study which obtained the average essential oil of 36.5 kg/ha. Moreover, Solomon & Beemnet (2010) studied the productivity of rosemary at a different age level and reported a maximum yield of essential oil of 39.7 kg/ha.

The total dry AGB of rosemary was 3,840 kg/ha, harvestable AGB 1,920 kg/ha, average dry leaves 1,171 kg/ha and the essential oil 36.5 kg/ha, which was considered the young rosemary crop fields. The total average estimated AGB of rosemary for the farms differs considerably from a minimum of 1,226 kg/ha for the younger crop plant of farm A2 and a maximum of 6,070 kg/ha in farm B. The total average AGB of lavandin was 1650 kg/ha. The biomass of rosemary was very high in comparison with the biomass of lavandin. Generally, the productivity of the crops depends on the number of plants, the irrigation system, management practice, the input used and soil conditions.

4.2. The relationship between the estimated AGB and vegetation indices

The AGB obtained using the allometric equation was used to assess the relationship between the vegetation indices and AGB using linear and multiple linear regression analysis. The result showed that there was a significant relationship between AGB and remotely sensed vegetation indices.

A remote sensing based method of biomass estimation can provide repeated measures without making destructive sampling and can monitor and evaluate the changes within the fields through time (Hatfield & Prueger, 2010). The MNDVI from the short wavelength of red-edge and long wavelength red-edge perform higher correlation with the biomass in comparison to the standard NDVI (Mutanga & Skidmore, 2004). This is like the result obtained in the study, that is the RENDVI show better correlation with the AGB in comparison to the NDVI for both rosemary and lavandin even though the correlation is very low in general due to many factors in the crop fields. The R^2 for the standard NDVI and RENDVI is 0.32 and 0.38 for the linear relationship with the AGB of rosemary respectively, which shows an improvement in R^2 of 0.06 with the red-edge band. Additionally, R^2 for the standard NDVI and RENDVI is 0.23 and 0.42 for the linear relationship with AGB of lavandin respectively, which showed an improvement in R^2 of 0.19 with the red-edge band. Moreover, the RVI showed an improvement of R^2 about 0.04 and 0.18 with the red-edge band for rosemary and lavandin respectively. Generally, the red-edge bands improve the accuracy of AGB estimation for both rosemary and lavandin.

Adan (2017), studied AGB estimation of the forest using the Sentinel-2 derived vegetation indices such as NDVI, enhanced vegetation index (EVI), normalized difference water index (NDWI), normalized difference infrared index (NDII), RENDVI, RERVI and red-edge enhanced vegetation index (REEVI) and found the best linear relationship between the RERVI and AGB which performed R^2 of 0.63. This is similar to the result obtained in this study, in that RERVI perform better linear relationship with AGB with R^2 of 0.43 and 0.45 for rosemary and lavandin respectively. Moreover, Jesús et al. (2011) studied the estimation green leaf area index and chlorophyll content using Sentinel-2 data and reported that the red-edge band significantly improve the accuracy of chlorophyll content estimation.

According to the study conducted by Mutanga & Skidmore (2004), simple ratio performed the highest correlation coefficient with the biomass in compare to the narrow band of NDVI and transformed vegetation index (TVI). Moreover, Das & Singh (2012), studied biomass using field data and remotely sensed vegetation indices such as NDVI, RVI, OSAVI and MSAVI, to estimate AGB of the forest, and obtained a significant positive correlation with AGB in which RVI perform better with R^2 of 0.79. In this study, regardless of the low coefficient of determination between the vegetation indices and AGB, the standard RVI and RERVI perform the highest correlation with the estimated AGB for both rosemary and lavandin for the simple linear relationship. Generally, all the indices used show a significant correlation with the AGB of rosemary, but for the lavandin, only RERVI show a significant positive correlation with the AGB for the simple linear regression. The correlation of the relationship between the vegetation indices and AGB was influenced typically by the green herb that boosts the value of the vegetation indices in the fields.

Furthermore, the linear relation between the dry AGB and vegetation indices is mainly affected by the soil background and green herbs in the field. So, to minimize the effect of the factors such as herb cover, soil cover, elevation (DEM), and plant age were considered to perform a multiple linear regression model. Therefore, the best-selected models are the NDVI with the soil cover % and plant age perform better for rosemary, and the RERVI with the soil cover % performs better for lavandin. In which it shows R^2 of 0.60 and 0.69 with the AGB of rosemary and lavandin respectively. Generally, the multiple linear regression model for AGB estimation was improved the accuracy of all indices in comparison to the simple linear regression model.

The green herb cover in the field of rosemary and lavandin has an influence directly on the value of vegetation indices so that it affects the estimated AGB based on the vegetation indices. In this case, some of the plots were classified in the high value of indices (high vegetation density) even though the crop plant is very young and small (spares density) see Figure 4.9. This is due to; the crop fields fully accompanied by the dense herb cover.

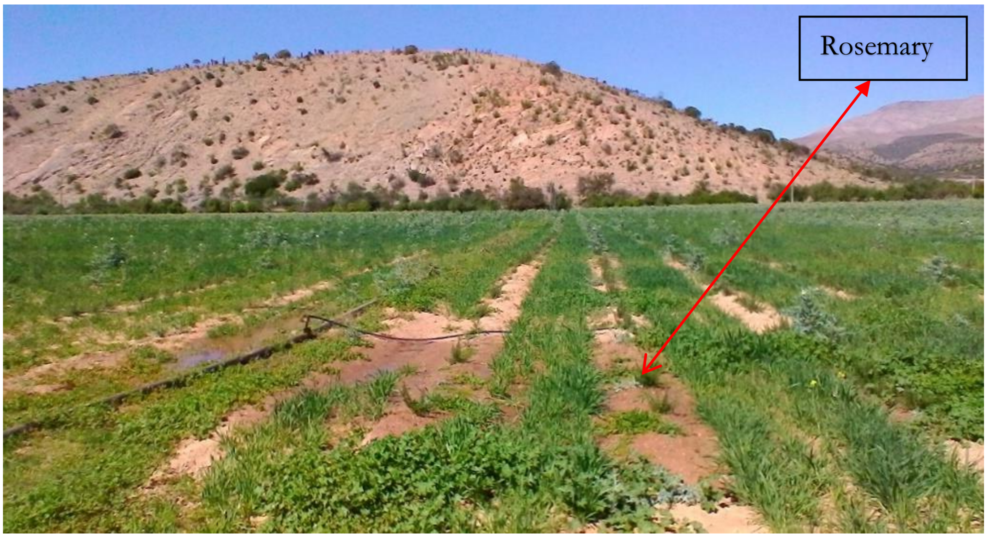

Figure 4-1. Plot A6 of the rosemary field that shows a dominant herb cover with very young rosemary.

Looking in the figure above it was shown with the dense vegetation cover in which it dominated with cover crops and other green herbs. But the rosemary plant is small and young. The NDVI value for this plot was 0.73 at the same time the real estimated AGB of the plot is 13.7 kg very low in comparison to plot B7 of farm B which comprises 146.4 kg/plot with the NDVI value of 0.66.

Remote sensing methods of agricultural monitoring have been developed to quantify the spatiotemporal dynamics of vegetation using the time series of vegetation indices (Suepa et al., 2016). Moreover, Biswal et al., (2013) stated that the normalized difference vegetation index is one of the most successful remotely sensed vegetation indices for land cover classification. It is also used as an important indicator to monitor the spatial and temporal dynamics of plant cover or vegetation density over time and issued for biomass estimation (Fung & Siu, 2000). The spectral profiles of vegetation clearly show that the peak reflectance can be found in the near-infrared wavelength due to the internal structure of green leaves and low at the red wavelength due to high absorption by the chlorophyll pigment (Biswal et al., 2013).

The time series NDVI profile shows the spatial and temporal growth trend of rosemary and lavandin. The spatial and temporal variation of the vegetation cover was identified using NDVI map, the value of NDVI time series, the mean NDVI time series and the standard deviation of the NDVI time series of the plots of rosemary and lavandin fields. The NDVI time series also shows the harvesting period to some extent even if it was affected by the non-harvestable part of the crops and the green herb be always there due to the irrigation system. Generally, the temporal profile of the mean NDVI shows the spatial and temporal variation of the rosemary within and between the plots of the fields over time.

The variability in the NDVI values within and between the plots of rosemary and lavandin fields through time could be affected by annual green herb cover, DEM, soil condition, irrigation type, management practice and the precipitations (rainfall). The spatial and temporal variation the crops within the plots of fields was shown from the NDVI time series profile but greatly influenced by the growing trend of the cover crops and other green herb vegetation cover which were growing in the fields. The green herb cover or cover crop were motivated to increase due to the precipitation and the irrigation system used. Moreover, the standard deviation in the NDVI values of plots of the farms showed the spatial and temporal variability of the vegetation density through time between and within the farms. As presented in Figure 3.16, the variation within and between the plots was higher in February, March and September due to higher precipitation see Figure 3.19. The harvesting period of the crops could be identified from the NDVI time series profile because most of the field has not yet harvested and the remained non-harvestable part of the crop plant, and irrigation system were also affecting the spatial, as well as the temporal variability of the sample plots and all crop fields in general, see Figure 3.14. It is difficult to identify the real spatial and temporal variation of crops in the plots as well as in the fields in general. This is due to the presence of dominant green herb cover in the fields. Generally, from my observation in the field the variability in the NDVI values (vegetation density) between the farms were mostly affected by the irrigation type, DEM and management practices.

4.3. The relevance of the study

The main aim of the this study was to find a good method for biomass estimation which could be cost-effective for monitoring of the crop plants of rosemary and lavandin. Based on the result of the study, Sentinel-2 satellite image derived VI's has the potential for crop biomass estimation. Additionally, the multispectral Sentinel-2 images having 13 bands including 3 Red-edge is available freely on the website of Copernicus Open Assess Hub. It also has a spatial resolution of 10 m which is higher in comparison to other medium resolution. The temporal resolution of 5 days also enables it to make a repeated measure for monitoring of the crops.

Moreover, the species-specific allometric equation developed is also a nice start for predicting the total AGB and yield of the crop plant in the study area. This will be used as a base and important beginning for monitoring the biomass and yield of rosemary and lavandin. The prediction of biomass and yield using the remote sensing and the allometric equation will be very important both for the farmers and stakeholders in Baviaanskloof and a productive base or reference for further study in the region. This a new explore for the study area. Because biomass estimation based on remote sensing and the allometric equation for lavandin and rosemary was never done before this study in that area. Therefore, both the allometric equation and remote sensing methods for biomass and yield prediction would be very important especially for the stakeholders in Baviaanskloof and the province of Eastern Cape in general.

4.4. Limitations and challenges of the study

Some of the farm's shapefiles were not actual rosemary and lavandin fields, in which the pest namely nematodes attacked two fields of lavandin and other two fields of rosemary were registered by mistake while they were grasslands. This caused the change of sample plots location to another field. The green herb cover grew in the field influence the vegetation indices values and as such influencing the estimated AGB. The field sample plot quadrants were shifted due to the accuracy of the GPS used. This brought some difficult to get the exact pixel of the plot of the crop plant sampled in the field. Thus, obliged to take the mean value of all the sounding pixels of 3×3 window. Time is a very critical factor for fieldwork to collect all the needed information. In that the crop fields were accompanied to a large extent by herb and soil cover, so to get a good estimation of these cover % in the ground it was a time-consuming activity.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study set out to explore and develop a good method for monitoring the biomass and production of rosemary and lavandin. This was done using the Sentinel-2 derived vegetation indices and field data. The result of the study shows that Sentinel-2 vegetation indices have a potential for biomass estimation which is comparable to other sensors. Furthermore, the simple linear model with the red-edge band improves the accuracy of the model for both rosemary and lavandin. Moreover, the relationship between the vegetation indices and AGB was fully affected by the green herb and cover crops were growing between the rows of the plantation. Therefore, a multiple linear regression model which consider the parameters of herb cover, soil cover, elevation and plant age was done. This improved the accuracy of the model in which the best model was developed with the NDVI, soil cover and plant age for rosemary and RERVI and soil cover for lavandin. Moreover, the spatial and temporal change in the vegetation cover of the plots was identified from the mean and standard values of AGB and NDVI time series profile. Additionally, the allometric equation for rosemary and lavandin was developed with an accuracy of greater than 0.92. It was developed as a mathematical relationship between the elliptical canopy area of the plants and measured AGB. The result obtained showed that power regression model was the best model used to estimate the dry AGB, which is very important for crop biomass monitoring and yield prediction without destructive sampling.

5.2. Recommendation

The result of this study contributes to the understanding of crop monitoring using remote sensing and field data. The following points are recommended for future studies:

- A more accurate GPS should be used for recording the coordinate of the plots to reduce the error so that the accuracy of the biomass estimation will improve.
- Future study should use Red-edge vegetation index in the case of dense vegetation cover rather than the standard vegetation indices.
- Since the cover crop or green herb and soil background were certainly affected the vegetation indices, future study should use other advanced method or technique (such as making sub-plots inside each plot using a fixed designed quadrant with digital vegetation cover estimation such as Canopeo) estimate herb and soil cover percent in the fields to minimize the effect of them.

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7. APPENDICES

1. Measured Fresh and Dried Biomass of Rosemary

Sn.no	Total fresh AGB biomass	Dry weight						
		Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Dry to fresh %**
1	592.6	324.1	225.7	220.3	218.5	218.5	218.5	**0.37**
2	3406.7	1635.9	1436.9	1432.5	1433.8	1434	1434	**0.42**
3	1689.6	798.4	741.9	741.9	742.6	741.3	741.3	**0.44**
4	174.5	70.7	68.4	67.5	68.9	68.2	68.2	**0.39**
5	554.8	251.1	249.1	247	249.4	247.8	247.8	**0.45**
6	37.1	12.5	12.5	11.6	12	11.5	11.5	**0.31**
7	84.1	28.3	27.4	27.1	27.5	27	27	**0.32**
8	348	98.6	101.2	101.8	102.5	102.2	102.2	**0.29**
9	377.8	131	112.7	109.9	112.5	112.1	112.1	**0.30**
10	2046.3	1109.4	1026.3	1009	1007.8	1007	1007	**0.49**
11	3023.8	1356.3	1262.6	1245.5	1246.8	1246.2	1246.2	**0.41**
12	525.5	243.2	237.7	235	236.1	235.7	235.7	**0.45**
13	1136.2	493.9	447.3	443.1	442.7	442.5	442.5	**0.39**
14	410.4	178	162.8	160.5	160.3	160.2	160.2	**0.39**
15	602.8	308.2	277.4	272.6	272.7	272.5	272.5	**0.45**
16	1269.8	605.2	506.5	499.6	498.9	498.9	498.9	**0.39**
17	292.3	127.9	122.9	121.4	121.1	121	121	**0.41**
18	1830.7	748.4	692.7	678.1	678.2	678.1	678.1	**0.37**
Total	**18,403.00**	**8,521.10**	**7,712.00**	**7,624.40**	**7,632.30**	**7,624.70**	**7,624.70**	
Average	**1022.39**	**473.39**	**428.44**	**423.58**	**424.02**	**423.59**	**423.59**	**0.40**

The total dry AGB of rosemary is 40 % of the total fresh AGB on average.

2. Measured Fresh and Dry Biomass of Lavandin

Sn.no	Total fresh biomass	Dry weight						
		Day 1	Day 2	Day 3	Day 4	Day 6	Day 6	Dry to fresh %
1	64.1	31.6	30.5	30.2	31	30.7	30.7	0.48
2	104	56.3	50.8	49.1	50	50.1	50.1	0.48
3	732.1	430	391.5	376.4	377	377.3	377.3	0.52
4	664.1	389.1	326.6	315	314.9	314.4	314.4	0.47
5	1342.5	734.7	677.5	667.5	668.3	667.9	667.9	0.50
6	587.6	288.9	266	262.6	260.6	260.6	260.6	0.44
7	97.7	40	37.4	36.7	37.7	37.6	37.6	0.38
8	334.6	166.4	144.5	141.9	144.5	144.6	144.6	0.43
9	684.8	356.3	320.4	312.9	312.6	312.5	312.5	0.46
10	312.9	148.3	142.7	138.9	138	137.7	137.7	0.44
11	382	235.8	194.5	181.1	180.5	180.6	180.6	0.47
12	92.6	39.8	39.3	38.8	38	38.2	38.2	0.41
Total	**5,399.00**	**2,917.20**	**2,621.70**	**2,551.10**	**2,553.10**	**2,552.20**	**2,552.20**	
Mean	**449.92**	**243.10**	**218.48**	**212.59**	**212.76**	**212.68**	**212.68**	**0.46**

3. Measured total fresh and dry AGB, canopy diameter, height, volume and area of rosemary

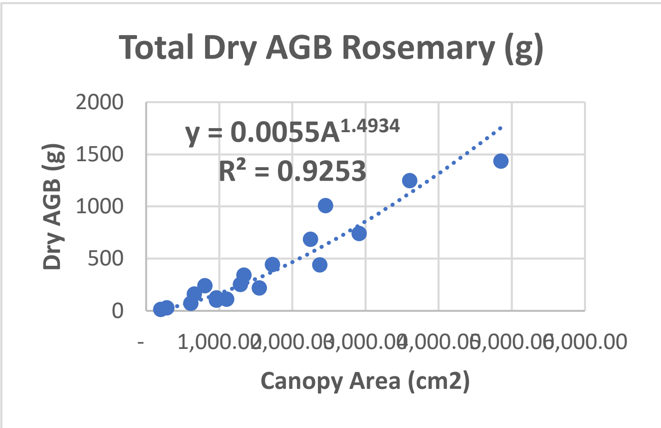
S. no	Diameter 1 (cm)	Diameter 2 (cm)	Height (cm)	Canopy Volume of Ellipse (cm^3)	Canopy Area of Ellipse (cm^2)	Total Fresh AGB (g)	Measured Total Dry AGB (g)	Estimated Total dry AGB (g)	Harvestable fresh AGB (g)	Harvestable dry (g)	Harvestable to Total AGB %	Measured dry leaves (g)	Dry leave to Harvestable %	Harvestable to Total ratio	Essential Oil from measured (g)
1	41	48	57	117,517.7	1,546.3	592.6	218.5	318.6	345	127	0.58	89.5	0.70	0.58	2.42
2	87	71	96	621,229.7	4,853.4	3406.7	1434	1,758.3	2458.6	980.1	0.68	529.9	0.54	0.72	17.21
3	65	57	60	232,885.7	2,911.1	1689.6	740.1	819.6	1158.3	466.7	0.63	305.9	0.66	0.69	8.11
4	30	26	47	38,405.7	612.9	174.5	71	80	96.3	35.7	0.50	26.5	0.74	0.55	0.67
5	40	41	50	85,904.8	1,288.6	554.8	250.8	242.7	340.9	141.5	0.56	95.6	0.68	0.61	2.39
6	17	15	20	5,342.9	200.4	37.1	11.3	15.1	0	0	0.00	0	0.00	0.00	0.00
7	20	18	23	8,674.3	282.9	84.1	27.8	25.2	0	0	0.00	0	0.00	0.00	0.00
8	34	36	30	38,468.6	961.7	348	102.6	156.8	251.3	71	0.69	53.3	0.75	0.72	1.76
9	40	35	30	44,000.00	1,100	377.8	110.7	191.6	267.3	74.3	0.67	64.3	0.87	0.71	1.87
10	52	60	65	212,457.1	2,451.4	2046.3	1006.8	634.1	1096	468.7	0.47	306.2	0.65	0.54	7.67
11	74	62	92	442,195.8	3,604.9	3023.8	1247.1	1,127.8	2069.5	773.6	0.62	418.3	0.54	0.68	14.49
12	30	34	50	53,428.6	801.4	525.5	239.1	119.4	248.9	96.9	0.41	70.2	0.72	0.47	1.74
13	50	44	75	172,857.1	1,728.6	1136.2	443.9	376.3	775.1	279.9	0.63	174.4	0.62	0.68	5.43
14	35	24	41	36,080	660	410.4	159.2	89.3	225.5	71	0.45	47.7	0.67	0.55	1.58
15	46	37	42	74,888	1,337.3	602.8	340.8	256.5	418.4	131.4	0.39	94.8	0.72	0.69	2.93
16	53	57	64	202,550.9	2,373.6	1269.8	439.1	604.2	830.2	291.2	0.66	189.1	0.65	0.65	5.81
17	36	34	34	43,597.7	961.7	292.3	121.7	156.8	180.8	61.4	0.50	44	0.72	0.62	1.27
18	54	53	62	185,893.7	2,248.71	1830.7	683.7	557.4	1067	337.6	0.49	228.3	0.68	0.58	7.47
Av	**44.7**	**41.8**	**52.1**	**145,354.4**	**1,662.5**	**1,022.4**	**424.9**	**418.3**	**657.2**	**244.9**	**0.50**	**152.1**	**0.61**	**0.56**	**4.6**
Sd	**17.9**	**15.9**	**21.7**	**161,581.9**	**1,223.2**	**1,002.5**	**437.5**	**462.7**	**695.6**	**274.1**	**0.20**	**151.0**	**0.23**	**0.22**	**4.9**

4. Measured total fresh and dry AGB, canopy diameter, height, volume and area of Lavandin

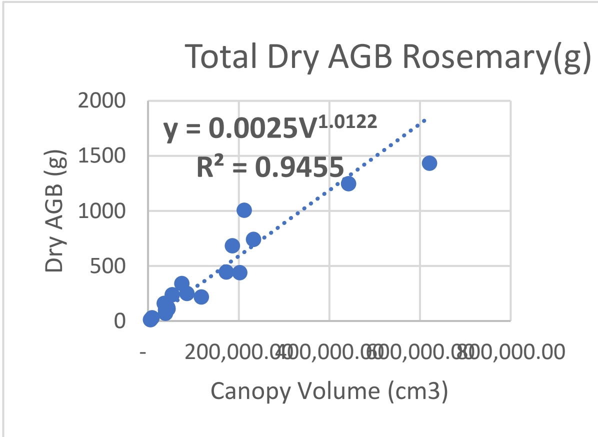
S.no	Diameter 1 (cm)	Diameter 2 (cm	Height (cm)	Canopy Volume of ellipse (cm3)	Canopy Area of ellipse (cm2)	Total Fresh Biomass (g)	Total Dry Biomass (g)	Dry to Fresh biomass ratio	Estimated Dry AGB
1	20	17	13	4,630.48	267.14	64.1	30.4	0.47	31.5
2	22	25	16	9,219.05	432.14	104	49.9	0.48	58.3
3	50	47	23	56,623.81	1,846.43	732.1	378.3	0.52	375.3
4	40	42	20	35,200.00	1,320.00	664.1	315.4	0.47	244.0
5	51	65	23	79,875.71	2,604.64	1,342.5	668	0.50	583.4
6	44	42	18	34,848.00	1,452.00	587.6	259.9	0.44	275.7
7	25	24	13	8,171.43	471.43	97.7	38.2	0.39	65.2
8	37	24	16	14,884.57	697.71	334.6	144	0.43	107.7
9	51	55	23	67,587.14	2,203.93	684.8	306.4	0.45	470.9
10	35	30	16	17,600.00	825.00	312.9	140.7	0.45	133.6
11	32	33	14	15,488.00	829.71	382	180	0.47	134.5
12	21	16	12	4,224.00	264.00	92.6	37.5	0.40	31.0
Average	**35.7**	**35**	**17.3**	**29,029.3**	**1,101.2**	**449.9**	**212.4**	**0.46**	**209.3**
SD	**11.8**	**15.4**	**4.1**	**26,037.8**	**783.7**	**375.8**	**187.8**	**0.04**	**183.4**

5. The scatterplot of the allometric equations of rosemary and lavandin.

(a)



(b)



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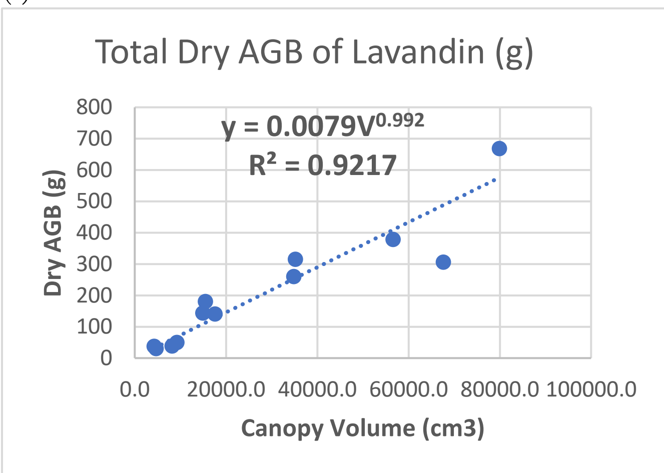
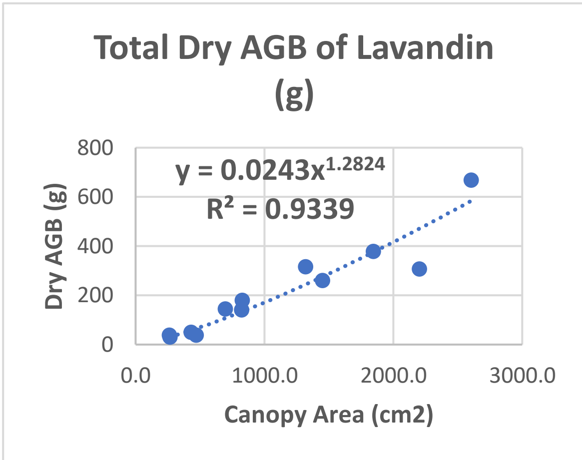


(d)



6. Total and harvestable fresh and dry AGB, VI-based Dry AGB, Dry leave and Essential oil of rosemary.

PlotID	Number of plant/plots	Estimated total fresh AGB (Kg/plot)	Estimated total dry AGB (kg/plot)	VI-based Estimated total dry AGB (kg/plot)	Estimated harvestable fresh AGB (Kg/plot)	Estimated Essential Oil (kg)	Allometric equation based harvestable dry AGB (kg/plot)	Estimated harvestable dry AGB as % of total AGB (kg/plot)	Estimated dry leave AGB (kg/plot)
A1	111	56.80	22.63	26.1	31.81	0.22	11.38	11.32	6.9
A2	125	59.22	23.5	40.6	33.16	0.23	11.55	11.75	7.2
A3	130	57.42	22.99	17.2	32.16	0.23	9.25	11.49	7.0
A4	85	18.17	6.88	35.8	10.18	0.07	-0.10	3.44	2.1
A5	106	161.63	68.97	52.7	90.51	0.63	38.25	34.48	21.0
A6	80	36.18	13.66	76.1	20.26	0.14	4.95	6.83	4.2
A7	147	49.38	18.86	63.4	27.65	0.19	8.31	9.43	5.8
B1	168	101.26	40.11	42.1	56.70	0.40	24.64	20.06	12.2
B2	210	85.25	33.18	31.2	47.74	0.33	16.20	16.59	10.1
B3	93	37.45	14.81	59.5	20.97	0.15	6.08	7.4	4.5
B4	164	159.04	65.94	70.3	89.06	0.62	37.77	32.97	20.1
B5	183	102.81	40.77	56.4	57.57	0.40	23.64	20.39	12.4
B6	170	137.60	55.14	81.5	77.06	0.54	36.79	27.57	16.8
B7	131	337.05	146.37	99.4	188.75	1.32	81.32	73.19	44.6
B8	180	216.90	89.24	92.1	121.46	0.85	58.19	44.62	27.2
C1	65	81.62	34.66	5.6	45.71	0.32	19.15	17.33	10.6
C2	57	65.97	27.23	9.5	36.94	0.26	17.19	13.61	8.3
C3	68	81.96	34.26	25.6	45.90	0.32	20.09	17.13	10.4
C4	77	59.06	23.8	38.9	33.07	0.23	14.90	11.9	7.3
C5	81	39.25	15.7	26.5	21.98	0.15	7.24	7.85	4.8
C6	80	71.29	28.88	22.6	39.93	0.28	18.73	14.44	8.8
C7	68	41.47	16.45	27.6	23.23	0.16	10.09	8.23	5.0
Average	**120**	**93.49**	**38.4**	**45.2**	**52.4**	**0.4**	**52.4**	**19.2**	**11.7**
SDV	**46**	**72.99**	**31.6**	**26.8**	**40.9**	**0.3**	**40.9**	**15.8**	**9.6**

7. **Upscaling the total harvestable and dry leave AGB of rosemary from plot level to per hectare and farm level**

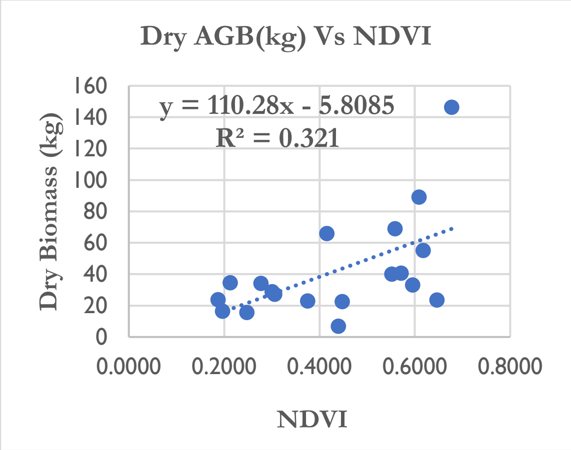
Farm ID	Average Harvestable AGB (kg/plot)	Average Harvestable AGB (kg/ha)	Total Harvestable AGB (kg/farm)	Average Dry Leave AGB (kg/ha)	Total Dry Leave AGB (kg/farm)
$A1_R$	14.50	1,449.50	6,783.66	884.5	19,809.5
$A2_R$	8.13	813.00	2,601.60	495.9	4,139.5
B_R	30.35	3,035.00	32,474.50	1,851.4	1,587
C_R	12.93	1,292.50	7,367.25	788.7	4,495.8
Average	**16.5**	**1,647.5**	**12,306.8**	**1,005.1**	**7,507.9**
STDEV	**9.6**	**963.8**	**13,611.7**	**587.9**	**8,302.7**

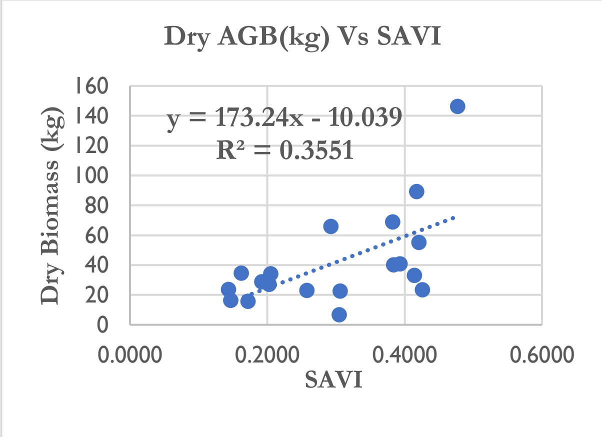
8. **Upscaling Essential Oil of rosemary from plot level to per hectare and farm level**

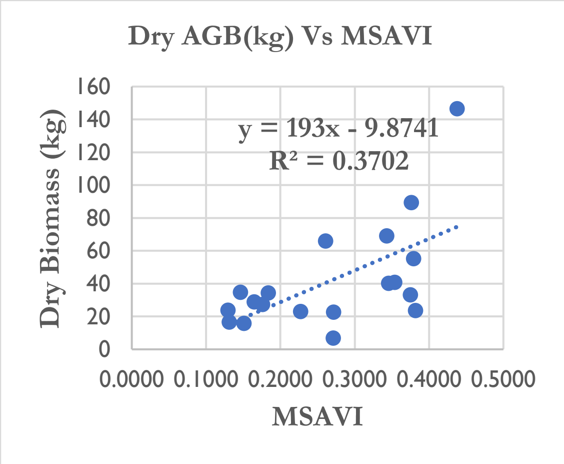
Farm ID	Number of plots	Area (ha)	Average Fresh Harvestable AGB (kg/plot)	Average Fresh Harvestable AGB (kg/ha)	Average Essential oil (kg/plot)	Average Essential oil (kg/ha)	Total Essential Oil (kg/farm)
BR	8	10.7	82.4	8,241	0.58	57.7	617.3
A1R	5	4.7	39.4	3,936	0.28	27.6	128.9
A2R	2	3.2	24	2,396	0.17	16.8	53.7
CR	7	5.7	35.3	3,525	0.25	24.7	140.7
Average			**45.2**	**4,525**	**0.3**	**31.7**	**235.1**
STDEV			**25.6**	**2,562**	**0.2**	**17.9**	**257.6**

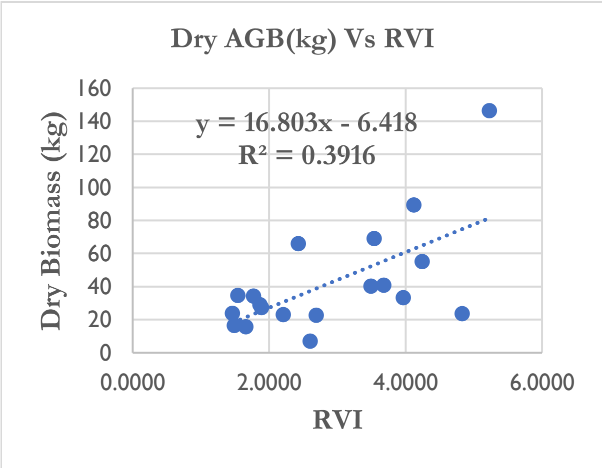
9. The scatterplots of linear relationship between Estimated AGB and VI's of Rosemary

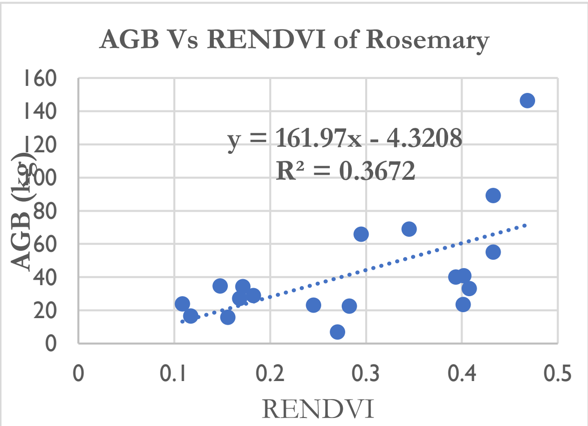
(A) Linear (B) linear

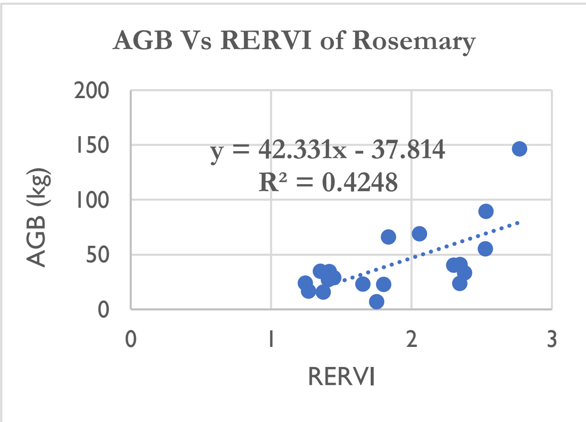






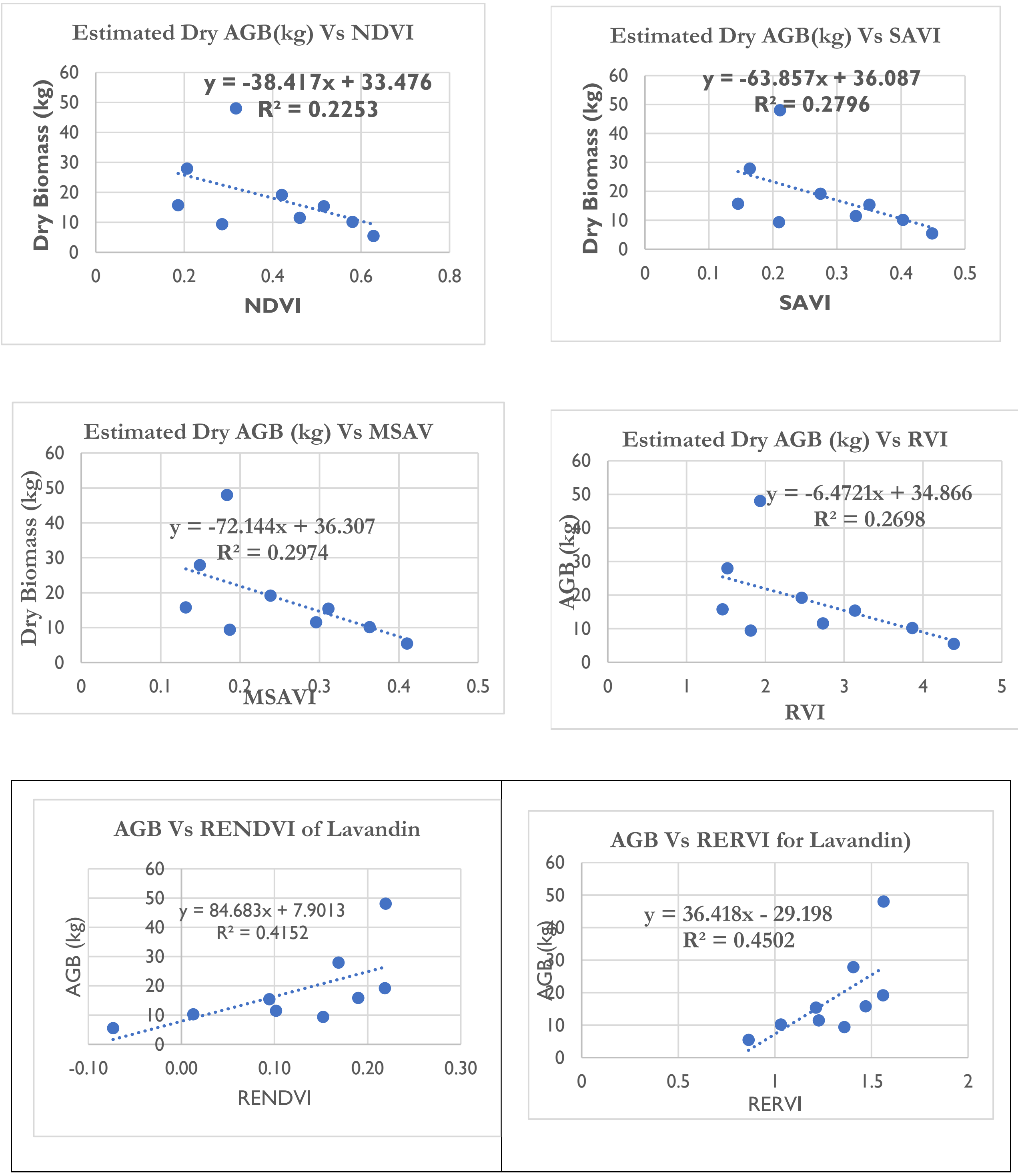




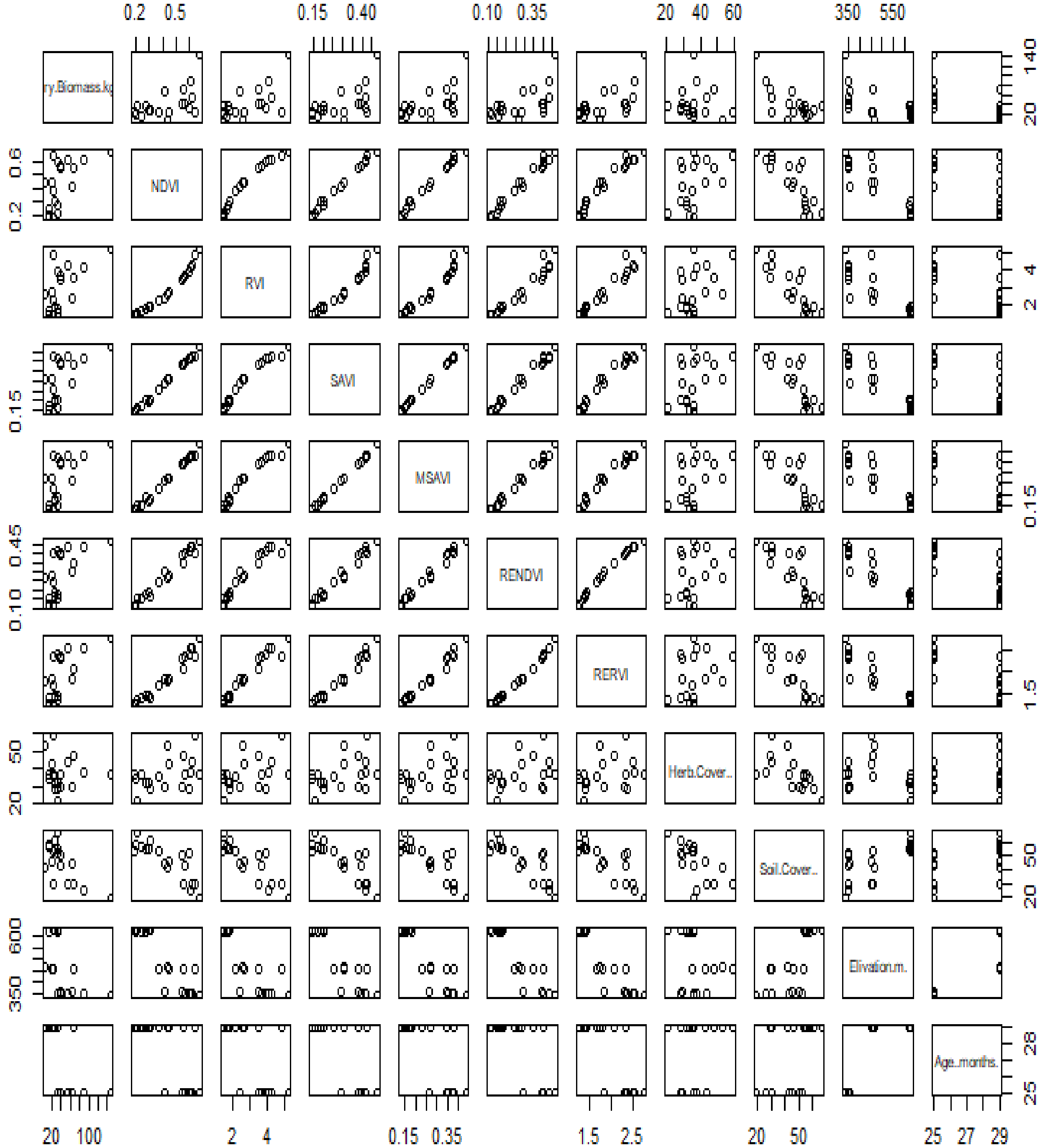


10. The scatterplots of the linear relationship between Estimated AGB and VI's of Lavandin

(A) Linear (B) Nonlinear



11. The scatterplot matrix of the response and explanatory variables in the field of rosemary.



12. Correlation matrices of response and explanatory variables.

Variables	Dry AGB	NDVI	RVI	SAVI	MSAVI	RENDVI	RERVI	HC %	SC %	Elevation	Age
Dry Biomass	1										
NDVI	0.57	1									
RVI	0.63	0.97	1								
SAVI	0.60	1.00	0.97	1							
MSAVI	0.61	0.99	0.98	1.00	1						
RENDVI	0.61	0.99	0.96	0.99	0.99	1					
RERVI	0.65	0.98	0.97	0.98	0.99	0.993	1				
Herb cover	-0.06	0.44	0.45	0.42	0.41	0.344	0.32	1			
Soil cover	-0.71	-0.83	-0.86	-0.83	-0.83	-0.806	-0.82	-0.63	1		
Elevation	-0.55	-0.89	-0.83	-0.91	-0.91	-0.933	-0.91	-0.22	0.69	1	
Age	-0.61	-0.67	-0.65	-0.70	-0.71	-0.764	-0.78	0.20	0.47	0.83	1

13. Multiple linear regression analyses between the Estimated AGB and VI's of rosemary

regr. model<-lm(c$Dry.Biomass.kg. ~ NDVI + Herb Cover + Soil Cover + Elevation + Age.)

The summary coefficients of the model

Source	Estimate	Std. Error	t value	Pr (>|t|)
Intercept	**2.136e+02**	**4.659e+01**	**4.586**	**0.000511 *** **
NDVI	**-9.904e+00**	**2.682e+01**	**-0.369**	**0.717820**
Herb cover	**-4.001e+00**	**3.420e-01**	**-11.696**	**2.84e-08 *** **
Soil cover	**-3.979e+00**	**2.551e-01**	**-15.600**	**8.50e-10 *** **
Elevation	**9.232e-04**	**3.938e-02**	**0.023**	**0.981653**
Age	**5.482e+00**	**2.101e+00**	**2.609**	**0.021614 * **

Residual standard error: 6.303 on 13 degrees of freedom
Multiple R-squared: **0.9731**
Adjusted R-squared: **0.9627**
F-statistic: 93.93 on 5 and 13 DF
p-value: **9.802e-10**

Analysis of Variance Table (ANOVA)

Source	DF	SS	MS	F-value	Pr(>F)
NDVI	**1**	6151.8	6151.8	154.8690	1.349e-08 ***
Herb cover	**1**	2300.3	2300.3	154.8690	3.850e-06 ***
Soil cover	**1**	9735.1	9735.1	245.0742	8.140e-10 ***
Elevation	**1**	198.7	198.7	5.0009	0.04349 *
Age	**1**	270.5	270.5	6.8094	0.02161 *
Residual	**13**	9735.1	39.7		

Variance inflation factor (vif)

NDVI	Herb. Cover.	Soil. Cover.	Elevation.	Age
9.16	4.46	5.19	10.65	7.86

The values of coefficient of determination and variance inflation factor (multicollinearity) of elevation is high with the other explanatory variables and herb cover has very low correlation with NDVI. So, they should be removed from the model. Additionally, the importance of the variable was also considered. Therefore, the model was determined with the explanatory variables of NDVI, soil cover and plant age.

AGB = NDVI + Soil cover % + Age

lm(formula = Dry.Biomass.kg. ~ NDVI + Soil cover + Age)

The summary coefficients of the model

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	452.69	126.50	3.58	0.00274 **
NDVI	-113.6025	63.6765	-1.784	0.09465.
Soil. Cover.	-2.2758	0.6749	-3.372	0.00419 **
Age	-9.3488	3.3882	-2.759	0.01461 *

Residual standard error: 20.61 on 15 degrees of freedom
Multiple R-squared: 0.6676,
Adjusted R-squared: 0.6011
F-statistic: 10.04 on 3 and 15 DF,
p-value: 0.0007043

Analysis of Variance Table (ANOVA)

	DF	SS	MS	F-value	Pr(>F)
NDVI	1	6146.8	6146.8	14.47	0.001729 **
Soil cover	1	3416.5	3416.5	8.04	0.012518 *
Age	1	3234.2	3234.2	7.61	0.014611 *
Residuals	15	6372.0	424.8		

The variance inflation factor of regression. model (VIF)

NDVI	Soil cover.	Age
4.83	**3.39**	**1.91**

Therefor the regression model of the rosemary crop plant is given as follow: -

AGB = 452.7 - 113.6*NDVI – 2.3*Soil Cover – 9.3*Age

Allometric and Vegetation index based AGB

PlotID	AGB based on allometric equation (kg)	AGB based on vegetation index (kg)
A1	22.6	26.1
A2	23.5	40.6
A3	23.0	17.2
A4	6.9	35.8
A5	69.0	52.7
B1	40.8	42.1
B2	33.2	31.2
B4	65.9	70.3
B5	40.8	56.4
B6	55.1	81.5
B7	146.4	99.4
B8	89.2	92.1
C1	34.7	5.6
C2	27.2	9.5
C3	34.3	25.6
C4	23.8	38.9
C5	15.7	26.5
C6	28.9	22.6
C7	16.5	27.6
Average	**42**	**42.2**
STDEV	**32.6**	**26.9**

Upscaling vegetation index based total dry AGB of rosemary to per hectare and farm level

Farm	Number of plots	Area (ha)	Average AGB (kg/plot)	Average Harvestable AGB (kg/ha)	Average Total AGB (kg/ha)	Total AGB (kg/farm)
A	5	4.68	39.1	1,955	3,910	18,298.8
B	8	10.70	67.6	3,380	6,760	72,332.0
C	7	5.70	19	950	1,900	10,830.0
Average			**41.9**	**2,095**	**4,190.0**	**33,820.3**
SD			**24.4**	**1,221.1**	**2,442.1**	**33,560.6**

Therefore, the influence of herb cover on the NDVI-based estimated AGB of rosemary is given below: - Analysis of Variance table for all variable

ANOVA

	df	SS	MS	F	Significance F
Regression	2	10243.68	5121.841	9.177867	0.002213
Residual	16	8929.03	558.0644		
Total	18	19172.71			

Analysis of Variance Table Without Herb cover

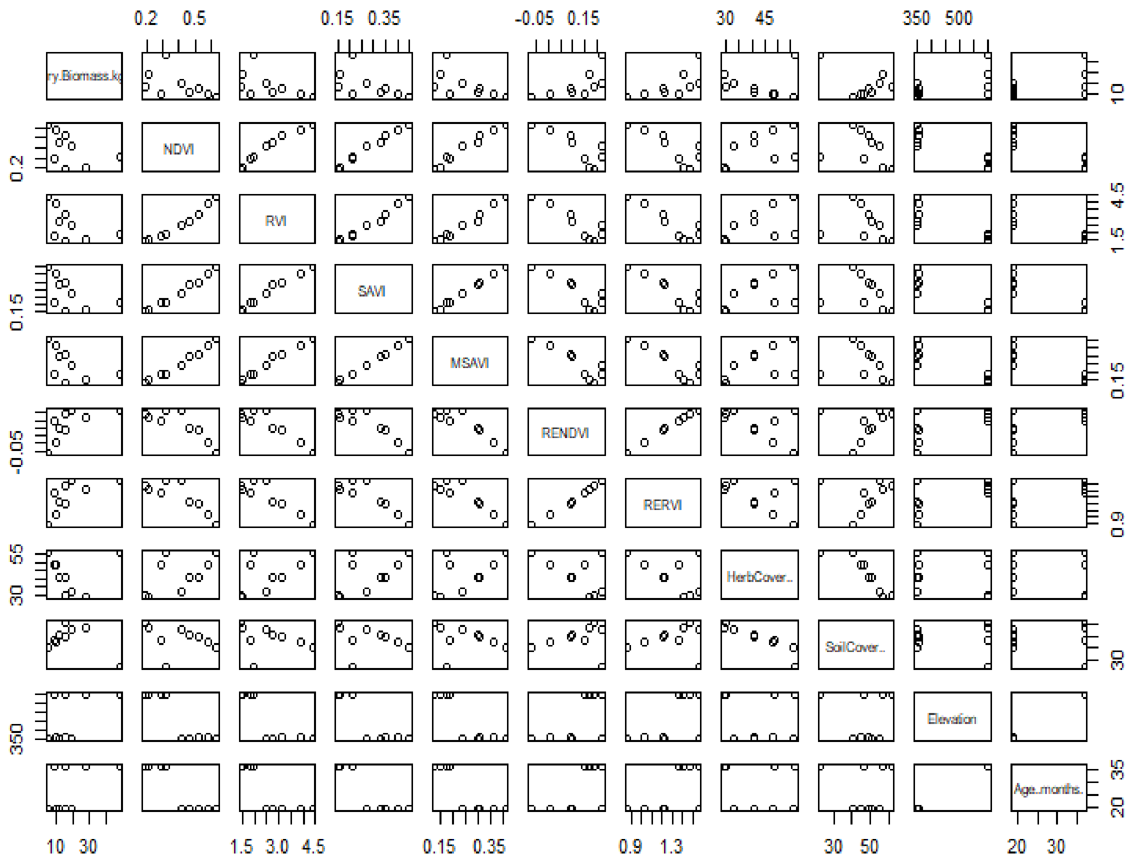
	df	SS	MS	F	Significance F
Regression	1	7508.708	7508.708	10.94376	0.004156
Residual	17	11664	686.1178		
Total	18	19172.71			

$$\text{Partial R2} = \frac{\text{SSR (with)} - \text{SSR (without)}}{\textbf{SSE (without)}}$$

Partial R2 = (10,243.7 – 7,508.7)/11,664
= 0.23

14. Multiple Linear regression analyses for the AGB of Lavandin

The scatterplot matrices of the explanatory variables



Correlation matrices of the response and explanatory variables of the model

Variables	Dry AGB	NDVI	RVI	SAVI	MSAVI	RENDVI	RERVI	Herb cover	Soil cover	Elevation	Age
Dry AGB	1										
NDVI	-0.47	1									
RVI	-0.54	0.99	1								
SAVI	-0.56	0.99	1.00	1							
MSAVI	-0.52	0.98	0.99	0.99	1						
RENDVI	0.65	-0.81	-0.87	-0.89	-0.90	1					
RERVI	0.67	-0.80	-0.86	-0.88	-0.88	1.00	1				
Herb cover	0.06	0.52	0.52	0.51	0.52	-0.48	-0.46	1			
Soil cover	-0.49	-0.28	-0.25	-0.23	-0.25	0.14	0.11	-0.89	1		
Elevation	0.52	-0.89	-0.87	-0.87	-0.83	0.60	0.59	-0.13	-0.06	1	
Age	0.53	-0.89	-0.87	-0.87	-0.83	0.60	0.60	-0.13	-0.06	1.00	1

formula = Dry.Biomass.kg. ~ NDVI + Soil cover. + Herb cover + Elevation + Age

The summary coefficients of the model

Source	Estimate	Std. Error	t value	Pr (>|t|)
Intercept	243.16825	19.15887	12.692	0.001055 **
RERVI	-4.57075	2.32803	-1.963	0.144379
Herb cover	-2.45798	0.07898	-31.122	7.29e-05 ***
Soil cover	-2.31578	0.09711	-23.848	0.000162 ***
Elevation	-0.12806	0.17106	-0.749	0.508417
Age	2.05957	2.41379	0.853	0.456230

Residual standard error: 0.7192 on 3 degrees of freedom
Multiple R-squared: 0.9988,
Adjusted R-squared: 0.9969
F-statistic: 519.2 on 5 and 3 DF,
p-value: 0.000133

Analysis of Variance Table (ANOVA)

Source	DF	SS	MS	F-value	Pr(>F)
RERVI	**1**	600.48	600.48	1161.037	5.557e-05 ***
Herb cover	**1**	432.50	432.50	836.248	9.080e-05 ***
Soil cover	**1**	281.48	281.48	544.247	0.0001725 ***
Elevation	**1**	27.88	27.88	53.900	0.0052218 **
Age	**1**	0.38	0.38	0.728	0.4562303
Residual	**3**	1.55	0.52		

Variance inflation factor (vif) of the model

RERVI	Soil Cover.	Herb Cover.	Elevation	Plant age
4.81297	12.40269	16.13427	8045.70920	8111.12417

The value of the correlation coefficient, the probability of significance and VIF for the explanatory variables of elevation and age of the plants is very high so, they should exclude from the model. So, the model is expressed as: -
AGB = NDVI + Herb cover % + Soil cover %

lm(formula = Dry.Biomass.kg. ~ NDVI + Herb cover. + Soil cover.)

The summary coefficients of the model

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	219.2655	32.7077	6.704	0.001118 **
RERVI	4.0956	6.2907	0.651	0.543744
Herb. Cover.	-2.3847	0.2635	-9.050	0.000275 ***
Soil. Cover.	-2.1848	0.3179	-6.872	0.000998 ***

Residual standard error: 2.442 on 5 degrees of freedom
Multiple R-squared: 0.9778,
Adjusted R-squared: 0.9645
F-statistic: 73.5 on 3 and 5 DF,
p-value: 0.0001479

Analysis of Variance Table for the response variable of Dry AGB

	DF	SS	MS	F-value	Pr(>F)
RERVI	1	600.48	600.48	100.736	0.0001680 ***
Herb cover	1	432.50	432.50	72.556	0.0003669 ***
Soil cover	1	281.48	281.48	47.221	0.0009981 ***
Residuals	5	29.80	5.96		

A variance inflation factor of the model

RERVI	Herb Cover.	Soil Cover.
3.049089	15.007	11.98

Herb cover has shown high multicollinearity with the explanatory variables of VI's and the soil cover. So, it was excluded from the model. Therefore, the model for lavandin biomass estimation is performed as a function of VI and the soil cover percent:

AGB = VI + Soil cover %

regr.model<-lm(Dry. Biomass ~RERVI + Soil Cover)

The summary coefficients of the model

	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	38.83	11.14	3.49	0.0131 *
RERVI	95.96	26.19	3.66	0.0105 *
Soil. Cover.	-0.68	0.23	-2.97	0.0249 *

Residual standard error: 7.237 on 6 degrees of freedom
Multiple R-squared: 0.7663,
Adjusted R-squared: 0.6883
F-statistic: 9.834 on 2 and 6 DF,
p-value: 0.01277

Analysis of Variance Table (ANOVA)

	DF	SS	MS	F-value	Pr(>F)
RERVI	1	600.48	600.48	11.5742	0.01446 *
Soil cover	1	432.50	432.50	8.3364	0.02779 *
Residuals	6	311.28	51.88		

Variance inflation factor (VIF)

RERVI	Soil Cover %
1.01	1.01

Therefore, the regression model is

$$\text{AGB} = 39.4 \times \text{RERVI} - 0.7 \times \text{Soil cover \%} - 2.1$$

AGB estimation based on the model of VI for lavandin

Plotid	Allometric equation based AGB (kg/plot)	Vegetation index based AGB (kg/plot)
A11	19.19	20.8
A12	15.4	10.9
A13	5.49	3.6
A14	11.53	10.5
A15	10.16	6.9
B11	15.76	12.7
B12	27.92	13.7
B13	48.02	43.4
B14	2.4	
B15	9.39	19.1
Average	**16.5**	**15.7**
STDEV	**13.0**	**11.7**

Upscaling vegetation indices based dry AGB of lavandin to per hectare and farm level

Farm	Number of plots	Area (ha)	Average number of plants/plots	Average AGB (kg/plot)	Average AGB (kg/ha)	Total AGB (kg/farm)
A_L	5	10.1	139	11.93	1,193	12,049.30
B_L	4	6.3	73	24.69	2,469	15,554.70
Average			**106**	**18.31**	**1,831**	**13,802**
STDEV			**47**	**9**	**902**	**2,478.7**

The influence of herb cover on the NDVI based AGB of lavandin is given below: -

Analysis of Variance Table for all variable

ANOVA

	df	SS	MS	F	Significance F
Regression	2	826.4077	413.2039	4.787511	0.05717
Residual	6	517.8523	86.30871		
Total	8	1344.26			

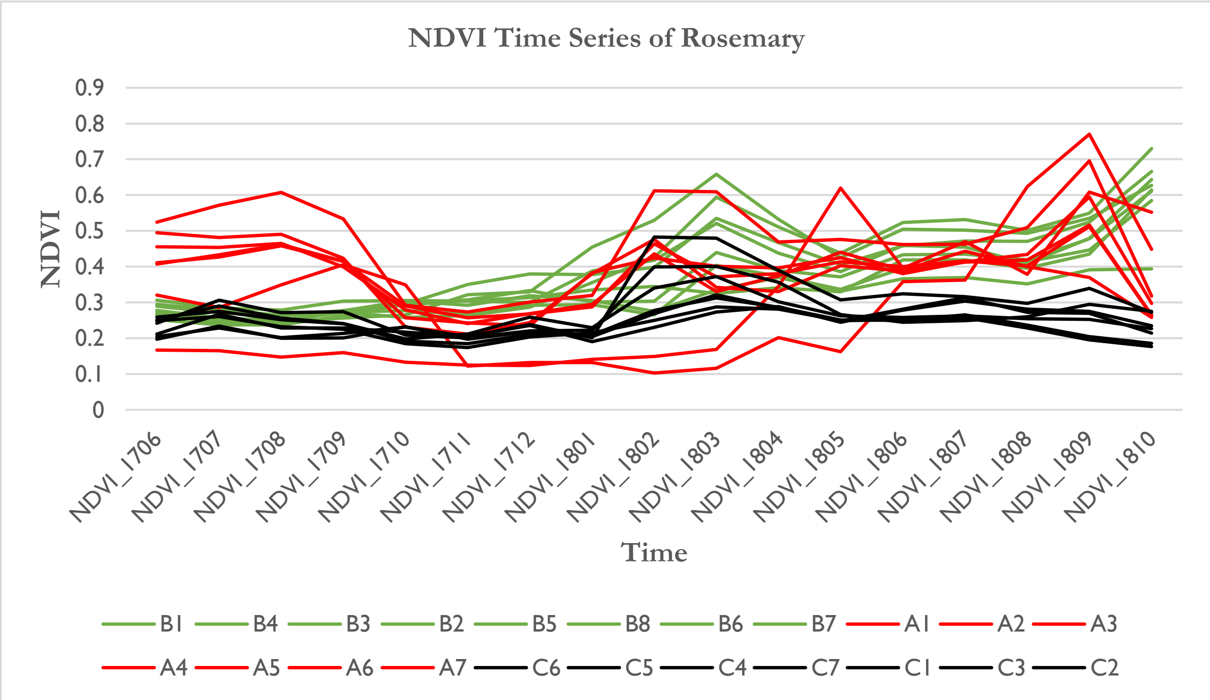
Analysis of Variance Table Without Herb cover

ANOVA

	df	SS	MS	F	Significance F
Regression	1	605.1555	605.1555	5.73138	0.047884
Residual	7	739.1045	105.5864		
Total	8	1344.26			

15. Temporal variation within and between the plots of rosemary and lavandin

NDVI temporal profile of rosemary of each plot



NDVI temporal profile of lavandin of each plot