

**Environmental change and soil organic carbon storage in a dust  
emission hotspot, Free State, South Africa**

**by**

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## **Table of Contents**

|                                                                                  |              |
|----------------------------------------------------------------------------------|--------------|
| <b>List of Figures.....</b>                                                      | <b>x</b>     |
| <b>List of Tables .....</b>                                                      | <b>xvii</b>  |
| <b>List of Symbols .....</b>                                                     | <b>xviii</b> |
| <b>Abbreviations .....</b>                                                       | <b>xix</b>   |
| <b>Declaration.....</b>                                                          | <b>xxi</b>   |
| <b>Acknowledgements .....</b>                                                    | <b>xxii</b>  |
| <b>Abstract.....</b>                                                             | <b>xxiii</b> |
| <b>Chapter 1: General introduction.....</b>                                      | <b>1</b>     |
| <b>1.1 Background to the study.....</b>                                          | <b>1</b>     |
| <b>1.1.1 Agricultural practices.....</b>                                         | <b>1</b>     |
| <b>1.1.2 Atmospheric Dust and Soil Loss.....</b>                                 | <b>4</b>     |
| <b>1.1.3 Land cover or land use.....</b>                                         | <b>7</b>     |
| <b>1.1.4 Climate change.....</b>                                                 | <b>10</b>    |
| <b>1.1.5 Ecosystem services.....</b>                                             | <b>12</b>    |
| <b>1.2 Problem Statement.....</b>                                                | <b>15</b>    |
| <b>1.3 Rationale of the study .....</b>                                          | <b>18</b>    |
| <b>1.4 Selection of study site and description of soil sampling points .....</b> | <b>19</b>    |
| <b>1.4.1 Description of study area.....</b>                                      | <b>19</b>    |
| <b>1.4.2 Climate.....</b>                                                        | <b>20</b>    |
| <b>1.4.3 Geology and soils .....</b>                                             | <b>21</b>    |
| <b>1.4.4 Land cover or Land uses.....</b>                                        | <b>22</b>    |
| <b>1.4.5 Vegetation.....</b>                                                     | <b>23</b>    |
| <b>Site 1: Grassland.....</b>                                                    | <b>24</b>    |
| <b>Site 2: Cultivated land.....</b>                                              | <b>26</b>    |
| <b>Site 3: Grassland.....</b>                                                    | <b>27</b>    |
| <b>Site 4: Cultivated land.....</b>                                              | <b>28</b>    |

|                                                                                                                           |    |
|---------------------------------------------------------------------------------------------------------------------------|----|
| Site 5: Grassland.....                                                                                                    | 29 |
| 1.5 Outline of the research.....                                                                                          | 32 |
| Chapter 2: Examining the changes in land cover or land use .....                                                          | 33 |
| 2.1. Significance of the chapter .....                                                                                    | 33 |
| 2.2 Aim.....                                                                                                              | 33 |
| 2.3 Objectives .....                                                                                                      | 34 |
| 2.4 Background to the study.....                                                                                          | 34 |
| 2.5 Literature review .....                                                                                               | 36 |
| 2.5.1 Summarized studies about impact of LCLU changes .....                                                               | 37 |
| 2.5.2 Dust Bowl.....                                                                                                      | 39 |
| 2.6 Methodology .....                                                                                                     | 42 |
| 2.6.1 Data collection.....                                                                                                | 42 |
| 2.6.1.1 LCLU data.....                                                                                                    | 42 |
| 2.6.1.2 MODIS EVI data .....                                                                                              | 43 |
| 2.6.1.3 Land cover and Crop data.....                                                                                     | 43 |
| 2.6.2 Data analysis .....                                                                                                 | 43 |
| 2.7 Results .....                                                                                                         | 44 |
| 2.7.1 Introduction .....                                                                                                  | 44 |
| 2.7.2 Spatial and temporal variation of LCLU in relation to dust.....                                                     | 45 |
| 2.7.3 MODIS enhanced vegetation index (EVI) time series for the different sites of the start of a dust in 2006-2016. .... | 51 |
| 2.7.4 Spatial and temporal variation of crop and land cover types in relation to dust .....                               | 57 |
| 2.7.5: Total percentage of crop and land cover around each dust event in Free State .....                                 | 64 |
| 2.7.6: Dust sources area composition .....                                                                                | 66 |
| 2.8 Discussion.....                                                                                                       | 68 |
| 2.8.1 Spatial and temporal changes of LC and their impact in dust production.....                                         | 68 |



|                                                                                          |           |
|------------------------------------------------------------------------------------------|-----------|
| 2.8.2 Role of vegetation in the occurrence of dust .....                                 | 69        |
| 2.8.3 Role of crop and land cover type in the occurrence of dust .....                   | 70        |
| 2.9 Conclusion.....                                                                      | 72        |
| <b>Chapter 3: Climate constraints and mitigations to Free State crop production.....</b> | <b>75</b> |
| 3.1 Significance of the chapter .....                                                    | 75        |
| 3.2 Aim.....                                                                             | 75        |
| 3.3 Objectives.....                                                                      | 76        |
| 3.4 Background to the study.....                                                         | 76        |
| 3.5 Literature review.....                                                               | 80        |
| 3.5.1 Likely impact of climate change on agricultural activities .....                   | 81        |
| 3.6 Methodology .....                                                                    | 85        |
| 3.6.1 Data collection.....                                                               | 85        |
| 3.6.1.1 Automatic weather station data .....                                             | 86        |
| 3.6.1.2 ARC rainfall data .....                                                          | 87        |
| 3.6.1.3 CHIRPS data .....                                                                | 88        |
| 3.6.1.4 Standardized Precipitation Evapotranspiration Index (SPEI) .....                 | 88        |
| 3.6.1.5 ARC temperature data.....                                                        | 89        |
| 3.6.1.6 ARC and ERA5 wind data.....                                                      | 90        |
| 3.6.1.7 ARC Reference Evapotranspiration (ET <sub>0</sub> ) data .....                   | 91        |
| 3.6.2 Data analysis .....                                                                | 91        |
| 3.6.2.1 Examining the shift on the onset of rainfall .....                               | 92        |
| 3.6.2.2 Temperature data .....                                                           | 92        |
| 3.6.2.3 ARC and ERA5 wind speed data .....                                               | 93        |
| 3.7 Results .....                                                                        | 93        |
| 3.7.1 Introduction .....                                                                 | 93        |
| 3.7.2 Seasonality of rainfall.....                                                       | 93        |
| 3.7.2.1 ARC rainfall data and CHIRPS data .....                                          | 93        |

|                                                                                           |     |
|-------------------------------------------------------------------------------------------|-----|
| 3.7.3 Drought.....                                                                        | 101 |
| 3.7.4 Timing of rain .....                                                                | 105 |
| 3.7.4.1 The shift on the onset of rainfall in Free State.....                             | 105 |
| 3.7.4.2 Trend on the onset of rainfall from 1981-2019 in Bultfontein.....                 | 112 |
| 3.7.4.3 Trend on the onset of rainfall from 1981-2019 in Hoopstad.....                    | 112 |
| 3.7.4.4 Trend on the onset of rainfall from 1981-2019 in Wesselsbron .....                | 113 |
| 3.7.4.5 Trend on the onset of rainfall from 1981-2019 in Wolmaranstad .....               | 113 |
| 3.7.4.6 Testing whether each decade is dependent on the other decade in Bultfontein ..... | 115 |
| 3.7.4.7 Testing whether each decade is dependent on the other decade in Hoopstad .....    | 115 |
| 3.7.4.8 Testing whether each decade is dependent on the other decade in Wesselsbron ..... | 115 |
| 3.7.4.9 Testing whether each decade is dependent on the other decade in Wolmaranstad..... | 116 |
| 3.7.5 Temperature variation .....                                                         | 116 |
| 3.7.6 Frost variation.....                                                                | 120 |
| 3.7.7 Wind speed data .....                                                               | 125 |
| 3.7.7.1 Daily average wind speed variation .....                                          | 125 |
| 3.7.7.2 Monthly average wind speed variation.....                                         | 126 |
| 3.7.7.3 Daily maximum wind speed variation .....                                          | 127 |
| 3.7.7.4 Monthly maximum wind speed variation.....                                         | 127 |
| 3.7.7.5 Total monthly wind run variation.....                                             | 128 |
| 3.7.7.6 Total number of hours with wind greater than 6 m/s per month .....                | 129 |
| 3.7.8 Evapotranspiration (ET <sub>O</sub> ) data .....                                    | 130 |
| 3.7.8.1 Relationship between wind speed and evapotranspiration (ET <sub>O</sub> ) .....   | 131 |
| 3.8 Discussion.....                                                                       | 134 |
| 3.8.1 Determining climate constraints to crop production .....                            | 134 |

|                                                                                   |     |
|-----------------------------------------------------------------------------------|-----|
| 3.8.2 Temperature variation and impact of frost in Free State crop production ... | 136 |
| 3.8.3 Impact of wind to the occurrence of dust in western Free State .....        | 137 |
| 3.9 Conclusion.....                                                               | 138 |
| Chapter 4: Soil Organic Carbon storage .....                                      | 141 |
| 4.1 Significance of the study .....                                               | 141 |
| 4.2 Aim.....                                                                      | 141 |
| 4.3 Objectives.....                                                               | 142 |
| 4.4 Background to the study.....                                                  | 142 |
| 4.5 Literature review.....                                                        | 145 |
| 4.5.1 Carbon cycle in grassland and cultivated land .....                         | 145 |
| 4.5.2 Biogeochemical models.....                                                  | 147 |
| 4.5.2.1 BIOME-BGC model.....                                                      | 148 |
| 4.5.2.2 PnET model.....                                                           | 149 |
| 4.5.2.3 DAYCENT carbon model.....                                                 | 149 |
| 4.5.2 Summarized studies about SOC and DAYCENT Carbon model.....                  | 152 |
| 4.6 Methodology .....                                                             | 154 |
| 4.6.1 Selection of sampling points.....                                           | 154 |
| 4.6.2 Data collection.....                                                        | 155 |
| 4.6.2.1 Materials.....                                                            | 155 |
| 4.6.2.2 Methods .....                                                             | 155 |
| 4.6.3 Soil analysis .....                                                         | 159 |
| 4.6.3.1 Total soil organic carbon (SOC) and nitrogen.....                         | 159 |
| 4.6.3.2 Texture analysis .....                                                    | 160 |
| 4.6.3.2.1 The Malvern Mastersizer 2000.....                                       | 161 |
| 4.6.3.2.2 Gradistat Analysis .....                                                | 162 |
| 4.6.3.3 Land management options.....                                              | 162 |
| 4.6.3.3.1 Bulk density.....                                                       | 162 |

|                                                                                                                                                                              |             |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| 4.6.3.3.2 pH analysis .....                                                                                                                                                  | 163         |
| 4.6.3.3.3 DAYCENT Carbon model set up.....                                                                                                                                   | 163         |
| 4.6.3.3.4 Schedule files description.....                                                                                                                                    | 166         |
| <b>4.7 Results .....</b>                                                                                                                                                     | <b>171</b>  |
| 4.7.1 Introduction .....                                                                                                                                                     | 171         |
| 4.7.2 SOC and nitrogen .....                                                                                                                                                 | 172         |
| 4.7.2.1 Soil organic carbon isotopes .....                                                                                                                                   | 175         |
| 4.7.3 Soil texture and grain size distribution .....                                                                                                                         | 177         |
| 4.7.4 Land management options.....                                                                                                                                           | 180         |
| 4.7.4.1 DAYCENT and MODIS PsnNet .....                                                                                                                                       | 182         |
| <b>4.8 Discussion.....</b>                                                                                                                                                   | <b>190</b>  |
| 4.8.1 Factors contributing to the storage and distribution of SOC.....                                                                                                       | 190         |
| 4.8.2 Establishing suitable land management options for storing more carbon.....                                                                                             | 191         |
| <b>4.9 Conclusion.....</b>                                                                                                                                                   | <b>192</b>  |
| <b>Chapter 5: Synopsis of the study, overall conclusion, and recommendations .....</b>                                                                                       | <b>195</b>  |
| 5.1 Synopsis of the study .....                                                                                                                                              | 195         |
| 5.2 Overall conclusion .....                                                                                                                                                 | 199         |
| 5.3 Recommendations .....                                                                                                                                                    | 206         |
| <b>References.....</b>                                                                                                                                                       | <b>xxiv</b> |
| Appendix 2.1: Example of Java script used to extract MODIS EVI for dust sources .....                                                                                        | xliii       |
| Appendix 2.2: Summary table of the growth conditions, as reflected by the EVI, for the sites of dust storm events during 2006-2016.....                                      | xliv        |
| Appendix 2.3: Spatial and temporal variation of crop and land cover types and dust sources in Free State from 2006-2016.....                                                 | lii         |
| Appendix 2.4: Crop and land cover spatial and temporal variation, dust points and weather stations from 2006 – 2016 zoomed into the western part of Free State Province..... | liv         |
| Appendix 2.5: Dust sources area composition in 2006 in the Free State Province.....                                                                                          | lvi         |
| Appendix 2.6: Dust sources area composition in 2007 in the Free State Province.....                                                                                          | lviii       |

|                                                                                                                                           |         |
|-------------------------------------------------------------------------------------------------------------------------------------------|---------|
| Appendix 2.7: Dust sources area composition in 2013-2014 in the Free State Province .....                                                 | lx      |
| Appendix 2.8: Dust sources area composition in 2014-2015 in the Free State Province ....                                                  | lxi     |
| Appendix 2.9: Dust sources area composition in 2015-2016 in the Free State Province ..                                                    | lxii    |
| Appendix 2.10: Dust sources area composition in 2016 in the Free State Province.....                                                      | lxv     |
| Appendix 3.1: Example of Java script used to extract CHIRPS for weather stations.....                                                     | lxix    |
| Appendix 3.2: Trend in ARC annual rainfall (a) Bultfontein, (b) Hoopstad, (c) Wesselsbron<br>and (d) Wolmaranstad. ....                   | lxx     |
| Appendix 3.3: Trend in CHIRPS annual rainfall (a) Bultfontein, (b) Hoopstad, (c)<br>Wesselsbron and (d) Wolmaranstad.....                 | lxxi    |
| Appendix 3.4: Total monthly rainfall from 2005-2016 in Bultfontein station: CHIRPS vs<br>ARC.....                                         | lxxii   |
| Appendix 3.5: Total monthly rainfall from 2003-2016 in Hoopstad station: CHIRPS vs ARC<br>.....                                           | lxxiv   |
| Appendix 3.6: Total monthly rainfall from 2004-2016 in Wesselsbron station: CHIRPS vs<br>ARC.....                                         | lxxvi   |
| Appendix 3.7: Total monthly rainfall from 2007-2016 in Wolmaranstad station: CHIRPS vs<br>ARC.....                                        | lxxviii |
| Appendix 3.8: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall<br>season from 1981-1990 Bultfontein.....   | lxxix   |
| Appendix 3.9: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall<br>season from 1991-2000 Bultfontein.....   | lxxx    |
| Appendix 3.10: Number of rainfall events greater or equal to 15 mm/ day in Free State<br>rainfall season from 2001-2010 Bultfontein ..... | lxxx    |
| Appendix 3.11: Number of rainfall events greater or equal to 15 mm/ day in Free State<br>rainfall season from 2011-2019 Bultfontein ..... | lxxxi   |
| Appendix 3.12: Number of rainfall events greater or equal to 15 mm/ day in Free State<br>rainfall season from 1981-1990 Hoopstad .....    | lxxxii  |
| Appendix 3.13: Number of rainfall events greater or equal to 15 mm/ day in Free State<br>rainfall season from 1991-2000 Hoopstad .....    | lxxxii  |

|                                                                                                                                         |          |
|-----------------------------------------------------------------------------------------------------------------------------------------|----------|
| Appendix 3.14: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Hoopstad .....     | lxxxii   |
| Appendix 3.15: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Hoopstad .....     | lxxxiii  |
| Appendix 3.16: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Wesselsbron .....  | lxxxiii  |
| Appendix 3.17: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Wesselsbron .....  | lxxxiv   |
| Appendix 3.18: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Wesselsbron .....  | lxxxiv   |
| Appendix 3.19: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Wesselsbron .....  | lxxxv    |
| Appendix 3.20: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Wolmaranstad ..... | lxxxv    |
| Appendix 3.21: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Wolmaranstad ..... | lxxxvi   |
| Appendix 3.22: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Wolmaranstad ..... | lxxxvi   |
| Appendix 3.23: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Wolmaranstad ..... | lxxxvii  |
| Appendix 3.24: Trend on the onset of rainfall in Bultfontein (1981-2019).....                                                           | lxxxvii  |
| Appendix 3.25: Trend on the onset of rainfall in Hoopstad (1981-2019).....                                                              | lxxxviii |
| Appendix 3.26: Trend on the onset of rainfall in Wesselsbron (1981-2019).....                                                           | lxxxviii |
| Appendix 3.27: Trend on the onset of rainfall in Wolmaranstad (1981-2019).....                                                          | lxxxix   |
| Appendix 3.28: Total number of frost hours per month .....                                                                              | xc       |
| Appendix 3.29: ERA5 daily maximum wind speed in a series of four weather stations in Free State, South Africa .....                     | xcvi     |
| Appendix 3.30: ERA5 monthly maximum wind speed in a series of four weather stations in Free State, South Africa .....                   | xcvi     |

|                                                                                                                                                   |        |
|---------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Appendix 3.31: ERA5 daily average wind speed in a series of four weather stations in Free State, South Africa .....                               | xcvii  |
| Appendix 3.32: ERA5 monthly average wind speed in a series of four weather stations in Free State, South Africa .....                             | xcvii  |
| Appendix 3.33: ERA5 total monthly wind run in a series of four weather stations in Free State, South Africa .....                                 | xcviii |
| Appendix 3.34: ERA5 monthly number of hours with wind greater than 6 m/s from a series of four weather stations in Free State, South Africa ..... | xcviii |
| Appendix 4.1: Carbon and nitrogen stored in cultivated land and grassland sites with different soil types.....                                    | xcix   |
| Appendix 4.2: Schedule files .....                                                                                                                | c      |

## List of Figures

|                                                                                                                                                                                                                                                                                                                                                                                                                           |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.1: Hourly diurnal weather observations for 17 of the 75 event days within 25 km of image plumes, with windspeed ( $\text{m s}^{-1}$ ) (A), relative humidity (%) (B) and temperature (degrees C) (C) in Free State. Depicted are cold fronts (CF) in solid lines and stationary troughs (ST) dashed lines as well as intermediates (CF/ST) dashed and solid (Eckardt et al., 2020)....                           | 6  |
| Figure 1.2: Types of ecosystem services (Arico et al., n.d.). The diagram summarizes the four ecosystem services and how they link to human well-being. ....                                                                                                                                                                                                                                                              | 12 |
| Figure 1.3: Thesis overview flow diagram .....                                                                                                                                                                                                                                                                                                                                                                            | 17 |
| Figure 1.3: Location of study area in South Africa. The focus of the study is Bultfontein area, which is the western part of Free State, South Africa. Red dots are dust sources from MSG data in (Eckardt et al., 2020) paper. Western part of Free State is the hotspot of dust sources and is dominated by false karoo, pure grassveld, and bushveld. Data extracted from Agricultural Research Council database. .... | 20 |
| Figure 1.4: Free State soil types (FAO-UNESCO Soil map of the world, no date). Map shows the five major dominating soils in Free State. Black dots are dust sources from MSG data in (Eckardt et al., 2020) paper.....                                                                                                                                                                                                    | 22 |
| Figure 1.5: Free State Land cover or Land uses. Map shows the land cover or land use in the entire Free State. Cultivated land and grassland covers most parts. Western part of Free State is dominated by dust source areas, cultivation, and grassland. Data extracted from Agricultural Research Council database. ....                                                                                                | 23 |
| Figure 1.6: Photographs showing vegetation type within Bultfontein area. Left image showing grassland and right image showing cultivated land and associated moving sand and wind erosion.....                                                                                                                                                                                                                            | 24 |
| Figure 1.7: Grassland soil sampling site 1 in Bultfontein, Free State. Image taken in September 2019.....                                                                                                                                                                                                                                                                                                                 | 25 |
| Figure 1.8: Cultivated land soil sampling site 2 in Bultfontein, Free State. Image taken in September 2019. ....                                                                                                                                                                                                                                                                                                          | 26 |
| Figure 1.9: Grassland soil sampling site 3 in Bultfontein, Free State. Image taken in September 2019.....                                                                                                                                                                                                                                                                                                                 | 28 |
| Figure 1.10: Cultivated land soil sampling site 4 in Bultfontein, Free State. Image taken in September 2019. ....                                                                                                                                                                                                                                                                                                         | 29 |



|                                                                                                                                                                                                                                                                                                                                                  |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1.11: Grassland soil sampling site 5 in Bultfontein, Free State. Left image where soil samples taken and right image where biomass measurements taken. Images taken in September 2019.....                                                                                                                                                | 30 |
| Figure 1.12: Grassland soil sampling site 6 in Bultfontein, Free State. Image taken in September 2019.....                                                                                                                                                                                                                                       | 31 |
| Figure 2.1: LCLU of the Free State Province in 2000. Data extracted from Agricultural Research Council database. Red LC is cultivated land and green is grassland. ....                                                                                                                                                                          | 46 |
| Figure 2.2: LCLU of the Free State Province in 2013-2014. Data extracted from Agricultural Research Council database. Red land cover is cultivated land and green is grassland. ....                                                                                                                                                             | 47 |
| Figure 2.3: LCLU of the Free State Province in 2000 focused on the main dust emission area. Data extracted from Agricultural Research Council database. Red is the cultivated land and green is grassland. Yellow dots represent dust sources from 2006-2016. ....                                                                               | 49 |
| Figure 2.4: LCLU of the Free State Province in 2013-2014 focused on the main dust emission area. Data extracted from Agricultural Research Council database. Red is the cultivated land; light blue is low shrubland and green is grassland. Black dots represent dust sources from 2006-2016.....                                               | 50 |
| Figure 2.5: Example of a dust event (red arrow) in 29 Aug 2006 (top) and 01 Nov 2016 (bottom), showing the date of the dust event along the EVI time series for the MODIS pixel. ....                                                                                                                                                            | 52 |
| Figure 2.6: MODIS enhanced vegetation index (EVI) time series for the site of the start of a dust cloud (red square) on 29 Aug 2006 (top) and 01 Nov 2016 (bottom) for the MODIS pixel. ....                                                                                                                                                     | 54 |
| Figure 2.7: Total number of dust events per month in Free State from 2006-2017 (Eckardt et al., 2020). ....                                                                                                                                                                                                                                      | 55 |
| Figure 2.8: Normalized Difference Vegetation Index (NDVI) time series from the Global Agriculture Monitoring (GLAM) project using MOD09 8-day product and applying a Landsat-derived crop extraction mask for the Free State. Comparing the wettest year 2011 and driest years 2015 and 2016 with the average during the observation period..... | 56 |
| Figure 2.9: Crop and land cover type spatial variation and dust points in 2006 (wet year) in the entire Free State. Data extracted from Department of Agriculture, Forestry and Fisheries database.....                                                                                                                                          | 58 |
| Figure 2.10: Crop and land cover type spatial variation and dust points in 2016 (dry year) in the entire Free State. Data extracted from Department of Agriculture, Forestry and Fisheries database.....                                                                                                                                         | 59 |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                  |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.11: Total amount of hectares covered by different crop and land cover types in the entire Free State from 2006-2016. There is a variation of crop and land cover amount from each year, generally pasture has increased from 2006-2016, maize has also increased, fallow land has decreased, and other crop and land cover types have remained low. Data extracted from Department of Agriculture, Forestry and Fisheries database..... | 60 |
| Figure 2.12: Crop and land cover spatial variation, dust points and weather stations in 2006 (wet year) focused into the western part of Free State. The square boarder line demarcates the main dust emission area. 10 km buffer around each dust source was created to identify crop and land cover types around each dust source. Data extracted from Department of Agriculture, Forestry and Fisheries database. ....                        | 61 |
| Figure 2.13: Crop and land cover spatial variation, dust points and weather stations in 2016 (dry year) focused into the western part of Free State. The square boarder line demarcates the main dust emission area. 10 km buffer around each dust source was created to identify crop and land cover types around each dust source. Data extracted from Department of Agriculture, Forestry and Fisheries database. ....                        | 62 |
| Figure 2.14: Total percentage of crop and land cover around each dust event with a 10 km radius from 2006-2016. Data extracted from Department of Agriculture, Forestry and Fisheries database.....                                                                                                                                                                                                                                              | 65 |
| Figure 2.15: Total amount of hectares covered by different crop and land cover types in dust source areas in Free State from 2006-2016. Fallow land, maize and pasture covered most of the land compared to other crop types. ....                                                                                                                                                                                                               | 67 |
| Figure 3.1: Annual minimum (a) and maximum (b) temperature anomalies (°C) for Namaqualand (1901–2009) based on the CRU TS 3.1 data set. Positive (red) and negative (blue) anomalies in temperature with respect to the long-term average climatology (1961–1990 mean). The black line shows the 5-year moving average (Davis et al., 2016). ....                                                                                                | 78 |
| Figure 3.2: Location of Agricultural Research Council weather stations in Free State. ....                                                                                                                                                                                                                                                                                                                                                       | 87 |
| Figure 3.3: Monthly number of rain days from a series of four ARC weather stations in Free State, South Africa. Data obtained from ARC database. ....                                                                                                                                                                                                                                                                                            | 94 |
| Figure 3.4: Comparison between measured ARC annual rainfall and estimated CHIRPS annual rainfall for (a) Bultfontein, (b) Hoopstad, (c) Wesselsbron and (d) Wolmaranstad. ....                                                                                                                                                                                                                                                                   | 95 |
| Figure 3.5: Total annual and average rainfall from CHIRPS and a series of four ARC weather stations in Free State, South Africa. The grey line is the annual average for CHIRPS and orange line is the annual average for ARC. ....                                                                                                                                                                                                              | 97 |

|                                                                                                                                                                                                                                                        |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 3.6: Rainfall anomalies from CHIRPS a series of four ARC weather stations in Free State, South Africa. ....                                                                                                                                     | 99  |
| Figure 3.7: Total monthly rainfall from CHIRPS and a series of four ARC weather stations in Free State, South Africa.....                                                                                                                              | 100 |
| Figure 3.8: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 3, bottom left = SPEI 12 and bottom right = SPEI 48 in Bultfontein. Graphs showing years with no drought to years with severe drought. ....        | 102 |
| Figure 3.9: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = .....)                                                                                                                                                  | 103 |
| Figure 3.10: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = .....)                                                                                                                                                 | 104 |
| Figure 3.11: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 12, and bottom left = SPEI 48 in Wolmaranstad. Graphs showing years with no drought to years with severe drought. ....                            | 105 |
| Figure 3.12: Number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations in September (top) and October (bottom), Free State (1981-2019).....                                                                        | 109 |
| Figure 3.13: Number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations in November (top) and December (bottom), Free State (1981-2019). ....                                                                       | 110 |
| Figure 3.14: Number of rainfall events greater or equal to 15 mm/day from 1981-2019 in a series of four weather stations.....                                                                                                                          | 111 |
| Figure 3.15: Trend on the onset of rainfall in in a series of four weather stations in Free State (1981-2019). Graph showing variation on the onset of rainfall in different years. Trendlines shows that the onset of rainfall is becoming late. .... | 114 |
| Figure 3.16: Daily average temperature from a series of weather stations in Free State, South Africa. Red circle shows the day that had the maximum temperature throughout the studied period. Data extracted from ARC database. ....                  | 117 |
| Figure 3.17: Monthly average temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database. ....                                                                                                         | 118 |
| Figure 3.18: Monthly maximum temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database. ....                                                                                                         | 119 |
| Figure 3.19: Monthly minimum temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database. ....                                                                                                         | 120 |

|                                                                                                                                                                                                                                                                                  |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 3.20: Total number of frost hours per month in a series of four ARC weather stations in Free State. Frost hours are observed from April- September. There are no frost hours observed from October- March. Data extracted in ARC database.....                            | 121 |
| Figure 3.21: Total number of frost hours per year in a series of four weather stations in Free State. Graphs showing the variation on the number of frost hours over the years. Trendlines illustrate that number of frost hours are decreasing. ....                            | 122 |
| Figure 3.22: Total number of frost hours per year in April Bultfontein (top left), Hoopstad (top rights), Wesselsbron (bottom left) and Wolmaranstad (bottom right). In Bultfontein only 3 years had frost in April, 1 in Hoopstad, 4 in Wesselsbron and 2 in Wolmaranstad. .... | 123 |
| Figure 3.23: Total number of frost hours per year in May Bultfontein (top left), Hoopstad (top rights), Wesselsbron (bottom left) and Wolmaranstad (bottom right). In Bultfontein 9 years had frost in May, 4 in Hoopstad, 7 in Wesselsbron and 6 in Wolmaranstad.....           | 124 |
| Figure 3.24: Onset of frost in a series of four weather station in Free State. Data starts from 2005 in Bultfontein, 2003 in Hoopstad, 2004 in Wesselsbron and 2007 in Wolmaranstad. Graphs showing the onset of frost is becoming late. ....                                    | 125 |
| Figure 3.25: Daily average wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa.....                                                                                                                                                   | 126 |
| Figure 3.26: Monthly average wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa .....                                                                                                                                                | 126 |
| Figure 3.27: Daily maximum wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa .....                                                                                                                                                  | 127 |
| Figure 3.28: Monthly maximum wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa .....                                                                                                                                                | 128 |
| Figure 3.29: Total monthly wind run from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa.....                                                                                                                                                     | 129 |
| Figure 3.30: Monthly number of hours with wind greater than 6 m/s from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa.....                                                                                                                       | 129 |
| Figure 3.31: Total evapotranspiration (ET <sub>0</sub> ) in Bultfontein station daily (top left), monthly (top right) and annually (bottom left) .....                                                                                                                           | 130 |
| Figure 3.32: Relationship between monthly ARC ET <sub>0</sub> and monthly ERA5 wind speed (left) and relationship between monthly ARC ET <sub>0</sub> and monthly ARC wind speed (right) in Bultfontein. ET is increasing with increasing wind speed.....                        | 131 |
| Figure 3.33: ERA5 monthly average wind speed (left) and ARC total monthly ET <sub>0</sub> (right) in crop and dry season in Bultfontein. ....                                                                                                                                    | 132 |

|                                                                                                                                                                                                                                                                                                                                                                                         |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 3.34: Relationship between ERA5 wind speed and ARC ET0 in a crop season (top left), relationship between ARC wind speed and ARC ET0 in crop season (top right), relationship between ERA5 wind speed and ARC ET0 in a dry season (bottom left), relationship between ARC wind speed and ARC ET0 in a dry season (bottom right) in Bultfontein.....                               | 133 |
| Figure 3.35: Relationship between ERA5 and ARC monthly wind speed in Bultfontein. There is a positive linear relationship between ERA5 and ARC monthly average wind speed. ....                                                                                                                                                                                                         | 134 |
| Figure 4.1: Carbon cycle (Scoltock, 2013). Diagram showing the movement of carbon in the ecosystem.....                                                                                                                                                                                                                                                                                 | 146 |
| Figure 4.2: Digging soil at different range of layers using an auger. Picture taken in September 2019.....                                                                                                                                                                                                                                                                              | 156 |
| Figure 4.3: Air drying collected soil samples for ~ 10 minutes. Picture taken in September 2019 .....                                                                                                                                                                                                                                                                                   | 156 |
| Figure 4.4: Measuring bulk density. Both pictures showing the procedure to get the bulk density soil sample. Picture taken in September 2019 .....                                                                                                                                                                                                                                      | 157 |
| Figure 4.5: Measuring grassland biomass using disk pasture meter. Picture taken in September 2019.....                                                                                                                                                                                                                                                                                  | 158 |
| Figure 4.6: Process of removing carbonates in the soil samples using HCl. Pictures taken in October 2019.....                                                                                                                                                                                                                                                                           | 160 |
| Figure 4.7: Measuring the grain sizes distribution using Malvern Mastersizer 2000. Both pictures showing the process of measuring grain size. Pictures taken in November 2019. ..                                                                                                                                                                                                       | 161 |
| Figure 4.8: Amount of Carbon and nitrogen stored in cultivated land and grassland sites with different soil types Arenosols cultivated land 1 (AR CL1), Luvisols cultivated land 2 (LU CL2), Arenosols grassland 1 (AR GL1), Calcisol grassland 2 (CA GL2), Luvisols grassland 3 (LU GL3), and Lixisol grassland 4 (LI GL4). Top graph showing carbon and bottom showing nitrogen ..... | 173 |
| Figure 4.9: Amount of carbon and nitrogen content in cultivated and grassland sites.....                                                                                                                                                                                                                                                                                                | 174 |
| Figure 4.10: Amount of carbon and nitrogen in different soil types under cultivated and native grasslands.....                                                                                                                                                                                                                                                                          | 175 |
| Figure 4.11: Standard corrected delta carbon 13 ( $^{13}\text{C}$ ) and carbon 12 ( $^{12}\text{C}$ ) in different soil sites .....                                                                                                                                                                                                                                                     | 176 |
| Figure 4.12: Relationship between the standard corrected delta $^{13}\text{C} / ^{12}\text{C}$ and C:N ratio in soil samples with different soil types, Bultfontein, Free State .....                                                                                                                                                                                                   | 177 |
| Figure 4.13: Grain size distribution in cultivated and grassland sites with different soil types. ....                                                                                                                                                                                                                                                                                  | 178 |

|                                                                                                                                                                                                                         |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 4.14: Sand silt clay diagram for different soil types at different sampling sites in Free State.....                                                                                                             | 179 |
| Figure 4.15: Sand, silt, and clay ratios in different soil types of Bultfontein .....                                                                                                                                   | 180 |
| Figure 4.16: Net primary production of grassland with and without herbivory in four different soil types and CHIRPS data from 2001-2020 in Free State, South Africa .....                                               | 183 |
| Figure 4.17: Net primary production of cultivated land with herbivory in two different soil types and CHIRPS data from 2001-2020 in Free State, South Africa.....                                                       | 184 |
| Figure 4.18: Net primary production of grassland with and without herbivory in four different soil types; Arenosols (AR), Calcisol (CA), Lixisol (LI) and Luvisols (LU) in 2019 .....                                   | 188 |
| Figure 4.19: Net primary production of cultivated land with herbivory in two different soil types; Arenosols (AR) and Luvisols (LU) in 2019.....                                                                        | 189 |
| Figure 4.20: Distribution of fine root biomass across the different soil depths in different soil types; Arenosols grassland (AR-GRASS), Calcisol grassland (CA-GRASS), Luvisols (LU-GRASS) and Lixisol (LI-GRASS)..... | 190 |

## List of Tables

|                                                                                                                                                                                                                                                           |     |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Table 1.1: Location of soil sampling sites in Free State, South Africa. ....                                                                                                                                                                              | 24  |
| Table 2.1: Summary of the data contained in LCLU maps. Table shows the number of hectares covered by each LC. Data obtained from Agricultural Research Council database.....                                                                              | 48  |
| Table 2.2: Summary of the data contained in LCLU maps around the main dust emission area. Table shows the number of hectares covered by each land cover in the western area of Free State. Data obtained from Agricultural Research Council database..... | 51  |
| Table 2.3: Spatial detail of how big each crop and land cover type around a 10 km buffer around dust sources in 2006. Data extracted from Department of Agriculture, Forestry and Fisheries database.....                                                 | 63  |
| Table 2.4: Spatial detail of how big each crop and land cover type around a 10 km buffer around dust sources in 2016. Data extracted from Department of Agriculture, Forestry and Fisheries database.....                                                 | 64  |
| Table 3.1: Summary of data required to achieve each objective .....                                                                                                                                                                                       | 85  |
| Table 3.2: Agricultural Research Council weather stations in Free State .....                                                                                                                                                                             | 86  |
| Table 3.3: Descriptive statistics of annual ARC and annual CHIRPS rainfall in a series of four weather stations.....                                                                                                                                      | 98  |
| Table 3.4: Descriptive statistics of CHIRPS and ARC rainfall in 2007 in a series of four weather stations .....                                                                                                                                           | 101 |
| Table 3.5: Total number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations per decade from 1981-2019 .....                                                                                                            | 112 |
| Table 4.1: Summary of biogeochemical models.....                                                                                                                                                                                                          | 150 |
| Table 4.2: Summary of how DAYCENT model was set up for each land management scenario in different soil types .....                                                                                                                                        | 164 |
| Table 4.3: Summary of soil types under two management options.....                                                                                                                                                                                        | 181 |
| Table 4.4: Predicted annual dry matter production (g DM m <sup>-2</sup> /year) using canopy cover and DPM method.....                                                                                                                                     | 185 |

## List of Symbols

|                      |                    |
|----------------------|--------------------|
| $^{12}\text{C}$      | Carbon 12          |
| $^{13}\text{C}$      | Carbon 13          |
| C                    | Carbon             |
| $\text{CaCO}_3$      | Calcium carbonate  |
| $\text{CH}_4$        | Methane            |
| $\text{CO}_2$        | Carbon dioxide     |
| HCl                  | Hydrochloric acid  |
| KCl                  | Potassium chloride |
| N                    | Nitrogen           |
| $\text{N}_2\text{O}$ | Nitrous Oxide      |
| $\text{NO}_3$        | Nitrate            |
| $\text{O}_3$         | Ozone              |
| $\mu\text{m}$        | Micrometre         |



## Abbreviations

|                 |                                                     |
|-----------------|-----------------------------------------------------|
| AGB             | Above ground biomass                                |
| AO              | Artic Oscillation                                   |
| AR              | Arenosols                                           |
| ARC             | Agricultural Research Council                       |
| CA              | Calcisols                                           |
| CCD             | Cold Cloud Duration                                 |
| CHIRPS          | Climate Hazard Infrared Precipitation with Stations |
| CSA             | Climate Smart Agriculture                           |
| DAFF            | Department of Agriculture, Forestry and Fisheries   |
| DOY             | Julian day of year                                  |
| DPM             | Disk Pasture Meter                                  |
| ECMWF           | European Centre for Medium-range Weather Forecasts  |
| ET              | Evapotranspiration                                  |
| ET <sub>0</sub> | Reference Evapotranspiration                        |
| EVI             | Enhanced Vegetation Index                           |
| GCMs            | Global Climate Models                               |
| GEE             | Google Earth Engine                                 |
| GHG             | Greenhouse gases                                    |
| GMO             | Genetically modified organisms                      |
| IPCC            | Intergovernmental Panel on Climate Change           |
| KNZ             | Konza tall grass                                    |

|       |                                                     |
|-------|-----------------------------------------------------|
| LAI   | Leaf Area Index                                     |
| LCLU  | Land cover or Land Use                              |
| LI    | Lixisols                                            |
| LU    | Luvisols                                            |
| MODIS | Moderate Resolution Imaging Spectroradiometer       |
| MSG   | Meteosat 2 <sup>nd</sup> generation                 |
| NAO   | North Atlantic Oscillation                          |
| NDVI  | Normalised Difference Vegetation Index              |
| NMR   | Nuclear Magnetic Resonance                          |
| NPP   | Net Primary Production                              |
| PET   | Potential Evapotranspiration                        |
| RA    | Regenerative Agriculture                            |
| RCMs  | Regional Climate Models                             |
| SOC   | Soil Organic Carbon                                 |
| SOM   | Soil Organic Matter                                 |
| SPEI  | Standardised Precipitation Evapotranspiration Index |
| VI    | Vegetation Index                                    |

## Declaration

I Nolusindiso Ndara declare that ***Environmental change and soil organic carbon storage in a dust emission hotspot, Free State, South Africa*** is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

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## **Dedication**

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## Abstract

Drylands farming areas are subject to land cover or land use change, climate change, and a variety of land management practices which may contribute to dust emissions and soil loss, a common symptom of land degradation. The goal of this study was to establish how the shift in land cover or land use change affects the occurrence of dust and determine the climate constraints and mitigations to crop production with focus on the dustiest parts of South Africa in the Free State. Moreover, the study wished to establish land management strategies suitable for enhancing the storage of soil organic carbon and associated ecosystem services.

To investigate how the shift in land cover or land use affects the occurrence of dust from 2006-2016, the study firstly identified the spatial and temporal changes of land cover (LC) using the 2000 and 2013-2014 land cover maps derived from Agricultural Research Council. The results showed that grassland is still dominating in 2013-2014 but has decreased by 22 % from 2000. Cultivated land on the other hand has increased by 26 % from 2000 to 2013-2014. Some of the changes seen in recent data might also be the result of the associated data products. The change is however continuous and significant as major LC changes occurred over long-time scales. Cultivated land and grassland are dominant land cover and cultivated land is substantially being used to meet the economic demand (international maize price).

Moderate Resolution Imaging Spectroradiometer Enhanced Vegetation Index (MODIS EVI) was used to assess vegetation cover for the site of the start of dust. MODIS EVI indicated that vegetation plays a significant role during the occurrence of atmospheric dust. Sparse vegetation (EVI ranging from 0 – 0.18) is directly proportional to dust production. Dust events were generally observed in cultivated land especially in 2015 and 2016. Moreover, findings showed that vegetation is not solely a factor that affects dust production; rainfall, temperature and wind speed also contribute. Crop and land cover data obtained from Department of Agriculture, Forestry and Fisheries (DAFF) identified the dominating crop and land cover around each dust source as fallow land, maize fields, and pasture. For instance, dust source August 29<sup>th</sup> 2006 had 11533 ha of fallow land and 10795 ha of maize, and dust source September 15<sup>th</sup> 2016 had 7737 ha of fallow land and 4599 ha of pasture which suggest that dust does not exclusively depend on the amount of vegetation but also on the type of vegetation.

To achieve the second aim, the study used data from Climate Hazard Infrared Precipitation with Stations (CHIRPS), Agricultural Research Council (ARC) and Standardised Precipitation

Evapotranspiration Index (SPEI) to determine the variation of rainfall in Free State. SPEI data showed that drought is becoming prominent and severe in Free State (2005, 2012, 2014 and 2016). ARC data showed a slight increase (357-408 mm/year) from two stations and a slight decrease from the other two stations in rainfall from 2005- 2016 and CHIRPS data showed a slight decrease (458-404 mm/year) from all the stations during the same period. Both CHIRPS and ARC data showed that there is a seasonal shift on the onset of rainfall; rainfall has shifted to late summer by approximately 62 days on average from 1981-2019 in Free State. Rainfall in Free State is becoming late (e.g., in 2011 rainfall adequate to make the soil moist was received in November) and number of rain events are decreasing (e.g., September 1981-2019 had 7 rainfall events greater or equal to 15 mm/day, 19 events in October, 52 events in November and 33 in December in Bultfontein weather station).

This study used temperature data from ARC weather stations to determine how temperature and frost variation affect crop production in Free State. Findings indicated that temperatures have increased by  $\sim 1-2^{\circ}\text{C}$  in Free State and frost has decreased, and its onset has shifted by  $\sim 11$  days. Frost occurred in Julian day of the year (DOY) 144 in 2005 and in 2016 there was no frost for the whole year in Bultfontein. The onset of frost is shifting to May and resulting to frost period decreased over the years. Decrease in frost is an advantage for crops that are planted in late summer, however increased temperatures are likely to result in crop failure, especially if rainfall is also low. Furthermore, the relationship between wind speed and dust occurrence was determined using the ARC and ERA5 datasets. The results showed that some years were characterised by high winds and some by low winds but generally there is no constant trend. The ARC maximum wind speed was 10 - 15 m/s and ERA5 maximum wind speed was 10 m/s. Both datasets showed that high wind speed occurs from August- November and many dust events are observed in these months. Additionally, high winds are mostly observed to occur on surfaces with sparse vegetation and in the absence of wind breaks which further promotes an increase in dust. Thus, it is important for farmers to leave crop residues after harvesting and practice moderate grazing.

To achieve the third aim, the study further established land management strategies suitable for enhancing the storage of soil organic carbon. Soils sampled in 2019 from different sites in Free State were used to determine the amount of carbon and nitrogen. It is apparent that grassland can store more carbon especially in the Lixisols which appeared to have stored an average carbon of 1.23 g and maximum of 1.86 g from 0-2 cm to 20-30 cm depths. Moreover, cultivated land can store less carbon especially in the Arenosols which stored an average of 0.18 g and

maximum of 0.22 g from 0-2 cm to 30-45 cm depths. Findings suggest that grassland can store more carbon than cultivated land due to minimal disturbance of the land when compared to cultivated sites. Moreover, the study demonstrated that soil texture and grain size distribution play an additional role in carbon storage with higher loads linked to higher silt content (Lixisols) and less carbon being stored in soils with high sand content (Arenosols). More carbon was observed to be stored in soils with moderate sand content (Lixisols = 40 % of sand) and high silt content (54 %) and less carbon was stored in soils with high sand content (Arenosols = 80 % of sand) and moderate silt content (18 %). More carbon was shown to be stored in the top layers of the soil 5-10 cm and was observed to decrease with increasing depth. DAYCENT carbon model was further used to simulate soil carbon in different land management scenarios to come up with suitable land management options for storing more carbon in future. Results illustrated that native grassland can substantially store more carbon than cultivated land, however moderate grazing should be applied. This would allow for a reduction of future dust emissions and increase ecosystem services in the cultivated lands of the Free State. Overall, the study demonstrated that combining the investigation of LCLU, climate change and land management was important to better understand land degradation and identified possible mitigation measures.

**Keywords:** Climate change, DAYCENT carbon model, Free State, Land cover/ Land use, soil carbon, South Africa

## **Chapter 1: General introduction**

### **1.1 Background to the study**

Agricultural practices, soil losses as part of atmospheric dust emissions, land cover or land use and climate change are among the main drivers of soil organic carbon disruption in the Free State. These factors are interconnected; with the consequence of one resulting to the occurrence of the other. This study aims to examine the shift in land cover or land use and how this may have contributed to occurrence of dust storms. To date, few studies have examined factors that cause dust emissions from South Africa's farmland and the role of vegetation in the occurrence of dust. This study also aims to contribute to the knowledge of climate constraints and mitigations to crop production in Free State. Furthermore, this study wished to contribute to the knowledge of land management strategies suitable for enhancing the storage of soil organic carbon in Free State. Currently, there are no land management strategies designed and implemented to improve the storage of soil organic carbon in Free State. The purpose of this chapter is to introduce agricultural practices, atmospheric dust and soil loss, land cover or land use, climate change and ecosystem services. These sections will further be investigated in depth in different chapters.

#### **1.1.1 Agricultural practices**

According to Post et al., (2001) extensive changes in land use and agricultural activities which have occurred during the last 200 years have transformed soils into net sources of atmospheric CO<sub>2</sub>. The long-term net balance between loss and accumulation of organic carbon in the soil result in SOC content (Wan, Lin, Xiong, Li, & Guo, 2011). SOC is the most important indicator of soil fertility and productivity and has been proposed by several studies to be a possible medium to sequester more CO<sub>2</sub> from the atmosphere and to ameliorate the impact of elevated CO<sub>2</sub> on climate change. Smith et al., (2005) state that decomposition and accompanying respiration becomes accelerated by increasing temperatures and therefore results in a loss of soil carbon especially where soil moisture is not a limiting factor. Whereas an increase in precipitation might result in unchanged decomposition.



Studies have found that land use is the main factor of SOC losses rather than climate change (Fantappi , L'Abate, & Costantini, 2011). However, one might argue that land use change is often driven by climate change therefore these factors are dependent on each other even though SOC losses might be the consequence of a single factor. Studies reported that approximately 10-20% of SOC losses could be due to climate change, however SOC losses can be reversed if proper land management strategies (such as no till, leaving crop residue after harvesting and managing fertilizer amount put in the soil) are practiced (Fantappi  et al., 2011).

Terrestrial soils are relatively the biggest sink of carbon in the world (1500 Gt) (Commission, 2006; Y. Zhou, Hartemink, Shi, Liang, & Lu, 2019). "As the largest pool of terrestrial organic carbon, soils interact strongly with atmospheric composition, climate and land cover changes" (Jobbagy and Jackson, 2000, p. 423). When the movement of SOC between soils and the atmosphere is not balanced, especially when more carbon is being lost, greenhouse gas tends to increase and thus affect the global climate. The changes in SOC affect the carbon cycle and may therefore substantially increase or decrease the carbon concentrations in the atmosphere. Focusing on CO<sub>2</sub> emission from regularly disturbed lands, CO<sub>2</sub> affect atmospheric gas composition and climate. According to House et al., (2002) approximately 180-200 PgC of carbon has been cumulatively lost due to changes in land use since 1987. Changes in atmospheric CO<sub>2</sub> and climate patterns play a significant role in vegetation productivity and soil decomposition (Brovkin et al., 2004). Sparse vegetation cover results in soil being the source of atmospheric carbon rather than being a sink and therefore soils with poor nutrient content and sparse vegetation are more likely to be subjected to soil degradation. This is common in areas that constantly use soil mainly for agricultural purposes as those soils tend to lose more nutrients than they can store. Bonan, (1997) add that crops have replaced much of the natural vegetation including grassland in most parts of the world. Studies have found that it is the conversion of forest and natural grassland to cropland that causes a decrease of SOC (Don et al., 2011).

According to Moeletsi & Walker, (2012b) rainfed agriculture in South Africa such as in Free State are subjected to climate change which may affect crop production, crop yields and potentially even resulting in crop failure. Crop yields are subjected to decrease when weather conditions are not favourable to a specific crop type. Changes in weather patterns i.e., decrease in rainfall and increase in temperature are likely to lead to crop failure especially for rainfed crops. The advantage of increased temperatures is that frost days decreases, however the disadvantage of increased temperature is that crops are subjected to fail if exposed to excessive

heat with less moisture. Moeletsi & Walker, (2012a) found that the onset, duration, and cessation of rainfall in Free State are changing with rainfall quantity decreasing. The shifting of rainy season leaves the farmers with an option of shifting the planting dates to accommodate the change and that change might result to crop failure or decrease yields. Furthermore, certain land management strategies need to be practised to mitigate climate change and continue with sustainable agriculture.

Agricultural production becomes a challenge when land is being extensively cultivated leading to soil degradation thus loss of nutrients. However, changes in agricultural management activities, such as reverting from cropland to grassland gives soils a great potential of sequestering more carbon. Cropland also has a potential of sequestering carbon if appropriate land management, such as leaving stubbles after harvesting is practised. However, continuous disturbance of the soil result to loss of carbon especial if the land is left bare. To effectively mitigate climate change by SOC sequestration, a net removal of C and storage in soil relative to atmospheric CO<sub>2</sub> must occur and persist for several hundred years (Lorenz & Lal, 2014). Increase in atmospheric CO<sub>2</sub> can be mitigated by storing carbon in the soil causing a net increase in SOC and enhanced soil fertility and resilience of crop land.

It is vital that studies not only focus on assessing the sequestration of SOC and its climate effect but also pay attention to mitigation measures to promote more SOC sequestration (Sommer & Bossio, 2014). This is important because if soils are managed as carbon sinks rather than sources then SOC will increase in the soil until it reaches a new SOC equilibrium. It is evident that CO<sub>2</sub> is a Greenhouse gas (GHG) that triggers increase in atmospheric temperature and thus global climate change. In essence as much as climate change affect SOC concentrations, loss of SOC contributes to climate change. SOC is affected by climate when temperatures increase resulting in increased decomposition. However, SOC is also a factor that contributes to increased temperatures as CO<sub>2</sub> in the atmosphere interferes with the movement of energy and thus leading to global warming. Climate change can be mitigated by reducing GHG emission or sequestration of C in aboveground biomass or soils (Sommer & Bossio, 2014). Agricultural practices, land cover and land use and climate change can result in atmospheric dust due to the continues disturbance of the soil and associated surfaces. Hence, the following section focuses on the causes and implications of soil losses due to dust emissions.

### 1.1.2 Atmospheric Dust and Soil Loss

Abouchami et al., (2013) defined dust storms as an atmospheric phenomenon triggered by numerous small particles evenly distributed in the air. Drylands are observed to be the major sources of dust storms. They are mainly associated with dust storms since desiccated, unconsolidated substrates with scarce vegetation cover allow turbulent winds to easily raise particles from the surface (Middleton, 2017). Aerodynamic roughness of the deforested land tends to decrease due to low precipitation and increased surface wind speed and these conditions result to dust production (Woodward, Roberts, & Betts, 2005). Precipitation is predicted to decrease over the years due to less transpiration in cleared vegetation areas, thus resulting in increased winds as there is minimal vegetation to trap or block wind and eventually result in the movement of particles. In areas with bare land, when wind speed is high ( $\sim 6$  m/s), particles are likely to start eroding. Wind erosion is thus an important factor that also contributes to soil erosion and causing dust. Schweitzer et al., (2018) state that the frequency of dust storms has increased in recent years and forecasts suggest that this will continue to rise in response to anthropogenic climate change activities.

Dust has direct effects on solar and thermal radiation (Shi et al., 2005) and indirect effects on cloud and precipitation processes (Jingfeng, Chidong, & Prospero, 2010; Sassen, 2002) thus regarded significant to climate change. Solar radiation becomes reduced due to absorption and backscattering of dust aerosols. Dust inhibits solar radiation resulting in loss of sunlight. Therefore, dust blocks solar radiation from being absorbed by vegetation and soil, resulting in imbalanced energy fluxes. “Dust can absorb solar radiation and generate local heating, which in turn changes the relative humidity and the stability of the atmosphere, thereby influences the cloud lifetime and cloud liquid water content” (Huang & Wen, 2014, p. 11,403).

Kingsland, (2012) report that dust events are being experienced more regularly in the central areas of South Africa. They are likely to occur in dry lands without vegetation cover, or surface lacking the stability to be protected by vegetation, such as the fore fields of glaciers or large fluvial deposits once falling dry (Shao, 2009). Bestelmeyer et al., (2015) also observed that land cover change associated with agricultural activities has increased the areas potentially affected by wind erosion significantly by removing the protective vegetation and exposing dry and loose soil to the forces of wind. Land cover plays a meaningful role in the ecosystem and is also observed to contribute to soil degradation. When the soil is covered it is rather stable,

whereas when the land is bare it is prone to wind erosion. Vos et al., (2020) states that dust emissions can lead to land degradation due to removal of fine soil particles and organic material, specifically in semi-arid and arid regions.

Wiggs and Holmes, (2011) were the first to quantify the degree of wind erosion on the agricultural soils in the Free State region. Free State wind erosion has been observed as a current and historical phenomenon. Wind erosion is induced by anthropogenic activities in cultivated land resulting in an area being susceptible to dust emissions (Eckardt et al., 2020; Wiggs & Holmes, 2011). The west-central Free State, where commercial dryland agriculture is practised is shown to be more vulnerable to wind erosion. Severe wind erosion of bare agricultural lands is observed late September – October (Wiggs & Holmes, 2011). These months are characterised by high winds, and low vegetation cover which when combined result to soil erosion. Rainfall also occurs in these months and in theory it should increase the erosion threshold. However, high erosion still arises despite the occurrence of rainfall in these months due to high winds and low vegetation cover (Wiggs & Holmes, 2011). Eckardt et al., (2020) add that wind speed plays a significant role in dust emission, a correspondence between maximum hourly average wind speed on the dust day and the detected dust emission was observed. Furthermore, relative humidity and temperature also play a role in the occurrence of dust. According to Figure 1.1 dust is likely to occur when wind speed and temperature are high, and relative humidity is low (Eckardt et al., 2020). When relative humidity decreases, the air above surface becomes dry and when temperature increases the soil becomes dry and thus the combination of these factors results to dust emission.

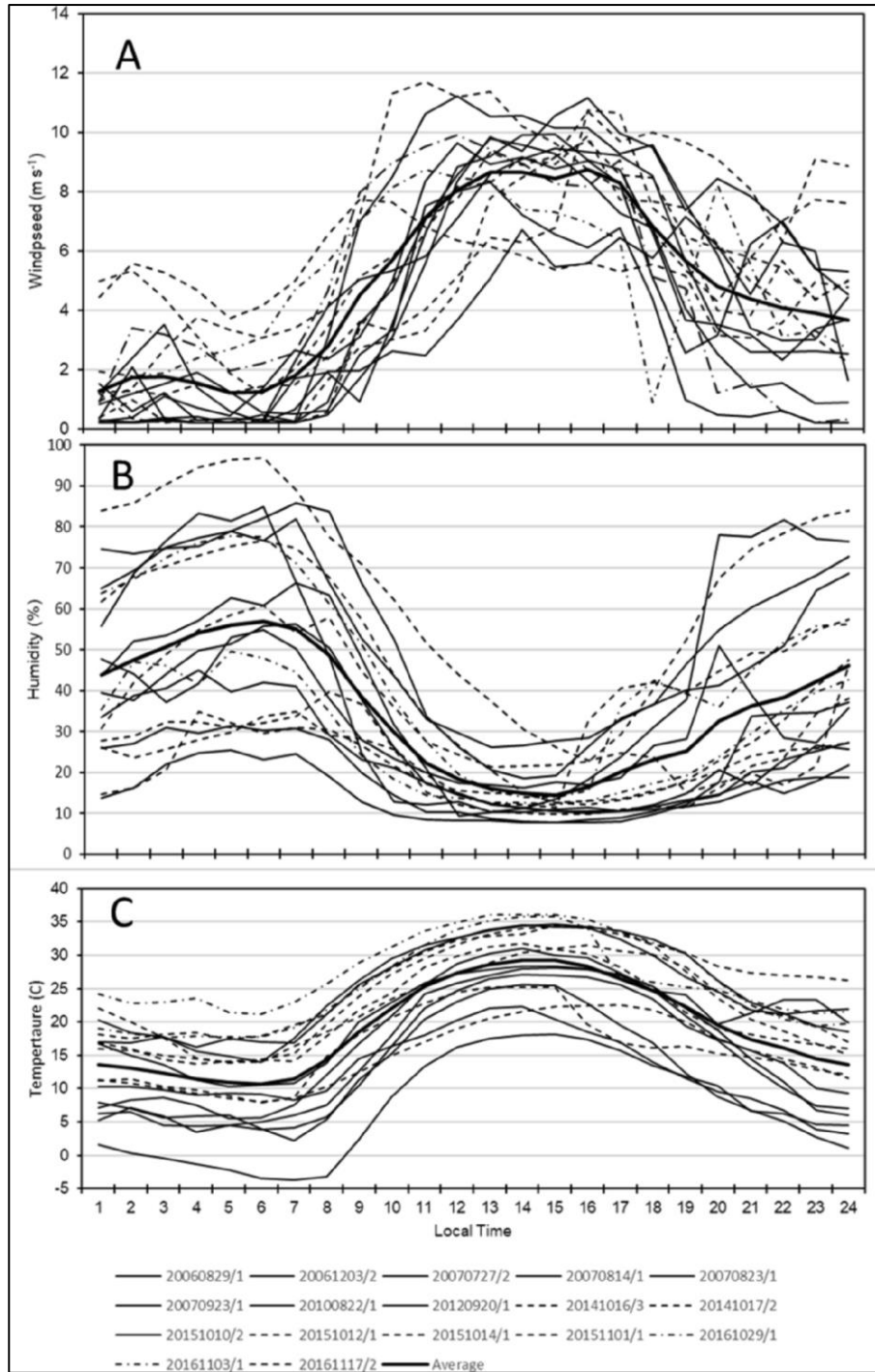


Figure 1.1: Hourly diurnal weather observations for 17 of the 75 event days within 25 km of image plumes, with windspeed ( $\text{m s}^{-1}$ ) (A), relative humidity (%) (B) and temperature (degrees C) (C) in Free State. Depicted are cold fronts (CF) in solid lines and stationary troughs (ST) dashed lines as well as intermediates (CF/ST) dashed and solid (Eckardt et al., 2020).

Wiggs and Holmes, (2011) suggest that surface roughness plays a role on the erodibility of the surface. Eckardt et al., (2020) further argue that dust events in Free State agricultural lands are associated with years of lower-than-expected rainfall, severe drought, low vegetation cover during the dry season and high wind speed. Both Eckardt et al.,( 2020); Wiggs & Holmes, (2011) suggest that fallow agricultural lands significantly contribute to dust sources especially during drought cycles. Agricultural lands in Free State are left fallow post harvesting and if there are no crop residues the land becomes susceptible to wind erosion. Vos et al., (2020) add that besides the above-mentioned factors, soil texture and cohesion can also control dust emission in croplands. Soil texture and cohesion are controlled by moisture content and the presence of a physical or biological crust. Crust has a potential to reduce dust (Vos et al., 2020), however the formation of crust is vulnerable due to regular disturbance of the surface of agricultural lands. Since Eckardt et al., (2020); Vos et al., (2020); Wiggs & Holmes, (2011) observed that Free State sandy croplands are the main dust sources in South Africa, there has been a growing concern about dust emissions and further a need to come up with land management strategies that will mitigate the current dust issue. Land cover or land use is one of the major contributing factors to dust emission, climate change and soil degradation. Therefore, the following section will broadly look at the effects of land cover or land use changes.

### **1.1.3 Land cover or land use**

Land cover (physical features that cover the land) or land use change (management and activities on land) (LCLU) affect climate change and vice versa. Mora and Herold, (2015) agree that local, regional, and global climate is impacted by land cover changes. This of course happens through the change in the flow of energy, water and greenhouse gases between the land and the atmosphere. Changes in LCLU also effect climate change through changes in albedo (Lambin, Geist, & Lepers, 2003). High albedo leads to cooling, as radiation is lost back through the atmosphere, whereas a low albedo leads to heat being retained by the earth surface. The rate, magnitude and spatial extent to which humans are changing the Earth's land surface is significant Lambin et al., (2001) and these changes affect the functioning of earth systems. According to Lambin et al., (2001) changes in LCLU have a direct impact in biotic diversity worldwide, as they contribute to climate change at local, regional and global scale. Moreover, changes in LCLU are found to be the main source of soil degradation. Additional to disrupting

ecosystem services, LCLU change affects the ability of biological systems to support human needs (Lambin et al., 2001). Changes in LCLU are dominant in South African regions. The land is mostly converted from its native state to cultivated land to meet economic demands. However, unsustainable agriculture is imposing a huge threat to the environment. Changes in climate such as increase in temperature and decrease in rainfall result in unsustainable agriculture in some areas (Engelbrecht et al., 2015; Mwenge Kahinda, Taigbenu, & Boroto, 2010; Ziervogel et al., 2014).

Anthropogenic LCLU change largely impacts climate and the environment (Dale, 1997; Mora & Herold, 2015). Deng, Zhao and Yan, (2013) noted that urbanization, deforestation, afforestation and agricultural practices mainly affect climate. Comarazamy et al., (2013) state that urbanization is one of the most extreme cases of LCLU change. Urbanization results in increased temperatures over urban centres compared to rural areas. Moreover, when vegetation and forests are cleared for building human settlements, more carbon gets released into the atmosphere, there is less transpiration which causes less cloud formation resulting in less rainfall. In addition, the energy reflected back to atmosphere increases because there is less vegetation to absorb the energy thus causing more heat in the atmosphere (Mercy, 2015). Deforestation is a leading cause for increases in cloud-base heights and thinner clouds in Central American rain forest thus resulting in increased regional droughts (Deng et al., 2013). Temperatures and sensible heat fluxes tend to increase and dewpoint temperatures and latent heat fluxes of the air masses tend to decrease due to deforestation (Comarazamy et al., 2013). However, regional climate change impacted by LCLU change differ significantly. For instance, deforestation may lead to increase in temperature in tropic zone and decrease in temperature in cold zone. Climate can be influenced by LCLU change by altering the properties of the land surface.

Impacts of land cover on global climate can be divided into biogeophysical and biogeochemical processes (Sitch et al., 2005; Snyder, Delire, & Foley, 2004). Biogeophysical processes directly affect the physical parameters that determine the absorption and disposition of energy at Earth's surface (Sitch et al., 2005; Snyder et al., 2004). Biogeochemical process affect climate by altering the rate of biogeochemical cycles, thereby changing the chemical composition of the atmosphere (Sitch et al., 2005; Snyder et al., 2004). LCLU change alter the rate of the biogeochemical cycle and thus the chemical composition of the atmosphere. Furthermore, LCLU affect climate through the absorption or emission of greenhouse gases. For instance, if land cover is native grassland, it acts as a carbon sink, whereas if land cover is cultivated land,

then the land mostly acts as a source of carbon, resulting in increased greenhouse gas in the atmosphere. When land is overgrazed, desertification can occur as overgrazing results in changes in the surface albedo and surface water budget and therefore leads to changes in the regional circulation and precipitation patterns. Furthermore, overgrazing can result in the increased amount of dust that successively causes decrease in precipitation and radiative cooling (Dale, 1997). Additionally, the way energy is received and distributed into latent and sensible heat fluxes is affected by surface hydrology and vegetation transpiration characteristics.

Climate change on the other hand affects land use through reduction of crop yield due to drought, floods, reduced water availability and increased spread of crop diseases (Mistry, 2014) and spatial shifts of agricultural potential (Dale, 1997). As a mitigation measure, irrigation schemes may have to be introduced when rainfall decreases and lack of access to these irrigation schemes might result in crop failure. Additionally, farmers can plant crops that can withstand the extreme weather changes. The indirect impact of climate change on land use includes, but is not limited to, the disturbance of regimes (i.e. frequency of fire, wind, or insect outbreaks) (Dale, 1997). Conversion of land back to its natural state (i.e. grassland and forest) is a major mitigation measure that can promote cooling, even though this is less feasible in urban areas and thus warming is still expected to intensify (Mora & Herold, 2015). Greenhouse gases concentration in the atmosphere can be reduced through increasing the land-based carbon storage or changing LU to one that will result in more carbon sequestration (i.e., grassland and forest). Reforestation promotes cooling which would result to a balanced energy budget in the ecosystem, increase solar radiation absorption and decrease albedo resulting to balanced energy fluxes and promotes transpiration resulting in more cloud formation and thus increase rainfall (Mora & Herold, 2015).

In South Africa, LCLU is impacted by climate change and these changes are observed to be severe in areas dominated by agricultural production such as Free State. Engelbrecht et al., (2015) projected a future increase in temperature and decrease in rainfall of South Africa and these patterns have an impact on agriculture especially in rainfed regions (Moeletsi & Walker, 2012). The western part of Free State is dominated by dryland agricultural activities (annual summer cropping and livestock production), and studies have shown significant change in LCLU of this region in response to climate change. Moeletsi & Walker, (2012a) conducted a study in Free State with the purpose of investigating how farmers respond to rainfall and temperature changes. Generally cultivated land has been observed to be a dominating LC more



than native grassland in Free State, however recently cultivated lands have been observed to be left bare. Farmers indicate that they choose to leave the land bare when minimal rainfall suitable for the start of ploughing has not occurred. The recently observed years with intensive bare lands in Free State corresponds with the recent drought years (2015-2016) that affected the whole of South Africa. It is therefore vital to continuously study its impacts on LCLU to come up with proper mitigation measures. The next section elaborates on the causes and impacts of climate change.

#### **1.1.4 Climate change**

According to IPCC, (2021) changes in climate are observed to be increasing worldwide. Climate change is evident in all components of the climate system. Warming has increased in the atmosphere and ocean, resulting in decreased snow and ice (IPCC, 2013). Sea levels are rising, ocean has become more acidified and de-oxygenated and concentrations of atmospheric greenhouse gases have increased (IPCC, 2013). Climate change is caused by natural and anthropogenic activities. The rate, scale, and magnitude of anthropogenic changes in the climate system has become more significant since the mid-20th century (Crutzen and Stoermer, 2000; Steffen et al., 2007). Human activities have been observed as a major component changing the Earth system and causing long term and permanent changes.

Temperature has been observed to increase by 1.09 °C from 1850–1900, until present (2011–2020) (IPCC, 2021). Carbon dioxide has been found to be the current strongest driver of anthropogenic climate change and has increased from  $285.5 \pm 2.1$  ppm in 1850 to  $409.9 \pm 0.4$  ppm in 2019; and concentrations of methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) have increased as well. These observed changes are assessed to be in line with known anthropogenic and natural emissions, when accounting for observed and inferred uptake by land, ocean, and biosphere respectively and are a key source of anthropogenic changes to the global energy balance. A higher exchange of water between the surface and the atmosphere is observed to be causing an intensified change in the water cycle (IPCC, 2021). This results to changes in regional precipitation patterns that constitute an increase in precipitation in the Northern Hemisphere temperate regions and decrease in precipitation of the sub-tropical dry regions in recent decades.

Mean annual temperatures have been observed to have increased over the past decades and rainfall has been observed to slightly decrease in South Africa. According to Ziervogel et al., (2014) climate change in South Africa is regarded as a key component to environmental change. South Africa is extremely vulnerable to temperature and rainfall changes (Engelbrecht et al., 2015) posing a threat to water resources, food security, health, infrastructure as well as ecosystem services and biodiversity.

Climate change has been studied and observed to be characterised by higher temperatures, lower rainfall, greater rainfall intensity, higher evapotranspiration, increased runoff, and soil losses. These mentioned factors affect agriculture significantly as they result to decreased crop yields, crop failure and fallow land during extreme weather conditions. Climate change also has a direct impact on livestock, the extreme hot temperatures result in thermal stress thereby increasing livestock mortality rates. Hatfield et al., (2014) argue that to maintain sustainability in food and livestock production, agriculture must continually adapt to climate change. The most commonly adaptive strategies for crop production that have been implemented are crop rotation, changing planting times, genetic selection, management of fertilizer, pests, and water, and shifting the area of crop production. These strategies have been found to be the most effective thus far across the world.

Climate is further observed to be changing most especially in semi-arid regions of South Africa that are dominated by agricultural production such as Free State. Temperatures are increasing and projections show further increase in the future and decrease in rainfall (Engelbrecht et al., 2015). These changes are currently affecting and will continue affecting agricultural production. Moeletsi & Walker, (2012a) noted that Free State's agricultural production is affected by climate change which results in reduced crop yields, crop failure and loss of ecosystem services. Moeletsi & Walker, (2012a) further argued that it is vital to study how climate change affects agricultural production to produce proper mitigation measures and continuously have sustainable ecosystem services. It is therefore important to understand how land cover or land use and climate change affect the ecosystem services.

### 1.1.5 Ecosystem services

Ecosystem services (ES) refer to the direct and indirect benefits that people obtain from ecosystems, including products and services (Costanza et al., 1997). There are four types of ecosystem services, namely, provisioning, regulating, cultural and supporting described in (Figure 1.1) (Braat & de Groot, 2012; Costanza et al., 1998). Carbon sequestration forms part of the supporting service. Positive support to the ecosystem will provide good vegetation and thus carbon sequestration is the consequence of good vegetation.

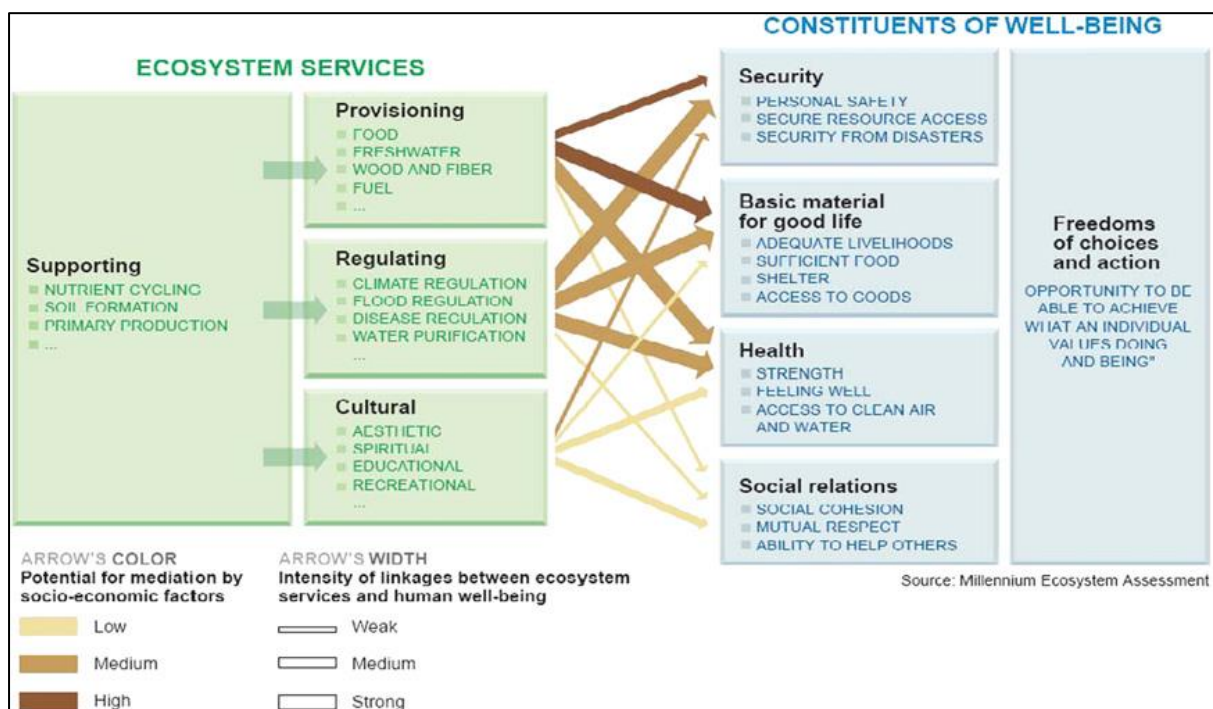


Figure 1.2: Types of ecosystem services (Arico et al., n.d.). The diagram summarizes the four ecosystem services and how they link to human well-being.

Research has shown that to enhance human well-being ecosystem services must be sustainable (Costanza et al., 1997). It is therefore through understanding the effects of human activities (land use) and climate change on ecosystem services (ES) that scientific targeted guidance for sustainable use of ES can be provided. Wu et al., (2007) argued that ES have declined in many areas due to overgrazing and degradation of the land, thus their urgency in studying or understanding the mechanisms that drive the ES changes. LCLU and climate change are the

main drivers of ES disruption (Bateman et al., 2013; Schröter et al., 2005). Changes in LCLU affect ecosystem patterns and processes consequently changing the supply of ES. Climate change factors such as temperature, relative humidity, solar radiation on the other hand alters the hydrological processes, and CO<sub>2</sub> concentration therefore directly or indirectly affect ES (Nelson et al., 2013). Studies have reviewed the effects of land use activities such as excessive grazing, cropping and urbanization and found that they result in the reduction of carbon storage, reduced water quality and reduced biodiversity and therefore result in a significant decrease in the ES that these types of activity can deliver (Fu, Li, Hou, Bi, & Zhang, 2017; Polasky, Nelson, Pennington, & Johnson, 2011). The impacts of climate change on the other hand include warming and drying in many regions. These impacts result in water shortages, increase in the occurrence of natural disasters (floods, fires, storm events) and desertification and they therefore put substantial pressure on the sustainable provision of ES (Schröter et al., 2005).

Human activities release GHGs into the atmosphere, resulting in greenhouse effects at the global scale and change the patterns of carbon storage through land use activities (Bounoua, DeFries, Collatz, Sellers, & Khan, 2002). Studies showed that approximately 61% of the anthropogenic greenhouse is the result of carbon dioxide increases. Carbon is also released to the atmosphere through burning of vegetation and becomes sequestered again when vegetation regrows. The regrowth of vegetation is believed to act as a net carbon sink globally, however burning of vegetation releases this back up to the atmosphere. Moreover human activities that change the earth's vegetation can change climate by changing the energy, and water balances between the biosphere and atmosphere (Bounoua et al., 2000; Pielke et al., 1998; Sellers et al., 1996). Land use activities that result in CO<sub>2</sub> being released into the atmosphere via respiration from decomposition and microbial activity include deforestation and clearing of natural wetlands to practice agricultural activities. Forests are relatively a large carbon sink and clearing them will result in more carbon being released into the atmosphere. Furthermore, clearing of natural wetlands containing peat results in a release of a biotic source of carbon dioxide. Vegetation thus plays a significant role in moderating the earth's climate system. The structure of vegetation matters the most as it influences the amount of absorbed radiation and the amount that is reflected to the atmosphere. Moreover, vegetation sequester carbon, which means due to healthy or good vegetation more carbon can be stored and thus greenhouse gases can be lowered in the atmosphere.

Changes in land use pose a great threat to an ecosystem and its services and has been regarded a global phenomenon (Lefcheck et al., 2015; Ramankutty & Foley, 1999; Tilman et al., 2017).

The effects of anthropogenic land use practices and climate change are observed to be putting pressure even on biodiversity hotspots (Ellis, Goldewijk, Siebert, Lightman, & Ramankutty, 2010; Fischer & Lindenmayer, 2007; Vermaat et al., 2017). Changes in land cover, anthropogenic climate change and biodiversity loss are all interconnected processes that experience the impacts of the global environment (Hellwig, Walz, & Markovic, 2019).

Biodiversity disruption and loss has become a major concern among conservationist in the 21<sup>st</sup> century as climate emerges as another major threat, with impacts at the genetic, species, community and ecosystem levels (Foden et al., 2013; Lawler et al., 2009; Xuyong Li et al., 2006). Studies Jetz et al., (2007; Mantyka-Pringle et al., (2015); Sala et al., (2000) have shown that biodiversity threat may increase as land cover and climate change impacts increases. The interaction of climate change with land cover change might intensify the impact of habitat loss and fragmentation on biodiversity by increasing the susceptibility of uneven biological populations. Climate change can limit the ability of species to cope and adapt in certain environments. Loss of habitat can affect species by inhibiting their movement and ability to cope with climate change (Mantyka-Pringle et al., 2015). Sala et al., (2000); Jetz, Wilcove and Dobson, (2007) therefore state that climate change and land cover change interaction has the potential to basically change the magnitude and spatial patterns of decrease in biodiversity and the degree of interaction varies regionally. To mitigate these negative impacts on the ES that a landscape can deliver, it is vital to develop effective ecosystem management and land use strategies.

SOC sequestration is a positive ecosystem service and is regarded as one of the indicators of soil fertility. However, SOC has been found to be negatively affected by continuous disturbance of the soil especially in agricultural lands with intensive grazing and cropping. Free State is one of the South African semi-arid regions that are dominated by agricultural practices (Eckardt et al., 2020; M. E. Moeletsi & Walker, 2012; Vos et al., 2020; Wiggs & Holmes, 2011) and SOC is observed to be critically disturbed. Loss of SOC has several consequences such as reduced soil fertility which then leads to poor crop production and increased atmospheric warming. These consequences thus cause an imbalance in ecosystem services. It is therefore important to understand the dynamics of SOC in agricultural lands to improve the functionality of ecosystem services. Certain mitigation measures to reverse the loss of SOC have been suggested by many studies and have been observed to be effective in many regions. It is then crucial to understand these mitigation measures and test their reliability in Free State as the area is mostly affected by SOC changes.

The current study will therefore explore how the land cover/ land use shift affects the occurrence of dust in Free State. The study will also determine the climate constraints and mitigations to crop production, and further establish land management strategies suitable for enhancing the storage of soil organic carbon in Free State.

## **1.2 Problem Statement**

It is important to understand the effects of land cover change, their trend and how they are managed in dryland areas. Dust storms have been observed to increase in Free State region and that is a clear indication that there is a problem with the system. The Meteosat Second Generation (MSG) clearly suggests that Southern African dust events are frequent and are significant in extent (Vickery *et al.*, 2013). Eckardt *et al.*, (2020) reported that 71% of all South African dust sources are situated in the Free State and are mainly associated with areas of extensive dryland crop farming. However, a comprehensive analysis of how land cover or land use change affects the occurrence of dust in Free State has not been done. The understanding of the effects of LCLU change in the occurrence of dust can contribute to the knowledge of dust mitigation measures in Free State.

It is also vital to recognize the influence of climatic conditions on agricultural activities. Weather parameters such as rainfall and temperature play a significant role in crop production and farmers consider them to make certain decisions. However, climate constraints and mitigations to Free State crop production have not been studied. This knowledge is important and can be used to guide farmers in planting decisions. Climatic conditions and LCLU changes in Free State, South Africa needs to be well understood. This is important as it will assist with deriving appropriate environmental mitigation measures.

Moreover, ecosystem services in South Africa are not always fully considered. For example, carbon storage is one of the fundamental ecosystem services needed in environmental cycles if we are to mitigate against climate change. However, land management strategies suitable for enhancing the storage of carbon in Free State have not been established. Carbon is needed for plant growth and reproduction, however loss of carbon to the atmosphere further contributes to the greenhouse effect and the associated consequences. Therefore, it is important to lower atmospheric CO<sub>2</sub> to help reduce the effects of global warming. Loss of soil carbon to the atmosphere has become a problem in agricultural lands, especially when cultivating the land

rather than leaving it at its natural state (grassland). Therefore, considering the negative effects that carbon has on the atmosphere, mitigation measures are being pursued. It is therefore important to come up with proper land management options that will render soils to be more of a carbon sink than a source.

These problems are interconnected; thus, it is vital to investigate them in an integrated manner and to come up with mitigation measures that will benefit them all. Grassland is being converted mostly to cultivated land in Free State. Cultivated lands are observed to be the source of dust and atmospheric carbon due to continuous disturbance of the soil and when the land is left bare. As the consequence of little to no rainfall in specific years agricultural lands tend to be left bare. Bare land is susceptible to soil loss. Furthermore, due to climate change and LCLU changes, value of ecosystem becomes affected. Cultivated land result to carbon being lost to the atmosphere. Also, when land is left bare less carbon becomes stored as compared to grassland. While carbon is supporting ecosystem service it is not well monitored in Free State. To investigate the problem, Bultfontein area in the western Free State was selected, because of the marked land cover and land use changes and being the hotspot of dust events in South Africa largely controlled by agricultural activities.

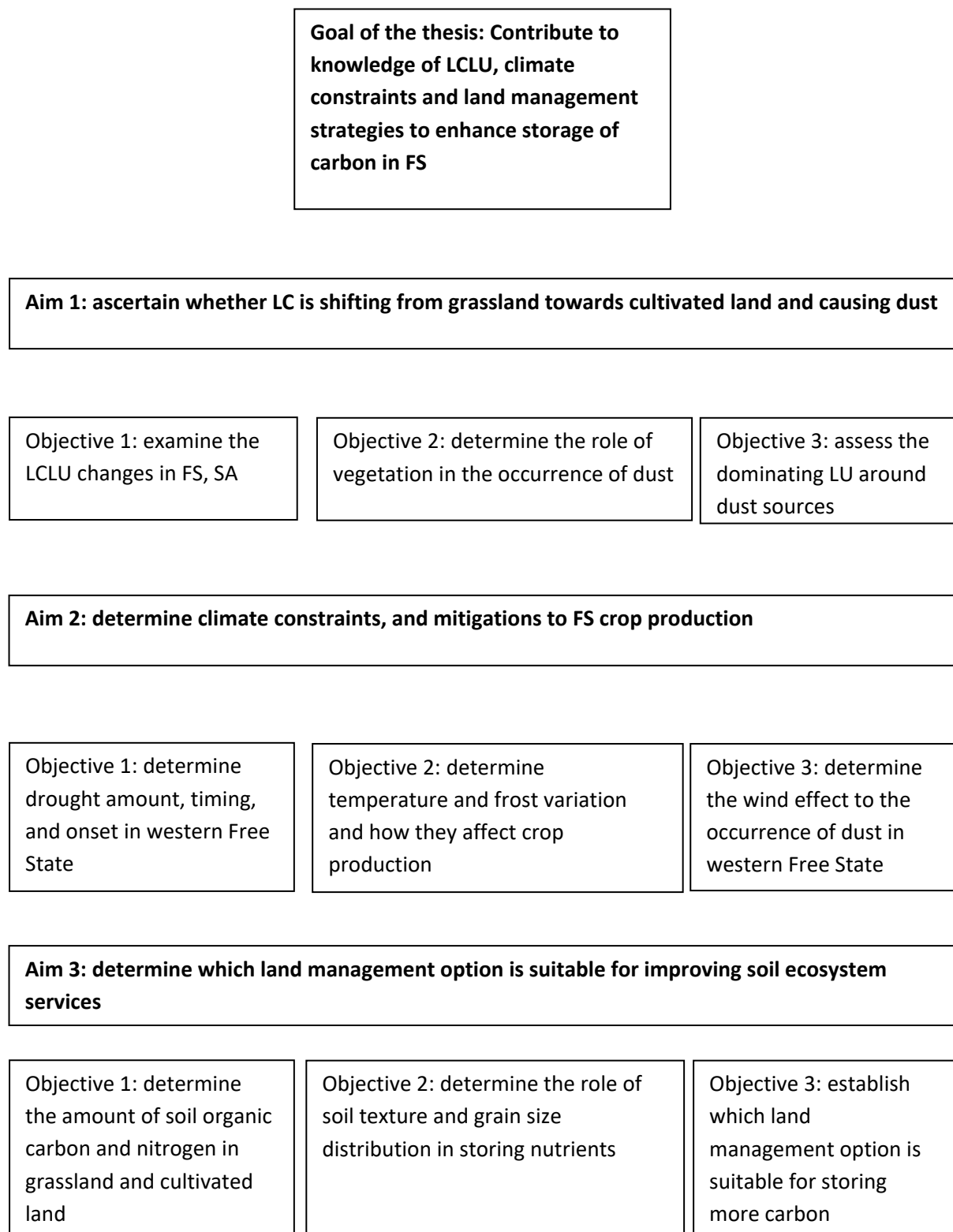


Figure 1.3: Thesis overview flow diagram



### **1.3 Rationale of the study**

An understanding of LCLU changes, climate change and the value of ecosystem services is very crucial. This will enable proper conclusions to be drawn based on the causes and consequences of climate and LCLU changes. This knowledge will further be valuable when recommending to the farmers the better land management options to prevent or reduce dust emission and storing more carbon. The knowledge application about how climate change affects agricultural activities, LCLU changes and the value of ecosystem services will generally provide positive effects in the ecosystem. These factors are observed to negatively affect the ecosystem resulting in the suffering of most biotic and abiotic organisms if they are not properly managed or mitigated.

There is inadequate knowledge on how the land can be properly managed to reduce soil loss and store more carbon. To fill this knowledge gap, trends of LCLU change over the years need to be understood. Land degradation has been observed to occur for a long time, therefore it is important that more research is conducted to investigate the trend, causes, the conditions that prompt it. With more of this information, better understanding of how to improve the use of LCLU can be developed. Additionally, land management options to store more carbon and reduce soil loss can be developed. The developed strategies might then crucially contribute to mitigating climate change.

Climate change increases the uncertainty of rainfall and temperature patterns. The onset and cessation of rainfall and temperature patterns are vital for farmers, as they play a significant role in crop production. Furthermore, SOC is the consequence of one of the ecosystem services that are observed to be ignored. Therefore, it is vital to understand the storage paths of carbon and land management options that are suitable to store more carbon. It is therefore important to equally study and understand climate and LCLU changes and the value of ecosystem services, to come with better climate mitigation measures and appropriate land management strategies.

## **1.4 Selection of study site and description of soil sampling points**

Bultfontein in Free State was selected to be the study area because of the four reasons: (i) highest percentage of dust events in South Africa, (ii) availability of ground measured weather data, (iii) land cover or land use changes and, (iv) dominated by farmers that are into both crop and livestock farming practices. The area is dominated by excessive agricultural activities which according to the literature can be the cause of soil degradation and erosion in semi-arid and arid regions. The research was narrowed down to Bultfontein within the Free State with the hope of expanding the findings from this area into the entire Free State and similar area elsewhere. Agricultural Research Council has four automated weather stations installed in Free State Province; each weather station installed in Bultfontein, Hoopstad, Wesselsbron and Wolmaranstad respectively. The data from weather stations was mainly used to answer the research questions of chapter 3. The land cover or land use changes data were used to determine whether cultivated land is certainly becoming the dominating land cover type and thus the source of dust. Lastly, land management options that are suitable for storing more carbon were determined. Within Bultfontein 6 sites were further selected to collect soil samples required to achieve chapter 4. The sites consist of 4 grassland and 2 cultivated land sites (Table 1.1). The sites were selected based on the different soil types (Arenosols, Luvisols, Calcisol and Lixisol), land cover type (grassland or cultivated land) and land management option (herbivory or no herbivory). There were no cultivated land sites in Calcisol and Lixisols soils, hence there were only two cultivated land sites (Arenosols and Luvisols).

### **1.4.1 Description of study area**

Bultfontein is an area in Free State Province that is situated approximately 105 km<sup>2</sup> to the north of Bloemfontein on the R700 provincial road and lies within the Tswelopele Local Municipality (Anonymous, 2018) (Figure 1.3). Bultfontein area is characterized by relatively flat topography, with an altitude range from 1.440 m in south-east to 1.320 m above sea level in north-west (Anonymous, 2018). The topography has generally been altered by the land use activities, such as farming activities and associated infrastructure, i.e., access roads and fences.

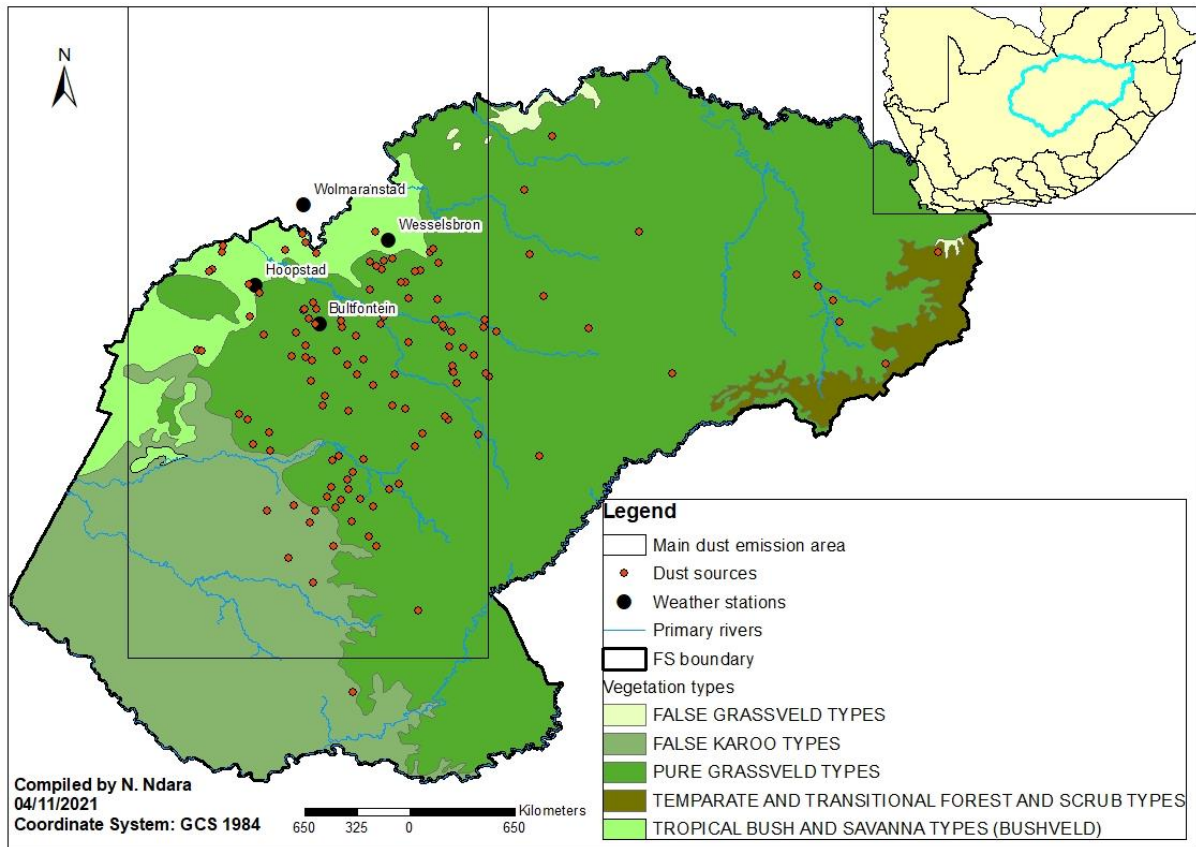


Figure 1.3: Location of study area in South Africa. The focus of the study is Bultfontein area, which is the western part of Free State, South Africa. Red dots are dust sources from MSG data in (Eckardt et al., 2020) paper. Western part of Free State is the hotspot of dust sources and is dominated by false karoo, pure grassveld, and bushveld. Data extracted from Agricultural Research Council database.

#### 1.4.2 Climate

Bultfontein area is characterised by warm wet summer and cold dry winters. The area normally receives approximately 369 mm/year to 549 mm/year of rain, with most rainfall occurring mainly during mid-summer (Raaijmakers et al., 2016). Rainfall varies significantly throughout the year with July receiving the minimum rainfall of  $\sim 1$  mm and January receiving the highest rainfall of  $\sim 65$  mm. Bultfontein average midday temperatures range from  $17^{\circ}\text{C}$  in June to

30°C in January. July is regarded as the coldest month as temperature drops to 0°C on average during the night in this month (Raan et al., 2016).

### **1.4.3 Geology and soils**

The study area is dominated by sandstone, mudstone and shale of the Karoo Super Group (mostly the Volksrust Formation, Eccra Group) interrupted by dolerite sills in some places (FAO-UNESCO Soil map of the world, no date). The area is mainly characterized by five different types of soils; Arenosols, Luvisols, Calcisol, Vertisol and Lixisol (Figure 1.4). Soil forms are mostly dry, clayey, duplex soils. The area is dominated by deep, sandy Rensburg soils, which are highly dispersive during windstorms (Aeolian), which promote depression-type pan wetland unit formation (FAO-UNESCO Soil map of the world, no date). Arenosols and Luvisols are the dominating soil types with high sand and silt content. Arenosols are characterised by sandy soil that makes them easily erodible and have low water and nutrient holding capacity. The in-situ weathering of quartz-rich parent material or recently deposited sands results in the development of Arenosols. In the absence of vegetation cover, they are susceptible to wind erosion. Luvisols are slightly acidic soils characterised by a subsoil that is clay-enriched, and they have high nutrient-holding capacity. The clay content in Luvisols increases with increase in depth. Luvisols have a good water-holding capacity due to their well-developed soil structure. Calcisol are soils with substantial secondary accumulation of lime. Vertisol are soils with high clay content that forms deep cracks in drier seasons and Lixisol are soils with subsurface accumulation of low activity clays and high base saturation.

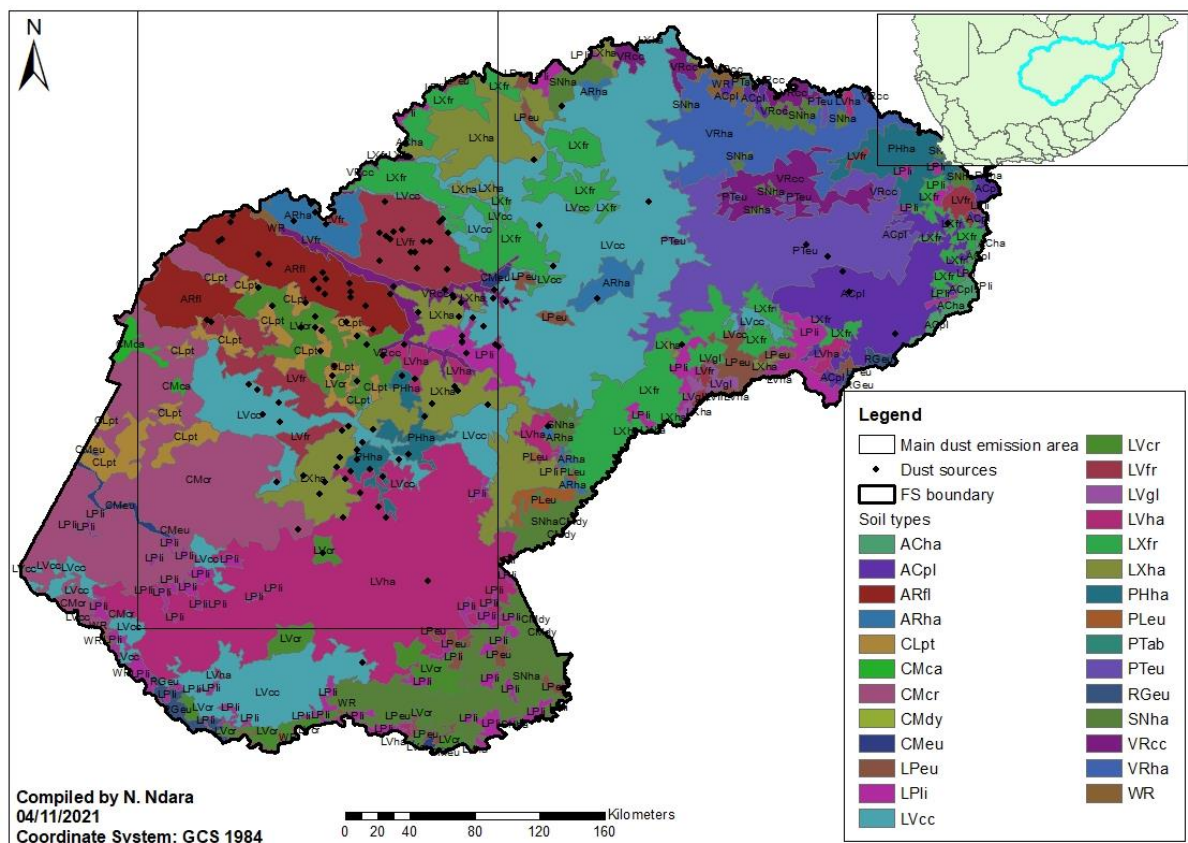


Figure 1.4: Free State soil types (FAO-UNESCO Soil map of the world, no date). Map shows the five major dominating soils in Free State. Black dots are dust sources from MSG data in (Eckardt et al., 2020) paper.

#### 1.4.4 Land cover or Land uses

The Bultfontein area is mainly dominated by cultivated land and grassland (Figure 1.5). The area is greatly impacted on by anthropogenic activities including livestock grazing, crop plantation and other land uses associated with farming/agricultural activities. The major crops that are planted in this area are: maize, wheat, sunflower, oats, and soybeans. According to Martin, (2015) there were extensive areas of marginal land which were ploughed in the past and the land has now been left fallow as it is not necessarily suitable for modern agricultural practices.

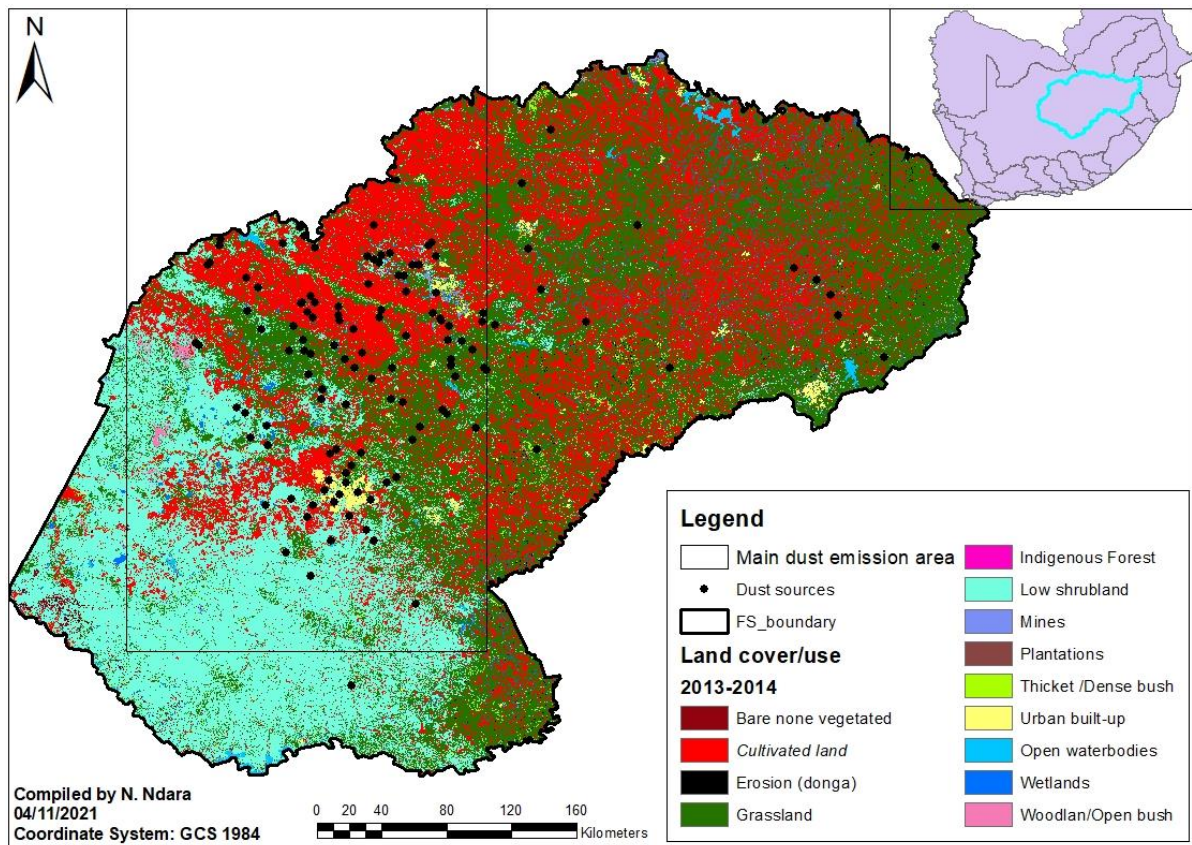


Figure 1.5: Free State Land cover or Land uses. Map shows the land cover or land use in the entire Free State. Cultivated land and grassland covers most parts. Western part of Free State is dominated by dust source areas, cultivation, and grassland. Data extracted from Agricultural Research Council database.

### 1.4.5 Vegetation

The vegetation of Bultfontein area belongs to the Grassland Biome and is situated in Veld type Gh 9 VaalVet Sandy Grassland, which has an endangered Conservation Status (Mucina & Rutherford, 2006) (Figure 1.6). This is largely due to large scale transformation to accommodate formal agriculture and the lack of substantial representation within formal conservation areas. The area is characterized by mainly flat bottomlands which support dry, species poor grassland with a high number of salt pans (playas) embedded.





Figure 1.6: Photographs showing vegetation type within Bultfontein area. Left image showing grassland and right image showing cultivated land and associated moving sand and wind erosion.

Table 1.1: Location of soil sampling sites in Free State, South Africa.

| Site no. and name       | Soil type | Latitude (S) | Longitude (E) |
|-------------------------|-----------|--------------|---------------|
| Site 1: Grassland       | Arenosol  | 28,15877     | 26,06620      |
| Site 2: Cultivated land | Arenosol  | 28,15946     | 26,06535      |
| Site 3: Grassland       | Calcisol  | 28,20361     | 25,90789      |
| Site 4: Cultivated land | Luvisol   | 28,28941     | 26,02509      |
| Site 5: Grassland       | Luvisol   | 28,28975     | 26,02473      |
| Site 6: Grassland       | Lixisol   | 28,34033     | 26,73535      |

### Site 1: Grassland

Site 1 is a grassland under Arenosols type of soil (Figure 1.7). The site is adjacent to cultivated land. During the sampling time there was evidence of minimal grazing in the site. The site falls under Vaal-vet sandy grassland (Gh10). This type of grassland is distributed in North-west and Free State Provinces. The dominant landscape features found in this type of grassland are plains with uneven undulating plains and hills. Vaal-vet sandy grassland is characterised mainly by three grass species: Dry *Cymbopogon-Themeda* Veld (47%), *Cymbopogon-Themeda* Veld (24%), and Dry Sandy Highveld Grassland (74%). *Themeda triandra* is a dominant feature of

this vegetation unit. However, low cover of *Themeda triandra* and related increase in *Elionurus muticus*, *Cymbopogon pospischilii* and *Aristida congesta* is an attribute to heavy grazing and/or irregular rainfall. Vaal-vet sandy grassland is Aeolian and colluvial sand overlying sandstone, mudstone and shale of the Karoo supergroup, as well as older Ventersdorp supergroup andesite and basement gneiss in the north (Mucina & Rutherford, 2006).



Figure 1.7: Grassland soil sampling site 1 in Bultfontein, Free State. Image taken in September 2019.



## Site 2: Cultivated land

Site 2 is a cultivated land under Arenosols (Figure 1.8). The site is adjacent to grassland site 1. During the sampling time there were residues of maize crop in the site. The type of crops planted are C4 plants.



Figure 1.8: Cultivated land soil sampling site 2 in Bultfontein, Free State. Image taken in September 2019.

### Site 3: Grassland

Site 3 is a grassland under Calcisol. Calcisol are types of soil with substantial secondary accumulation of lime. These types of soils are usually not ploughed because they are rich in calcium carbonates and have high calcrete content which is a disadvantage for growing crops. Calcium carbonate dunes were present at the site (Figure 1.9), which is a clear indication that the site has high content of calcium carbonates. There was evidence of minimal grazing in the site during the sampling period. This site falls under Western Free State clay grassland (Gh9). This is a type of grassland that is distributed in the Free State Province, and it covers the parts of western Bloemfontein district (south), Boshof (southwest), Hertzogville (west), Wesselsbron (north) and Brandfort (east). The structure of landscape is limited to flat bottomlands which support dry, species-poor grassland with a high number of salt pans embedded. Dwarf Karoo shrublands surround the playas in disturbed habitats. The geology is made up of deposits of sandstone, mudstone and shale underlie extensive areas of flat to undulating plains, interrupted by dolerite sills in places. There is no river or streams that drain away from these plains, all the water drains into the numerous pans (Mucina & Rutherford, 2006). Pans are a unique feature of this landscape. The dominated grass species at site 3 were Dry *Cymbopogon-Themeda* Veld with Varroid shrubs, *Fingerhuthia sesberefomers*, *Heteropogon contortus*, *Blepharus sp.* and *Eragrostis lehmanniaia*.



Figure 1.9: Grassland soil sampling site 3 in Bultfontein, Free State. Image taken in September 2019.

#### **Site 4: Cultivated land**

Site 4 falls under Luvisols and is adjacent to grassland site 5. The site was rockier and consisted of clay-enriched subsoil. Due to the site being rockier and clay-enriched, the auger could not go deeper than 30-45 cm depth. This site is mainly used for planting maize, however during the sampling period maize was harvested, and the land was fallow with no crop residues (Figure 1.10). Maize is a C4 type of plant.





Figure 1.10: Cultivated land soil sampling site 4 in Bultfontein, Free State. Image taken in September 2019.

### Site 5: Grassland

Site 5 is a grassland and falls under Luvisols. This site is adjacent to site 4 and they are both in Luvisols, however site 5 the maximum depth reached with an auger was 81 cm whereas at site 6 cultivated land 30-45 cm was the deepest depth reached. The point where samples were taken was intensively grazed by wildlife animals (Figure 1.11 left), but there was a plot nearby with minimal or no grazing and that is where the biomass for the site was measured (28.29566 S, 26.03167 E) (Figure 1.11 right). Site 5 falls under Eastern Free State Clay Grassland (Gm3). This grassland is characterised by vegetation and landscape features which include flat to gentle rolling land surfaces that are covered with grassland dominated by *Eragrostis plana*, *Setaria sphacelate*, *Elionurus muticus* and *Aristida congesta*. This type of grassland is distributed in the low-lying areas of the eastern regions of Free State Province. The geology associated with this type of grassland is mudstones and sandstones of the Adelaide formation underlying the north part and Tarkastad formation underlying the south (Mucina & Rutherford, 2006).



Figure 1.11: Grassland soil sampling site 5 in Bultfontein, Free State. Left image where soil samples taken and right image where biomass measurements taken. Images taken in September 2019.

### Site 6: Grassland

Site 6 is a grassland and falls under Lixisols. The site has high clay content, and an impermeable layer was reached at 35 cm depth with an auger. There is also minimal grazing at the site (Figure 1.12). This site falls under Central Free State grassland (Gh6). This type of grassland is dominated by the following grass species: Transitional *Cymbopogon-Themeda* Veld and Moist Cool Highveld Grassland. Central Free State grassland is distributed in Free State Province and slightly into Gauteng Province with a broad zone from around Sasolburg in the north to Dewetsdorp in the south. Kroonstad, Ventersburg, Steynsrus, Winburg, Lindley and Edenville are other major settlements located within this unit. The vegetation and landscape features include undulating plains supporting short grassland. In natural conditions *Themeda triandra* dominates, whereas in degraded habitats *Eragrostis curvula* and *E. chloromelas* become dominant. In severely degraded clayey bottomlands Dwarf karoo bushes are found and overgrazed low-lying areas with substantial clayey soils are susceptible to *Acacia karro* invasion. “The geology is made up of sedimentary mudstones and sandstones mainly of the Adelaide Subgroup as well as those of the Eccia Group found in the extreme northern section of this grassland, giving rise to vertic, melanic and red soils” (Mucina & Rutherford, 2006).



Figure 1.12: Grassland soil sampling site 6 in Bultfontein, Free State. Image taken in September 2019.

## **1.5 Outline of the research**

The study is organised into 5 chapters. Chapter 1 represents the background of the study, problem statement and the rationale of the study and further describes the study area: climate, geology and soils, land cover and land use, and vegetation. The chapter also describes the soil sampling sites.

Chapter 2 deals with the land cover or land use changes. It firstly determines the LC or LU changes in Free State Province, South Africa. Secondly, the chapter assess the vegetation cover for the sites of the start of dust and lastly it establishes the LU practices in relation to dust sources.

Chapter 3 is addressing the climate change mainly focusing on rainfall and temperature patterns in Free State. The chapter is divided into 3 data sections which deals with i) determining the rainfall variation and its influence on agricultural activities, ii) establishing the impact of temperature and frost on agriculture and iii) determining how wind affects Free State agricultural land and initiates dust storms.

Chapter 4 illustrates and discusses the value of ecosystem services and the consequences of their loss. This is achieved by determining the amount of soil organic carbon and nitrogen in grassland and cultivated land, determining the soil texture and grain size distribution for each sampled soil type and lastly by establishing the land management option that is suitable for storing more carbon.

Chapter 5 combine the results of the 3 data chapters and explain how they contribute to international published research in this field. Chapter 5 further draws conclusions based on the results found and discussed from the 3 data chapters. Recommendations are also made in this chapter.



## **Chapter 2: Examining the changes in land cover or land use**

### **2.1. Significance of the chapter**

To combat the negative effects of LCLU, appropriate environmental strategies need to be implemented. These strategies include maintaining and increasing soil organic carbon in croplands. SOC is regarded as vital to carbon sequestration, nutrient availability and water holding capacity. Conversion of croplands to grasslands will further reduce runoff, sequester more carbon, and reduce wind erosion (Jiao, Xu, & Zhao, 2009; Qiu, Yin, Tian, & Geng, 2011). Moreover, agroforestry practices that offer food and fibre yet uphold habitats for threatened species can also be used. Therefore, it is crucial to understand the effects of LCLU changes. This chapter wishes to contribute to the knowledge of how shift in land cover/land use changes affects the occurrence of dust storms. Few studies have drawn attention to factors that contribute to dust originating from South Africa's farmland and the role of vegetation in the occurrence of dust. Thus, that gap in knowledge encouraged the following investigation.

There is insufficient knowledge on how the land can be properly managed to reduce dust and store more carbon. To fill this knowledge gap, trends of LCLU change over the years in relation to dust need to be understood. Secondly, using the data for the present study suitable environmental management options to reduce dust and have soils with high nutrient content can be identified. It is vital to combat the negative effects of LCLU change as they cause a great threat in present and more especially in the future. The spatial trends of LC, types of LC and their intensity of related land management information is crucially needed when trying to discover and measure the impact of LC change on wind erosion. Thus, this chapter will specifically focus on land cover or land use changes, the associated role of vegetation in the occurrence of dust and lastly the different crop and land cover types in associated dust source areas.

### **2.2 Aim**

To ascertain whether the land cover is shifting from grassland towards cultivated land and causing dust.



## 2.3 Objectives

- To examine the LCLU changes in Free State, South Africa.
- To determine the role of vegetation in the occurrence of dust.
- To assess the dominating crop and LC around dust sources.

## 2.4 Background to the study

Land cover or Land use (LCLU) has largely been considered a local issue, however it is now becoming a force of global importance (Foley, et al., 2005). Land use activities have changed a huge amount of the planet's land surface. This has been done by either changing natural landscapes for human use or altering management practices on human-dominated lands. Clearing of forests, practicing subsistence agriculture, increasing farmland production, or expanding urban centres are predominant world's landscape changes. Land use practices differ significantly across the world; nevertheless, their definitive consequence is usually similar. Foley, et al., (2005) note that these outcomes include the acquisition of natural resources for prompt human needs, often at the expense of degrading environmental conditions.

LCLU changes have several causes and consequences. According to the studies done across the globe about environmental impacts of land use, it is evident that LCLU practices have played a significant role in changing climate globally (Foley, et al., 2005; Perrings et al., 1997). Foley et al., (2005), argue that from 1850 approximately 35 % of anthropogenic carbon dioxide [CO<sub>2</sub>] emissions were the result of land use. Land use practices such as cultivation, results in the disturbance of soil which then result in the release of CO<sub>2</sub> by microbes that are exposed to oxygen on the surface, thus leading to reduction in the SOC store.

Changes in LCLU also affect biodiversity whereby soil and water are degraded and native species are overexploited (Lambin et al., 2001; Perrings et al., 1997). Biodiversity is also reduced by LCLU changes by converting the native landform to farming land (Perrings et al., 1997), for instance during deforestation loss of species may occur.

Climate can also be affected by LC changes through water balance and surface energy changes. Lambin et al., (2003) state that "changes in LCLU affect climate through its effects on net radiation, also by dividing the energy into sensible and latent heat, and partitioning of precipitation into soil water, evapotranspiration, and runoff". Studies showed that LC changes

affect climate mainly through changes in water balance, whereas temperature and boreal vegetation changes impact climate largely through surface radiation balance changes (Foley, et al., 2005; Lambin et al., 2003). Climate is expected to be warmer and drier if tropical forests are cleared, although clearing temperate and boreal forest is usually believed to cool the climate, mainly through increased albedo. Research shows that evaporation can be lowered by reduced vegetation cover, impermeable surfaces, and buildings. Urbanization and other land use changes are the result of temperature increase in the US over several decades (Foley, et al., 2005). Air quality also changes due to land use practices by changing emissions and atmospheric conditions that affect reaction rates, transport, and deposition. Land use change also affects air quality by causing Ozone ( $O_3$ ) to increase due to high urban temperatures.

Changes in LCLU and land management practices have also resulted in issues like wind erosion. Rezaei et al., (2016) argue that wind erosion is a factor of land degradation and has therefore been regarded as a main problem in arid regions. Wind action has been recognised as a vital environmental problem in erosion, transport, and deposition of fine particles. According to Rezaei et al., (2016), there are inadequate studies that investigated the influence of LCLU changes on wind erosion. Thus, the present study wishes to close that gap in knowledge.

Wind erosion is a crucial process in land degradation, nonetheless there is little knowledge about it in relation with LCLU changes. Erosion rates are affected by soil physical and chemical characteristics, roughness and land management practices (Rezaei et al., 2016). These factors differ significantly between different LCLUs such as croplands and rangelands. Wiggs and Holmes, (2011), conducted a study which focused on wind erosion and dust generation in the western-central Free State. The investigation indicated that the western-central Free State where commercial dryland agriculture is practised is susceptible to dust emissions and human activities are the main driver of wind erosion. Furthermore, Eckardt et al., (2020), investigated South Africa's dust sources and the findings showed 178 dust sources which mostly originated from Free State, South Africa. Commercial agriculture, grassland and shrubland were found to be the major dust sources in Free State. Moreover, most events occurred between 2015 and 2016 and according to the Standardised Precipitation Evapotranspiration Index (SPEI) these years had severe drought (Eckardt et al., 2020). Factors such as low rainfall, severe drought, sparse vegetation cover, and high wind speed play a significant role in generating dust (Eckardt et al., 2020). Dust events are thus observed to occur in regularly disturbed lands which are left bare during dry and windy seasons. Moreover, Vos et al., (2020) states that dust emissions can

lead to land degradation due to removal of fine soil particles and organic material, specifically in semi-arid and arid regions.

Remote sensing has been widely used for better understanding of land surface characteristics, dynamics and monitoring LC or LU changes. Rezaei et al., (2016) state that multispectral satellite data have proven to be a valuable resource for monitoring LC or LU changes. Amongst the existing multi-spectral imaging systems, Landsat satellites have been commonly used to derive information on LC or LU changes.

Even though environmental conditions are suffering due to changes in LC, food production has grown significantly over the years. Research shows that cropland and pasture have become one of the major terrestrial biomes on the planet, occupying approximately 40% of the land surface (Foley, et al., 2005). The world grain harvested have doubled since the past four decades and now they surpass approximately 2 billion tons per year and about 12 % of this increase is official world cropland area. Irrigated crop land area has increased by ~ 70 % over the past 40 years (Foley, et al., 2005). Food production has considerably increased due to modern agriculture, however the negative impact about agriculture is that it has caused an extensive damage such as soil erosion, reduced fertility, and overgrazing. Agriculture is therefore triggering a great but short-term increase in food production while causing a long-term loss in ecosystem services.

## **2.5 Literature review**

Human modification of landscapes is one of the impacts of land cover change that may contribute up to 60 % of global wind erosion. Additionally, anthropogenic land cover changes such as cropland development into rangelands contribute approximately 25 % of wind eroding areas globally (Galloza et al., 2018). Studies have reported on the impact of LCLU on wind erosion and the present study also wish to improve on this knowledge. To come up with mitigation measures to soil degradation and build and strong agricultural system, the impacts of land cover change on wind erosion needs to be precisely resolved. Studies that investigated the impact of LCLU are reviewed, together with the methods used to achieve this.

### 2.5.1 Summarized studies about impact of LCLU changes

Midekisa et al., (2017) state that for better understanding many of the Earth's land surface processes, it is vital to measure and monitor the spatial and temporal dynamics of the global LCLU. Land surface dynamics such as drought, urbanization, and flood are affected by human-induced LC changes and therefore have an impact in the world's population. Therefore, better understanding of these changes can allow quantifying and monitoring trends in agriculture, freshwater resources, forest cover and disease transmission. However, the lack of frequently updated, continental-scale, and high resolution (30 m) land cover data limit the capability to better understand the spatial extent and the temporal dynamics of land surface changes. Midekisa et al., (2017), therefore applied an approach to quantify continental land cover and impervious surface changes over a long period of time (2000-2015) using high resolution Landsat satellite observation and Google Earth Engine cloud computing platform. Landsat 7 was used, annual LCLU maps for continental Africa between 2000-2015 were produced. The results indicated that the continent has changed during the study period. The study thus suggested that the approach taken here can be used to produce continental LCLU products.

Wind erosion is a complex process influenced by different factors, LCLU is one of them and these land management practices are observed to change progressively. Rezaei et al., (2016), investigated the impact of LCLU changes and land management on wind erosion in southern Iran. Remote sensing data (Landsat ETM+ and Landsat 8 imagery of 2004 and 2016) was used for LC or LU mapping. Iran Research Institute of Forest and Rangeland (IRIFR) model was used to estimate wind erosion changes. Cross-tabulation was used to quantify the quantity of changes in wind erosion and LCLU between the two years. To distinguish LCLU related to wind erosion, results were found by merging the original spectral bands with synthetic bands and using maximum likelihood classification algorithm (Kappa Coefficient of 0.8 and 0.9 for Landsat ETM+ and Landsat 8 respectively). The IRIFR modelling results indicated that wind erosion has likely improved from 2004 - 2013.

When comparing the change in the potential of wind erosion with LCLU change, it was apparent that soil erosion and dust occurrence has increased generally in harmony with increase of area of agricultural practices. The alteration of rangeland to agricultural land was a main land use change which led to more agricultural practices and associated soil loss. Furthermore, results indicated an increase in sandification which is also clear evidence of increasing in soil erosion. Areas with high sediment yield potential were observed to have increased. The current

study will also adopt a similar approach to ascertain whether the land cover is shifting from grassland to cultivated land and if land use is shifting to fallow land and causing dust.

Changes in land cover intensify wind erosion in dryland and these have become a global problem (Galloza et al., 2018). Ecological land classification was used to explore dust emission responses to land cover change. A dust emission model was applied over a rangeland in the northern Chihuahuan Desert, New Mexico, USA and evaluated spatiotemporal patterns of modelled horizontal sediment mass flux and dust emission in the context of ecological sites and their vegetation states, representing a diversity of land cover types. The results indicated that land cover change, determined by changing patterns of land use and land management intensity, have a large impact on global rates of wind erosion. Detecting and quantifying the impacts of land cover change on wind erosion requires information about spatial patterns of land cover, linked with information about the types and intensities of associated land management. The present study therefore aims to improve this knowledge by identifying the trends of LCLU changes and providing mitigation measures for land management in Free State and South Africa.

Webb & Pierre, (2018), argued that LCLU changes influence the rate of wind-driven soil erosion and mineral dust emissions. They conducted a study to critically review the drivers of anthropogenic dust emissions. The results showed that human land activities, such as agriculture and livestock grazing, possibly caused the disturbance in soil surface and changes in vegetation species composition, structure, and spatial patterns. These land cover changes can upsurge the vulnerability of landscapes to wind erosion. The high rates of wind erosion and dust emission impact human health, soil organic carbon and nutrient cycles, the energy budget, hydrologic cycle, and climate. The wind-driven soil loss and nutrient decline and dust-climate feedbacks, in turn have an impact in agricultural production and rates of ecological change and dryland expansion. It was concluded that LCLU changes have a possibly enormous impact on rates of wind-driven soil erosion and dust emission, but the extent of these impacts remains highly uncertain. This literature has motivated the present study which seeks to improve the knowledge about factors or environmental conditions that results into dust events in Free State, South Africa and find suitable land management options.

Wiggs and Holmes, (2011), conducted a study which focused on wind erosion and dust generation in the western-central Free State Province of South Africa. According to (Wiggs &

Holmes, 2011), this study was the first to quantify the degree of wind erosion on agricultural soils in the region under prevailing winter to spring climatic conditions and land management practices. The data for the study was collected using arrays of cup anemometer, dust deposition traps and saltation impact sensors. The results indicated that substantial extents of dust are mobilized, predominantly during the months of September and October. These months are not the driest months, but rather the very windy months. Additionally, the amount of collected dust was found to correlate well with measures of wind erosivity that weight the impact of higher wind speed (Wiggs & Holmes, 2011). Thus, the threshold of wind erosion responded closely to changes in surface and aerodynamic roughness. As surface roughness is known for its substantial role in controlling erosion threshold, the results indicated that opportunities exist for well-designed farming practices to control wind erosion. Such opportunities include ploughing ridges perpendicular to the most erosive winds to effectively mitigate the wind erosion hazards, even in strong winds.

### **2.5.2 Dust Bowl**

Studies have shown that changes in LCLU happens globally, regionally, and locally. It is therefore of interest to quantify whether we are having another Dust Bowl. The first Dust Bowl was observed during 1930 and lasted for a decade (Hansen & Libecap, 1940). The US Great Plains were hit by severe drought and excessive wind-driven soil erosion of overgrazed rangeland and soil exposed by the use of farming practices that were not suitable for the semiarid region (Baumhardt, 2014; Hansen & Libecap, 1940). Dust coming from the eroding soils filled the air and subsequently buried the farm equipment, and buildings therefore making the living conditions of many Great Plains residents intolerable (Baumhardt, 2014). Woster (2004), state that Dust Bowl began as fulvous dirt that blown all the way from the plains to the East Coast and beyond. Throughout this Era climate change played a substantial role in causing dust storms.

Nightmare, (2009), state that drought is the most persistent problem caused by climate change. Baumhardt, (2014), supported this argument and stated that it was the climatic conditions of drought from 1930 to 1940 that fundamentally triggered wind erosion of excessively tilled land and Dust Bowl. During drought the precipitation patterns shift, resulting in long dry seasons and very short wet season if any. The evaporation demand becomes high and if the soil is

relatively dry, then the solar radiation goes into baking the soil, leading to further increase in temperatures (Nightmare, 2009). In the 1930s the spring and summer seasons received little rainfall over a large part of the eastern United States. A combination of extended intensive drought and severe land use thus caused the Dust Bowl.

During the 1930s agricultural production began to increase significantly on the American Plains, and natural grasslands were gradually cultivated for crops in the late nineteenth century (Hornbeck, 2012). According to Hansen & Libecap, (1940), approximately 480 tons of topsoil per acre were blown away by strong winds leaving the soil degraded, air quality declined and causing harm to health. Hornbeck (2012), state that these dust storms were unexpected and there was a fear that the region would become the once imagined American Desert. The Dust Bowl period continued through 1938 and ended with the return of wetter weather and increased ground cover.

The farming practices contributed to Dust Bowl as the result of extreme cultivation of land in the 1930s, which exposed dry soil to wind. The agriculture in Great Plains developed a reliance on overgrazing and extreme cultivating, which then exposed loose soil to the wind. Baumhardt, (2014) argued that the farming practices did not match to natural conditions of the Great Plains and therefore resulted in an unstable agriculture and unsafe economy. Thus, the harmful effect of extreme cultivation contributed meaningfully to soil erosion during the Dust Bowl. Soil erosion was also caused by overgrazing and drought conditions, which were then decreased through better cattle management and the use of irrigation. Dust Bowl resulted in a radically change in LCLU. The Great Plains were initially dominated by cultivated dry lands. However, large dust storms swept the topsoil from those lands such that, by the 1940s many Plains areas had cumulatively lost more than 75 % of their original topsoil (Hornbeck, 2012). The farmland was left severely eroded. In severe dust storms light and fertile topsoil turn out to be airborne and was carried far away. However, these materials were critical for dryland wheat farming, which dominated the Plains. Each loss of soil from consecutive dust storms removed more plant nutrients, until remaining ground was rather sterile. The loss of soil also took with it most of the organic carbon and this component takes longer to be accumulated again especial in cultivated land. This therefore left the US Great Plain soils carbon depleted by the 1940s. Several mitigation measures were made in response to the effects of Dust Bowl.

Responding to the disastrous effects of the Dust Bowl, agriculture was empowered with the new noninverting tillage implements that can penetrate the hard-dry soils like the

Grahamtloeme plough for controlling weeds while retaining crop residue at the soil surface (Baumhardt, 2014). The innovative wheat-sorghum cropping sequences enhanced soil water storage chances and enhanced the probability of capturing rain for crop use (Baumhardt, 2014). Using the innovative crop sequences with fallow periods and reduced tillage, the efficiency of precipitation storage in the soil improved from about 20 % during the Dust Bowl to more than 40 %. The effects of Dust Bowl were also mitigated by re-establishing the natural grasses using the hay method (Hornbeck, 2012). These inventions have resulted in considerably stable economies and reduced the depopulation trend. In contrast to the farmers of the Dust Bowl, farmers of today are more proactive managers that respond to adverse growing conditions with alternative technology. For instance, when the drought conditions resurfaced in the early 1950's Kansas farmers largely implemented irrigation to stabilize the production. However, Baumhardt, (2014), argued that if irrigation was the dominant factor to prevent soil erosion during the 1950's by offsetting drought conditions, it is likely that the Dust Bowl depressions may eventually return when irrigation becomes impracticable.

Looking at the U.S Dust Bowl case study similar situation have been observed in South Africa. Dust has become a growing concern even in South Africa, especial in Free State which is dominated by agricultural activities. Dust has adverse effects on the entire ecosystem. Dust affect temperatures through the absorption and scattering of solar radiation (Goudie & Middleton, 2001). It may also affect climate through its influence on marine primary productivity, and there is some evidence that it may cause ocean cooling. The dust depositions also provide considerable quantities of nutrients to ocean surface waters and seabed. On the land surface the additions of dust may affect soil formation and can play a major role in the delivery of sediments to the oceans. Dust storms also have direct implication for human, as they cause human health problems. Shepherd et al., (2016) state that the inhalation of fine dust particles exposes individuals not only to hazardous fine mineral particles, but also to harmful combinations of pollutants, sores, bacteria, fungi, and potential allergens carried along with mineral dusts. The reviewed studies have motivated the current study to investigate the shift or change in LCLU and how the change is possible contributing to dust in Free State, South Africa. More dust events (71 %) originated from Free State (Eckardt et al., 2020); hence this region was used as a study area.

The review above has helped to determine the suitable method for this chapter. These methods and type of data that will be used in this chapter are widely used to answer similar research questions elsewhere.



## **2.6 Methodology**

### **2.6.1 Data collection**

The aim of this chapter was to ascertain whether the land cover is shifting from grassland towards cultivated land and causing dust. The type of data that were used to achieve this investigation were LCLU data, the remote sensing data (MODIS enhanced vegetation index EVI) and crop data obtained from Department of Agriculture, Forestry and Fisheries (DAFF) for the period 2006-2016. This period was used because Meteorsat 2nd generation (MSG) first recorded the dust event in Free State in 2006 and saw an increase towards 2016, thus the study seeks to find the link between the occurrence of dust and LCLU changes during the 2006-2016 period. ArcGIS was used as a tool to create LCLU and crop type maps. A Google Earth Engine (GEE) Java script was written to extract the time-series (2006-2016) of the MODIS EVI for each dust event detected by MSG imagery. The LCLU maps contributed to identifying how the LCLU have changed spatially and temporally. The purpose of MODIS EVI data was to determine the amount of vegetation before and during dust event. The crop and land cover type maps contributed to the understanding of what was occupying the land or what were the land surface conditions during the onset of each dust event. The crop type information will also be linked with the weather data, to determine the relationship between climate change and cultivation activity changes.

#### **2.6.1.1 LCLU data**

To determine the spatial and temporal changes of LCLU, data were extracted from Agricultural Research Council database for 2000 and 2013-2014 period using ArcMap 10.6.1. The study only used the 2000 and 2013-2014 national LCLU maps because the study was more interested in the change that took place in Free State from 2006 – 2016. The two maps were sufficient for the present study to demonstrate the change of LCLU over the years. The 1990, 2018 and 2020 national land cover maps were not used because they were out of scope, however the study recommends them for long term variation or shift of land cover. The data was presented in ArcMap and spatial and temporal changes of LCLU were determined.

### **2.6.1.2 MODIS EVI data**

To assess the vegetation cover for the site of the start of dust MODIS EVI was used. In a wide variety of terrestrial science, satellite vegetation index (VI) products are commonly used to monitor and characterize the Earth's vegetation cover from space (Jiang, Huete, Didan, & Miura, 2008). These VI measure vegetation canopy, a composite property of leaf chlorophyll, leaf area and canopy cover. Enhanced Vegetation Index (EVI) is one of the VI products that was developed for Terra and Aqua Moderate Resolution Imaging Spectroradiometers (MODIS) (Jiang et al., 2008). EVI offers enhanced sensitivity in high biomass regions while minimizing soil and atmosphere influences. Nevertheless, in addition to the red and near-infrared bands, EVI is limited to sensor systems designed with a blue band, making it difficult to generate long-term EVI time series as the normalized difference vegetation index (NDVI) counterpart (Jiang et al., 2008). MODIS EVI was chosen to be used in this study because of its medium resolution (500m), more features can be detected from the pixels. Moreover, MODIS has a temporal resolution of every 16 days, which is an advantage when the study wishes to understand the trend of vegetation. MODIS EVI data was analysed using a GEE tool. GEE makes the data available in various ready-to-use computed products such as NDVI and EVI vegetation indices (Gorelick et al., 2017).

### **2.6.1.3 Land cover and Crop data**

Land cover and crop data was used to better understand the land surface conditions during each dust event. Land cover and crop data was extracted from Department of Agriculture, Forestry and Fisheries (DAFF) database for the period 2006-2016 using ArcMap 10.6.1. The maps that show spatial and temporal variation of crop and land cover over the years were plotted. Furthermore, pie charts that shows the percent of crop and land cover types around each dust source were plotted using excel.

## **2.6.2 Data analysis**

ArcGIS was used for processing of LCLU layers (2000 and 2013-2014 shapefiles). Google Earth Engine (GEE) was used to analyse MODIS enhanced vegetation index (EVI) time series

for the different sites of the start of a dust in 2006-2016. A script for MODIS enhanced vegetation index (EVI) time series for the different sites of the start of a dust in 2006-2016 was ran on GEE (Appendix 2.1). EVI for the actual day of each dust event was compared with the EVI of the same day in the previous year with the purpose of identifying whether there is a certain trend that vegetation follows that might lead to occurrence of dust. Additionally, annual EVI average of the dust source year was compared with the annual EVI average of five previous years. Five years were chosen for analysis because they are sufficient to provide the clear trend of vegetation cover.

ArcGIS was also used for processing of land cover and crop types and dust points from 2006-2016. Different land cover and crop types were overlaid with dust points for each year (2006-2016). Maps that showed the spatial variation of all the land cover and crops across the entire Free State from one year to another were created. The maps were created with the purpose of identifying the change in crop cover over 2006-2016 period. A 10 km radius buffer was further created around each dust source to include all the crop and land cover types within each dust event point. Land cover and crop cover percent was calculated from buffer area and crop area, with the purpose of identifying the percent of crop and land cover within each dust event. To obtain the crop and land cover percentage within each dust event, land cover and crops around each 10 km buffer were clipped and area geometry was calculated. The area for land cover and crops was then divided by the area of the 10 km radius buffer and multiplied by 100 to get the percentage. Additionally, the area of crop and land cover around each 10 km radius buffer was calculated with the purpose of identifying the area composition. Land cover and crop type data were analysed to find the dominating land cover and crop types within each dust source. Line graph and pie charts were used to present this data.

## **2.7 Results**

### **2.7.1 Introduction**

Firstly, the 2000 and 2013-2014 LCLU maps are presented to address objective 1. These maps were analysed with the purpose of identifying the spatial and temporal LCLU changes in Free State over the years. Secondly, MODIS EVI for different sites of the start of a dust in 2006-2016 are presented to address objective 2. These results are presented with the purpose of

answering the second objective which is to determine the role of vegetation in the occurrence of dust. Thirdly, crop and land cover maps are presented with the purpose of identifying the spatial and temporal crop and land cover types that covered the land. The crop and land cover maps are further focused into the western part of FS where many dust sources were recorded to determine the crop and land covers in the dust sources. Total percentage of crop and land cover within each dust event and dust area composition and are also presented.

### **2.7.2 Spatial and temporal variation of LCLU in relation to dust**

The 2000 LCLU map classified by Agricultural Research Council has various land cover types (Figure 2.1). Unimproved natural grassland is a dominating land cover type covering most of the Free State (78,859,819 ha) followed by shrubland & low fynbos (41,099,178 ha), Thicket/dense bush (49,370,46 ha) and cultivated land (34,527,13 ha) respectively. There are other land cover types visible in small extents. The 2013-2014 LC/ LU is characterized by various land cover types (Figure 2.2). Grassland is the most dominating land cover (37,727,2 ha) followed by cultivated land (28,472,7 ha), and shrubland & low fynbos (25,167,8 ha) respectively. Even though grassland is still dominating in 2013-2014 it has decreased by 22 % from 2000. Cultivated land on the other hand has increased by 26 % from 2000 to 2013-2014.

These maps were compared with the purpose of determining the spatial land cover changes over the years. Even though these two maps are different in data products, they show that Free State LCLU has changed from 2000 to 2013 and 2014. In 2000 natural grassland was a dominating land cover, and 13 years later it was still a dominant land cover but cultivated land has also significantly dominated the area. Shrubland and low fynbos are also becoming more prominent as shown in the 2013-2014 map. In accordance with the observations from the 2000 and 2013-2014 land cover maps cultivated land has generally increased but its extent is lower than grassland spatial extent. However, it is not evident that these are real land cover changes. It is possible that the changes observed are differences in data products or error in data products rather than the actual changes in land cover.

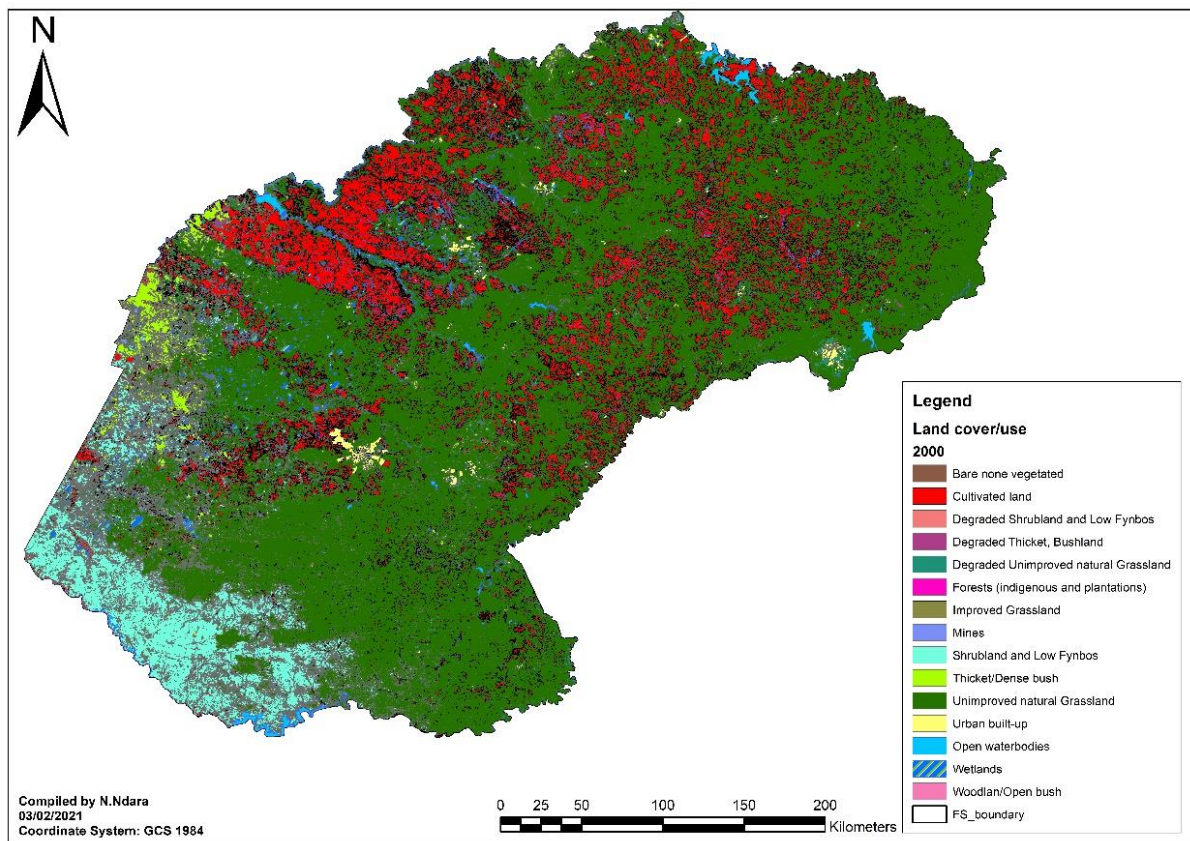


Figure 2.1: LCLU of the Free State Province in 2000. Data extracted from Agricultural Research Council database. Red LC is cultivated land and green is grassland.

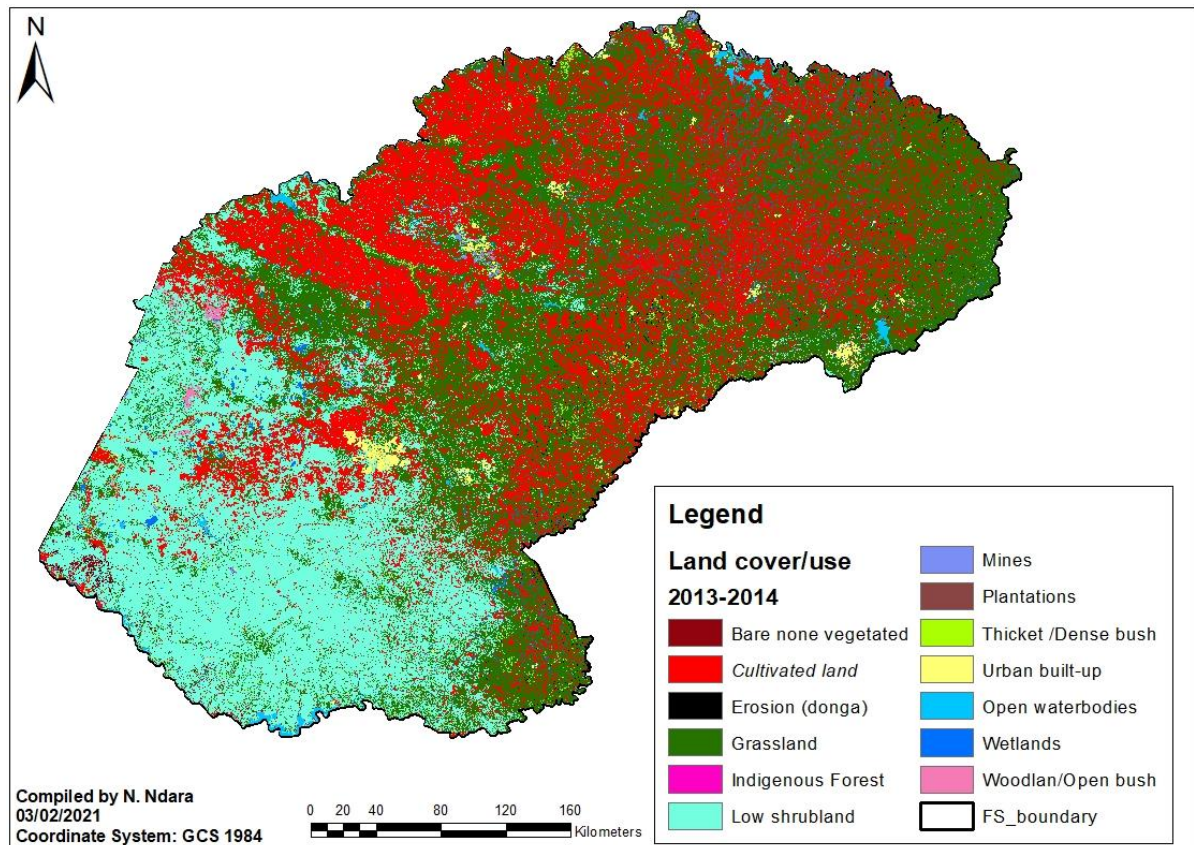


Figure 2.2: LCLU of the Free State Province in 2013-2014. Data extracted from Agricultural Research Council database. Red land cover is cultivated land and green is grassland.

Table 2.1 summarizes the LCLUs that were present in 2000 and 2013-2014 maps. Approximately 95 % of the LCLU in 2000 map were also present in 2013-2014 map, however spatial extent has changed. Grassland has decreased from 2000 to 2013-2014 by 22 % and cultivated land has increased by 26 %. LCs such as degraded shrubland & low fynbos, degraded thicket bushland, and degraded unimproved natural grassland were only present in 2000 map. Generally, there is relatively less modification in LCLU, however the extent of each LCLU has changed.

Table 2.1: Summary of the data contained in LCLU maps. Table shows the number of hectares covered by each LC. Data obtained from Agricultural Research Council database.

| LC/LU description                     | 2000 LC/LU |            | 2013-2014 LC/LU |            |
|---------------------------------------|------------|------------|-----------------|------------|
|                                       | ha         | Percentage | ha              | Percentage |
| Bare none vegetated                   | 10708      | 0.0        | 4198            | 0.0        |
| Cultivated land                       | 3452713    | 3.0        | 284727          | 29.0       |
| Degraded shrubland & low fynbos       | 12188      | 0.0        | 0.0             | 0.0        |
| Degraded thicket, bushland            | 9240       | 0.0        | 0.0             | 0.0        |
| Degraded unimproved natural grassland | 226807     | 0.0        | 0.0             | 0.0        |
| Erosion (donga)                       | 47322      | 0.0        | 2065            | 0.0        |
| Forest (indigenous)                   | 459        | 0.0        | 514             | 0.0        |
| Improved grassland                    | 7585       | 0.0        | 377272          | 39.0       |
| Mines                                 | 19969      | 0.0        | 1795            | 0.0        |
| Plantations                           | 12660      | 0.0        | 3823            | 0.0        |
| Shrubland & low fynbos                | 41099178   | 32.0       | 251678          | 26.0       |
| Thicket/dense bush                    | 4937046    | 4.0        | 11308           | 1.0        |
| Unimproved natural grassland          | 78859819   | 61.0       | 0.0             | 0.0        |
| Urban built-up                        | 113523     | 0.0        | 7782            | 1.0        |
| Open waterbodies                      | 168261     | 0.0        | 7225            | 1.0        |
| Wetlands                              | 245439     | 0.0        | 16763           | 2.0        |
| Woodlan/Open bush                     | 124        | 0.0        | 8496            | 1.0        |

Maps were further focused on the western part of Free State which is the main dust emission area (Figure 2.3 and 2.4). From the 2000 LCLU map (Figure 2.3) the main dust emission area was dominated by shrubland & low fynbos covering 40914664 ha, followed by unimproved natural grassland (39507824 ha), thicket/dense bush (4784946 ha) and cultivated land (1502412 ha) respectively. It is apparent from the map that many dust sources originated from the western part of Free State in shrubland, grassland, thicket/dense bush, and cultivated land. These land covers were thus the hotspot of dust events in 2000. The 2013-2014 LCLU (Figure 2.4) was dominated by shrubland & low fynbos (144528 ha), improved grassland (115128 ha) and cultivated land (128308 ha) respectively in the dust emission area. This again provide evidence that shrubland & low fynbos is the main hotspot of dust emission. In 2013-2014 cultivated land was the second largest area that produced dust whereas in 2000 it was unimproved natural grassland.



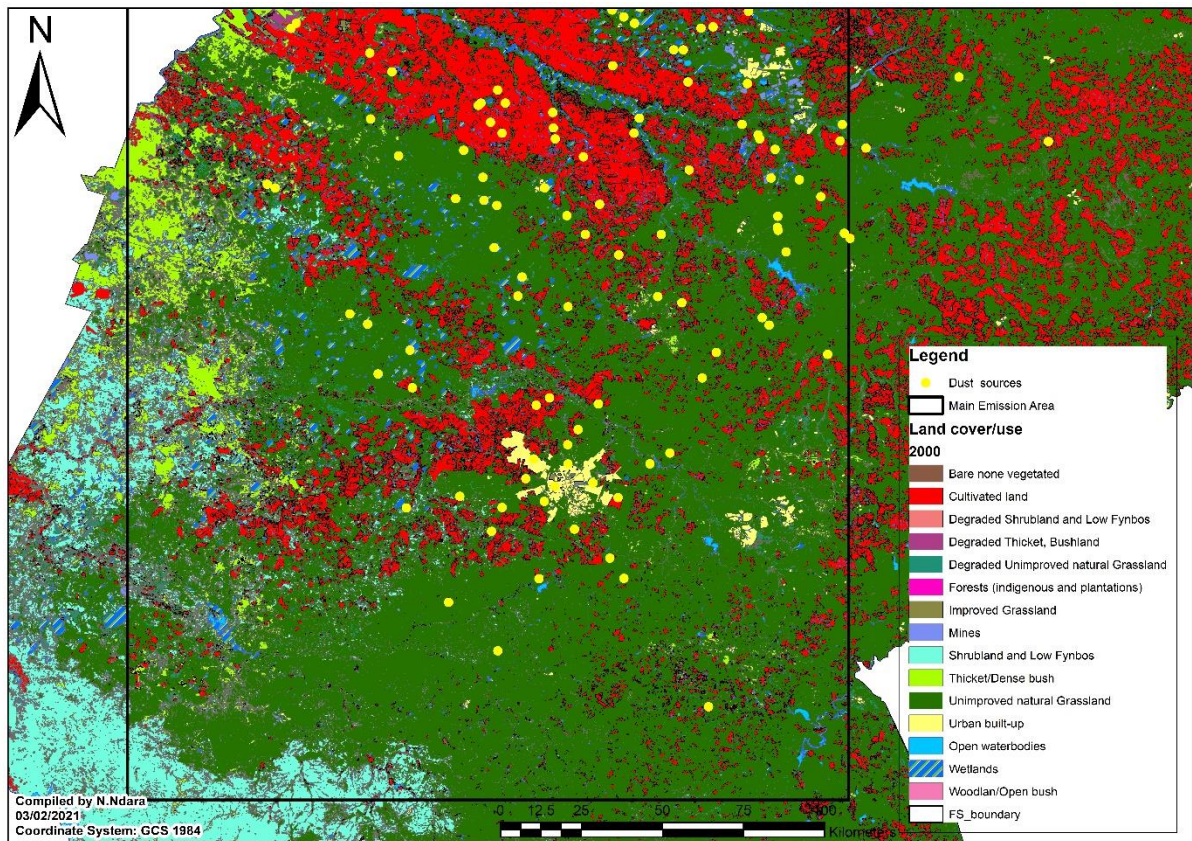


Figure 2.3: LCLU of the Free State Province in 2000 focused on the main dust emission area. Data extracted from Agricultural Research Council database. Red is the cultivated land and green is grassland. Yellow dots represent dust sources from 2006-2016.



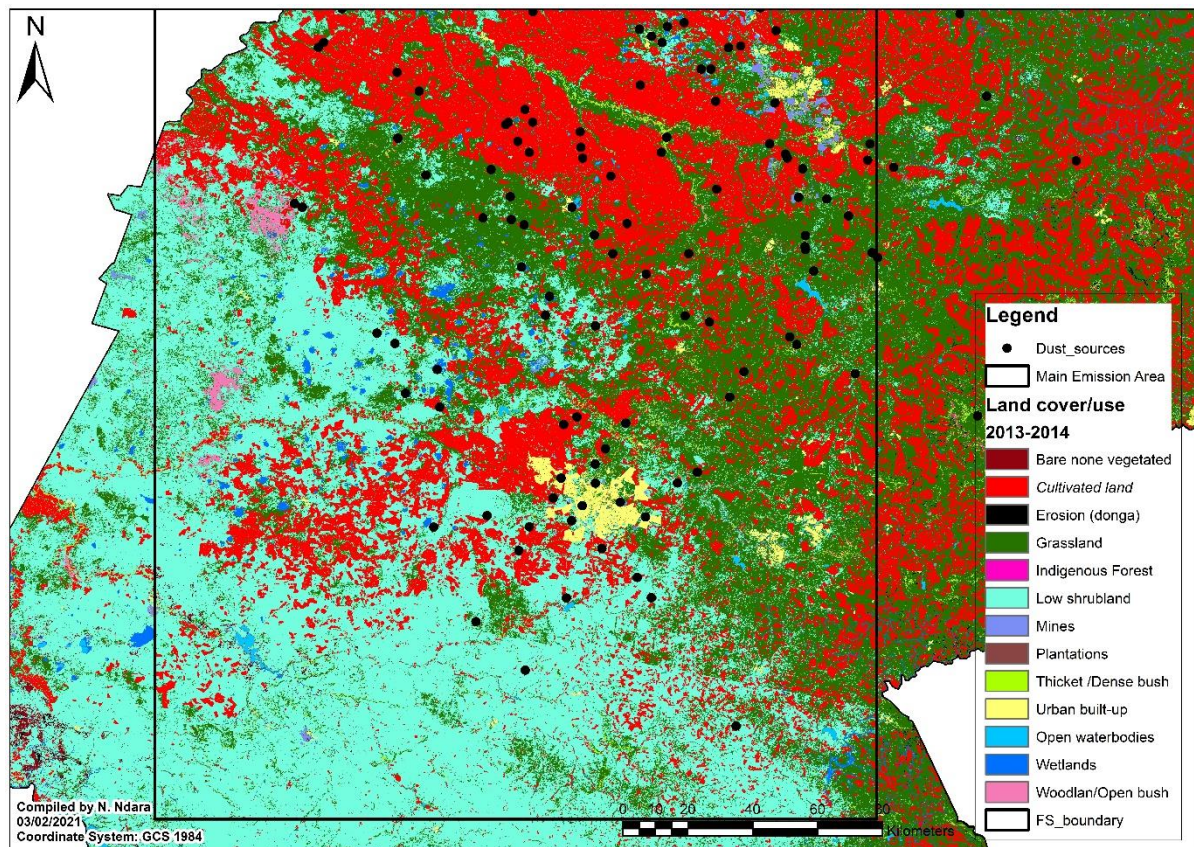


Figure 2.4: LCLU of the Free State Province in 2013-2014 focused on the main dust emission area. Data extracted from Agricultural Research Council database. Red is the cultivated land; light blue is low shrubland and green is grassland. Black dots represent dust sources from 2006-2016.

Table 2.2 shows the number of hectares and percentage of land cover in the main dust emission area. According to 2000 land cover map, the western side of Free State which is the main dust emission area is mostly covered by shrubland & low fynbos (47%), followed by unimproved natural grassland (45%), thicket/dense bush (5%) and cultivated land (2%) respectively. This means shrubland & low fynbos was the hotspot of dust emission. According to 2013-2014 land cover map, western part of Free State is dominated by shrubland & low fynbos (35%), cultivated land (31%) and grassland (28%) respectively. This means shrubland & low fynbos was still the major hotspot of dust emission. Grassland has decreased by 17% in the western side of Free State and cultivated land has increased by 29% from 2000 to 2013-2014.

Table 2.2: Summary of the data contained in LCLU maps around the main dust emission area. Table shows the number of hectares covered by each land cover in the western area of Free State. Data obtained from Agricultural Research Council database.

| LC/LU description                     | 2000 LC/LU |            | 2013-2014 LC/LU |            |
|---------------------------------------|------------|------------|-----------------|------------|
|                                       | ha         | Percentage | ha              | Percentage |
| Bare none vegetated                   | 1899       | 0.0        | 932             | 0.0        |
| Cultivated land                       | 1502412    | 2.0        | 128308          | 31.0       |
| Degraded shrubland & low fynbos       | 8704       | 0.0        | 0.0             | 0.0        |
| Degraded thicket, bushland            | 7725       | 0.0        | 0.0             | 0.0        |
| Degraded unimproved natural grassland | 60962      | 0.0        | 0.0             | 0.0        |
| Erosion (donga)                       | 9703       | 0.0        | 160             | 0.0        |
| Forest (indegenuous)                  | 0.0        | 0.0        | 22              | 0.0        |
| Improved grassland                    | 5779       | 0.0        | 115128          | 28.0       |
| Mines                                 | 11954      | 0.0        | 1161            | 0.0        |
| Plantations                           | 4059       | 0.0        | 970             | 0.0        |
| Shrubland & low fynbos                | 40914664   | 47.0       | 144528          | 35.0       |
| Thicket/dense bush                    | 4784946    | 5.0        | 3969            | 1.0        |
| Unimproved natural grassland          | 39507824   | 45.0       | 0.0             | 0.0        |
| Urban built-up                        | 54556      | 0.0        | 4392            | 1.0        |
| Open waterbodies                      | 40066      | 0.0        | 1903            | 0.0        |
| Wetlands                              | 175535     | 0.0        | 4178            | 1.0        |
| Woodlan/Open bush                     | 16         | 0.0        | 4282            | 1.0        |

### 2.7.3 MODIS enhanced vegetation index (EVI) time series for the different sites of the start of a dust in 2006-2016.

There were 176 dust events observed in Free State from 2006- 2016, and the MODIS pixel EVI for each dust source was extracted (Figure 2.5). Furthermore, the EVI conditions preceding a dust event were determined. The purpose was to ascertain whether vegetation plays a significant role in the occurrence of dust. The EVI for a dust event day was compared with the EVI of the same day in the previous year. This was done for all the dust events and results showed that some dust sources had a high EVI in a year preceding the dust event (for example 20050829 had higher EVI (0.144) than 20060829 (0.135)). However, some dust sources had a low EVI in a year prior the dust event year (for example 20150905 had a low EVI (0.126) than 20160905 (0.152)). This means it is not only vegetation that plays a role in soil erosion but also

other factors such as rainfall, wind speed and temperature. When the area has received rainfall below average coupled with high wind and temperature, the area becomes vulnerable to soil erosion. The year 2009 was the wettest year (760 mm/year) amongst the other years from 2006-2016 and therefore did not have dust events. Generally, there are high chances of dust occurrence in the following year if the previous year also had low EVI. Therefore, current state of the vegetation is not the only factor affecting dust occurrence but also the state of vegetation in the previous year. The range of values for EVI is -1 to 1 (that's the same as an NDVI) where active green vegetation falls between 0.20 to 0.80.



Figure 2.5: Example of a dust event (red arrow) in 29 Aug 2006 (top) and 01 Nov 2016 (bottom), showing the date of the dust event along the EVI time series for the MODIS pixel.

Moreover, annual maximum and average EVI of 5 preceding years were calculated to compare with the annual maximum and average EVI of the dust event year. The results are summarized in Appendix 2.2, and it is noted that some dust sources had a good vegetation (annual average EVI greater than the annual average EVI of the dust event year) in the 5 years prior to the dust event and other dust sources had bad vegetation (annual average EVI lower than the annual average EVI of the dust event year) in the 5 years prior to the dust event. The fact that some years did not have low EVI, but dust still occurred on the 5th year ascertains that dust does not solely rely on the amount of vegetation cover but also on the vegetation type. Dust sources were from different LC types such as riparian zone, cultivated land, bare land and grassland and different soil types (Figure 2.6). However, most dust sources were found in cultivated land (59 dust source areas), followed by bare land (49 dust source areas), grassland (30 dust source areas), and riparian zone (29 dust source areas). This clearly indicates that Free State dust mainly originate in agricultural fields. The red arrow in Figure 2.5 indicates the low EVI that occurred prior to each event. There was clearly no cover crop planted during that growing season. There were approximately 58 dust sources in Luvisols, 46 in Arenosols and 35 in both Calcisols and Lixisols. These observations are rather evidence that dust largely occurs in cultivated land followed by bare land. The processed crop cover data in Figure 2.11 provides further evidence that maize, pasture, and fallow land are the major LU types that have been the sources of dust events.



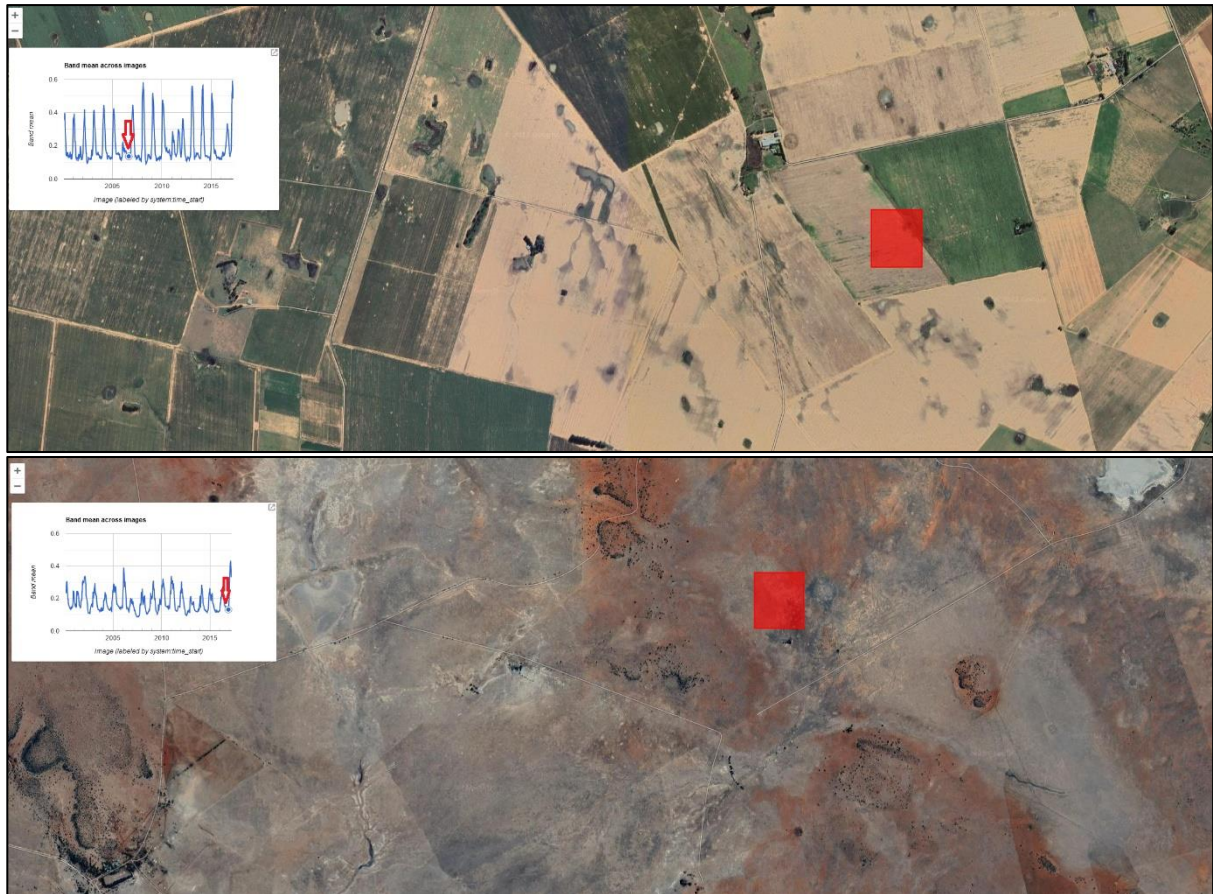


Figure 2.6: MODIS enhanced vegetation index (EVI) time series for the site of the start of a dust cloud (red square) on 29 Aug 2006 (top) and 01 Nov 2016 (bottom) for the MODIS pixel.

Generally, the EVI has been observed to mostly range between 0.1-0.2 from May until December and this is the period where dust events are likely to occur (Figure 2.7). The number of dust events per month in Figure 2.7 corresponds with low EVI period. It is observed that the range from mid-January to April is normally above 0.2 which is an indication of good vegetation, and that period corresponds with no dust event period. This period also corresponds with full maturity of crops that were planted in the previous year. Therefore, sparse, or poor vegetation cover plays a significant role in the occurrence of dust. Wiggs and Holmes, (2011), in their investigation revealed that surface roughness plays a meaningful role in controlling erosion threshold. Additionally, leaving the land fallow for one year does not necessarily result into dust, given that there is a considerable rainfall occurring in that year. However, if the land

is left fallow for more than 1-year, and excessive grazing occurs the soil is bound to lose its structure and thus be vulnerable to erosion.

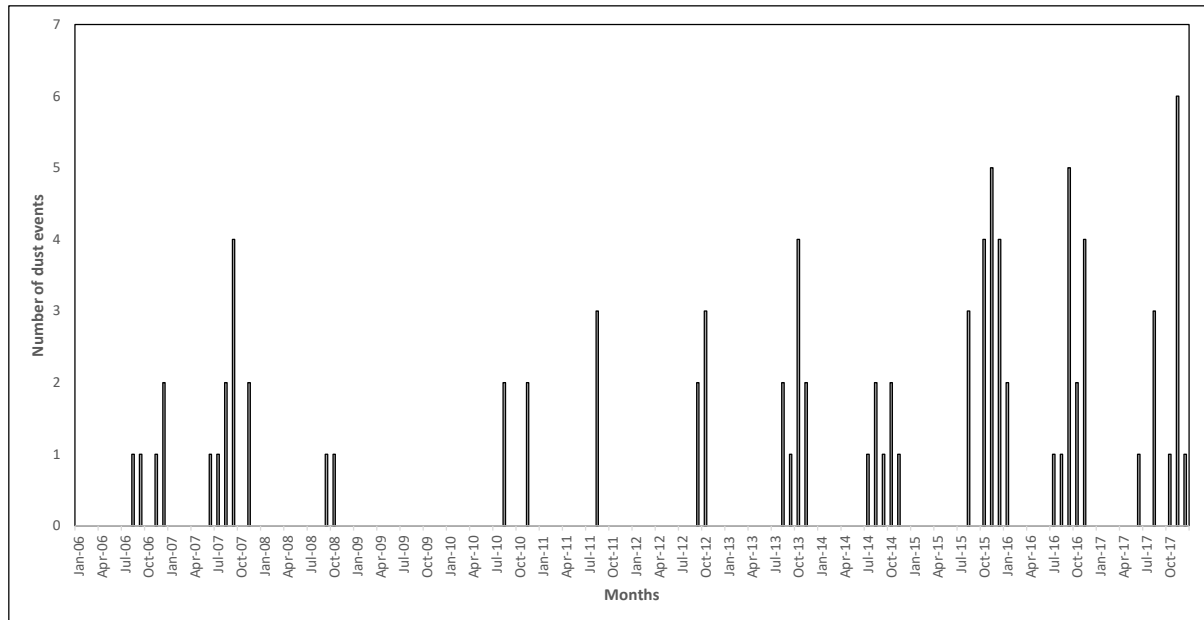


Figure 2.7: Total number of dust events per month in Free State from 2006-2017 (Eckardt et al., 2020).

Vegetation cover in this study was quantified using the vegetation amount for the MODIS pixel. The present study found this analysis not adequate to draw proper conclusions about the relationship between vegetation and occurrence of dust in Free State since the analysis was done in a point form. Therefore, findings from (Eckardt et al., 2020) who investigated at the bigger scale the role of vegetation in the occurrence of dust in Free State were adopted. The study used MODIS – NDVI time series from the Global Agriculture Monitoring (GLAM) project (MOD09 8-day product), and extracted a mask for the whole Free State (Eckardt et al., 2020). The findings were further supported by annual crop data for Free State that was obtained from South African Department of Agriculture, Forestry and Fisheries for selected years under observation. The study used 2011 as the wettest year and 2015 and 2016 as the driest years. Figure 2.8 therefore shows the NDVI levels of the three years compared with the average. NDVI levels for 2011 which is the wettest year start by being higher than the average and drops during winter months but remain higher than the average. In November the average becomes

higher than 2011 NDVI levels. NDVI levels for 2015 at start is above the average and drops in February and remained below average until December. NDVI levels for 2016 at start is lower than the average and remain below average until end of August and peak in September. Generally, the NDVI levels for all the three observed years follow the same trend; starts high then decrease during winter season and starts recovering again at the beginning of summer season. NDVI levels for 2015 and 2016 are low which ascertains why there were a lot of dust events in these years.

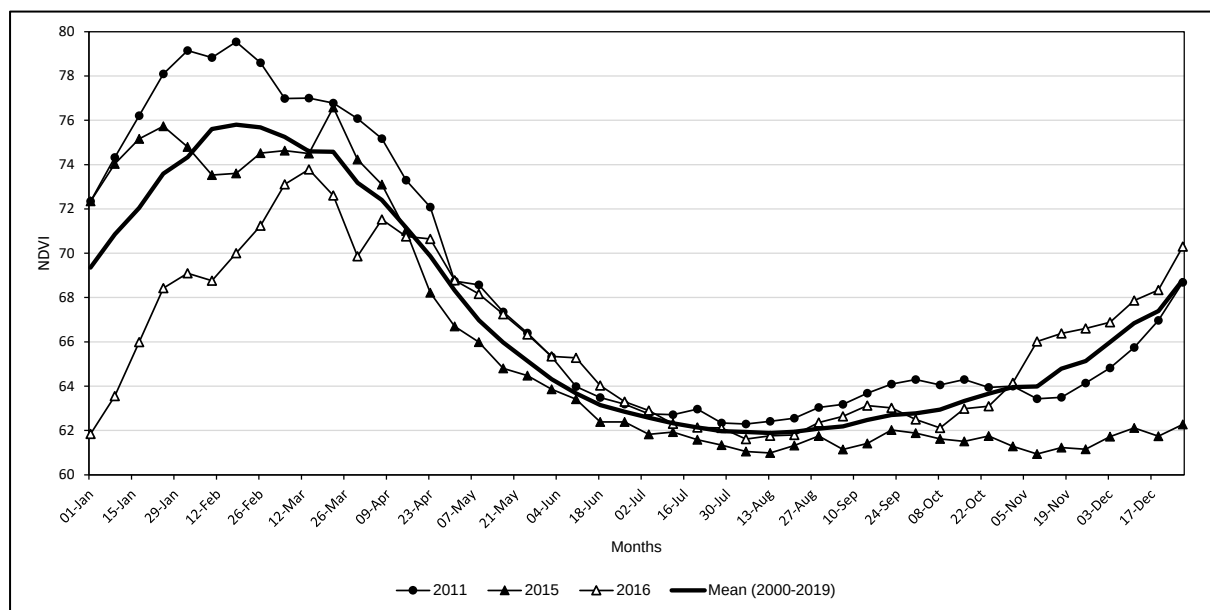


Figure 2.8: Normalized Difference Vegetation Index (NDVI) time series from the Global Agriculture Monitoring (GLAM) project using MOD09 8-day product and applying a Landsat-derived crop extraction mask for the Free State. Comparing the wettest year 2011 and driest years 2015 and 2016 with the average during the observation period.

#### **2.7.4 Spatial and temporal variation of crop and land cover types in relation to dust**

The results in Figure 2.9 and appendix 2.3 shows the spatial and temporal variation of crop and land cover types in the entire Free State Province from 2006-2016. It is apparent that there was a variation in crop and land cover types over the years. According to the crop and land cover maps Free State is mainly dominated by three crop and land cover types: Pasture, fallow land, and maize. These three crop and land cover types cover different parts of the province, with pasture mainly covering north-east part and east- south part of the province. Fallow land and maize mostly cover the western part of the province. Interestingly a year dominated by maize was found to have few patches of fallow land for instance 2007 and a year dominated by fallow land had few patches of maize specifically in the western part of the province (e.g., 2015 and 2016). This simple means when maize has been planted a small amount of land is left bare. 2009 was considerable different from all other years, there was notable spatial variation of crop and land covers with maize being the dominating one across the province followed by Pasture. There were also significant patches of other crop cover types such as wheat in the eastern and western parts of the province and no dust events were observed in this year. It is observed that the dust sources were generally found in the western part, and they corresponded mostly with fallow land (e.g., 2015 and 2016). A study by Cho et al., (2015), proved that excessive bare land has resulted to more dust in Asia and this is also evident in the present study.

The crop and land cover patterns were not consistent over the years, i.e., some years had a notable variation of different crop and land cover types (2009), some years were mostly dominated by pasture and maize (winter 2014- summer 2015) and other years were dominated by fallow land and pasture (2015 and 2016). According to Figure 2.9 and appendix 2.3, it is evident that dust sources were mostly found in 2006, 2015 and 2016 and these years were dominated by fallow land and pastureland cover types. Figure 2.9 is the 2006 map which was chosen to represent the wet years and Figure 2.10 is the 2016 map representing the dry years. Zou and Zhai, (2004) in their study conducted in Northern China, presented evidence that vegetation is an important factor that affects the occurrence of dust events. The evidence that emerged in this paper showed that poor vegetation results in the occurrence of dust. These findings rather match with the findings of the present study, as many dust sources were found to correspond with fallow land.



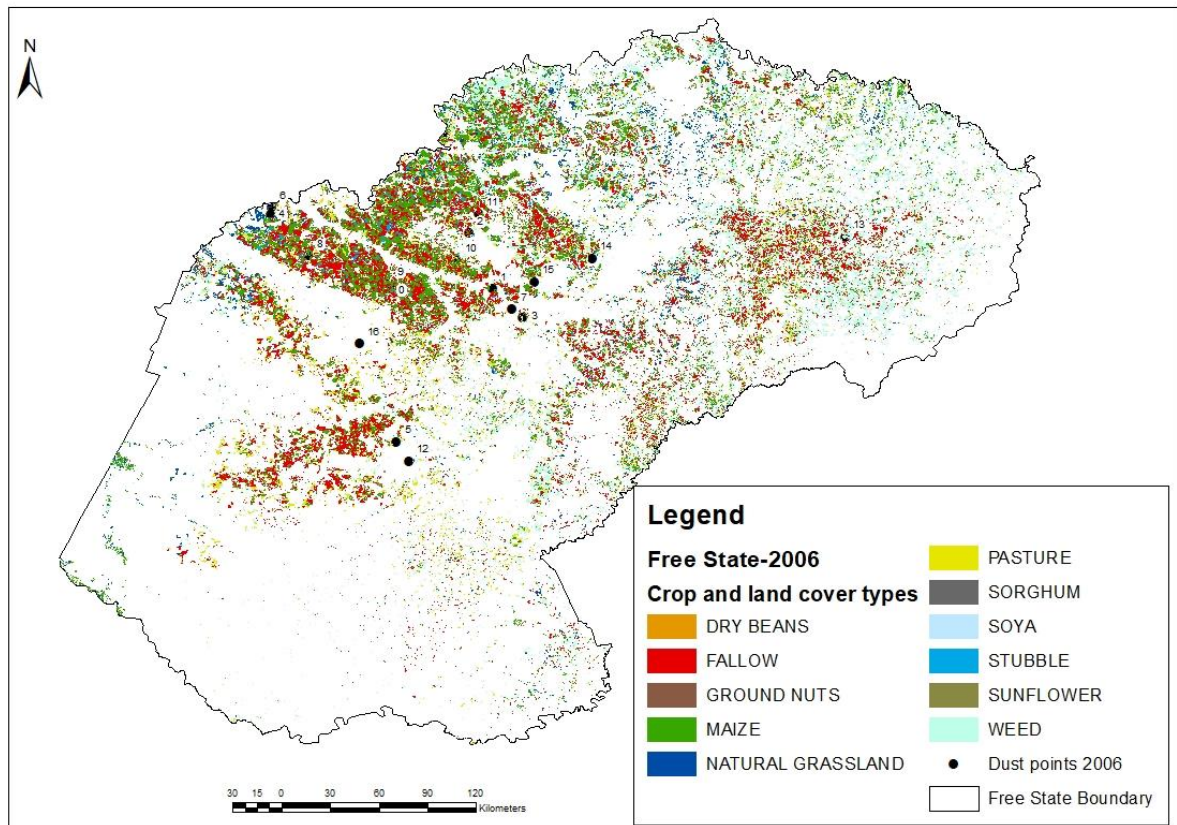


Figure 2.9: Crop and land cover type spatial variation and dust points in 2006 (wet year) in the entire Free State. Data extracted from Department of Agriculture, Forestry and Fisheries database.

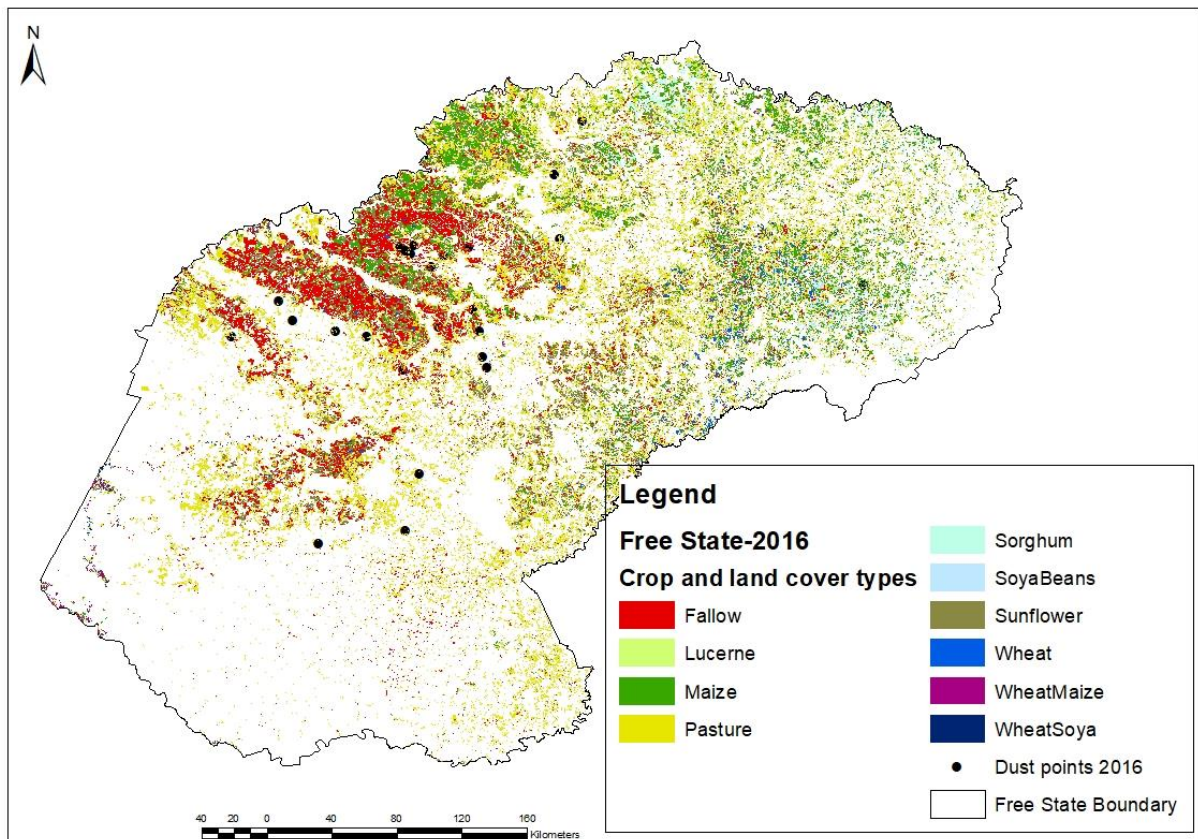


Figure 2.10: Crop and land cover type spatial variation and dust points in 2016 (dry year) in the entire Free State. Data extracted from Department of Agriculture, Forestry and Fisheries database.

Figure 2.11 illustrates the number of hectares that were covered by each land cover and crop type from 2006-2016 in the entire Free State. It is evident from Figure 2.11 that there has been a radical change in the amount of crop and land cover types covering the entire Free State from 2006-2016 especially the pasture, maize, and fallow land. Pasture has increased from 534247 ha in 2006 to 1493188 ha in 2016, maize has also increased from 715777 ha in 2006 to 1180588 ha 2016, fallow land has decreased from 1631229 ha in 2006 to 333019 ha in 2016, and other crop types have remained relatively the same.

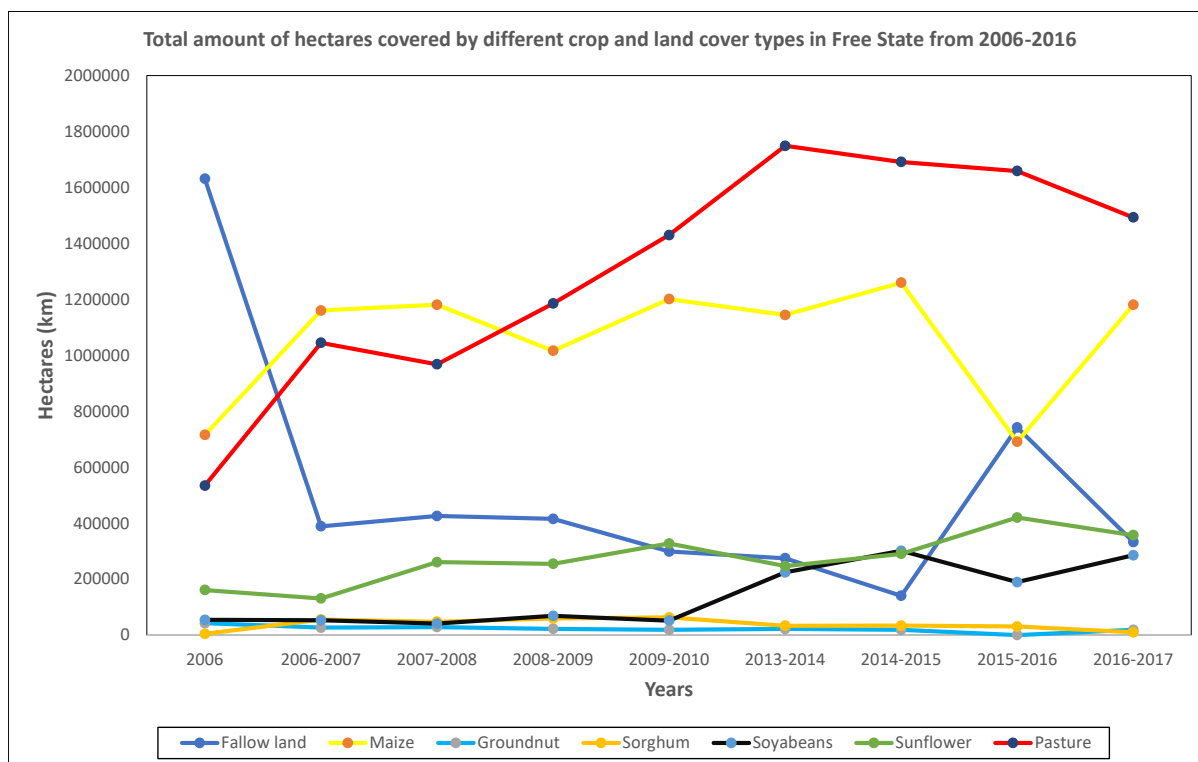


Figure 2.11: Total amount of hectares covered by different crop and land cover types in the entire Free State from 2006-2016. There is a variation of crop and land cover amount from each year, generally pasture has increased from 2006-2016, maize has also increased, fallow land has decreased, and other crop and land cover types have remained low. Data extracted from Department of Agriculture, Forestry and Fisheries database.

With the interest of crop and land cover types around each dust source, maps were focused into the western part of Free State which is the hotspot of dust events. Dust events were first recorded in 2006 and this year was further chosen to represent wet years (Figure 2.12) and 2016 represent dry years (Figure 2.13). It is noted in Figure 2.12 that in 2006 (wet year) both maize and fallow land were dominant but fallow land is slightly more than maize in the dust emission area. Figure 2.13 indicates that in 2016 (dry year) fallow land and pasture dominated and number of dust sources have increased as compared to 2006. According to Figure 2.12 and 2.13 and appendix 2.4, fallow land, maize, and pasture cover most parts and patches of wheat are also dominant from south-west parts in most years. It is evident from the maps that an

increase in dust events was observed when fallow land and cultivated land were dominating (2016). Table 2.2 and 2.3 provides clear summary that fallow land, maize and pasture were the major dominating crop and land cover types around dust sources. It is therefore apparent that dust mainly occurs in fallow land and cultivated land.

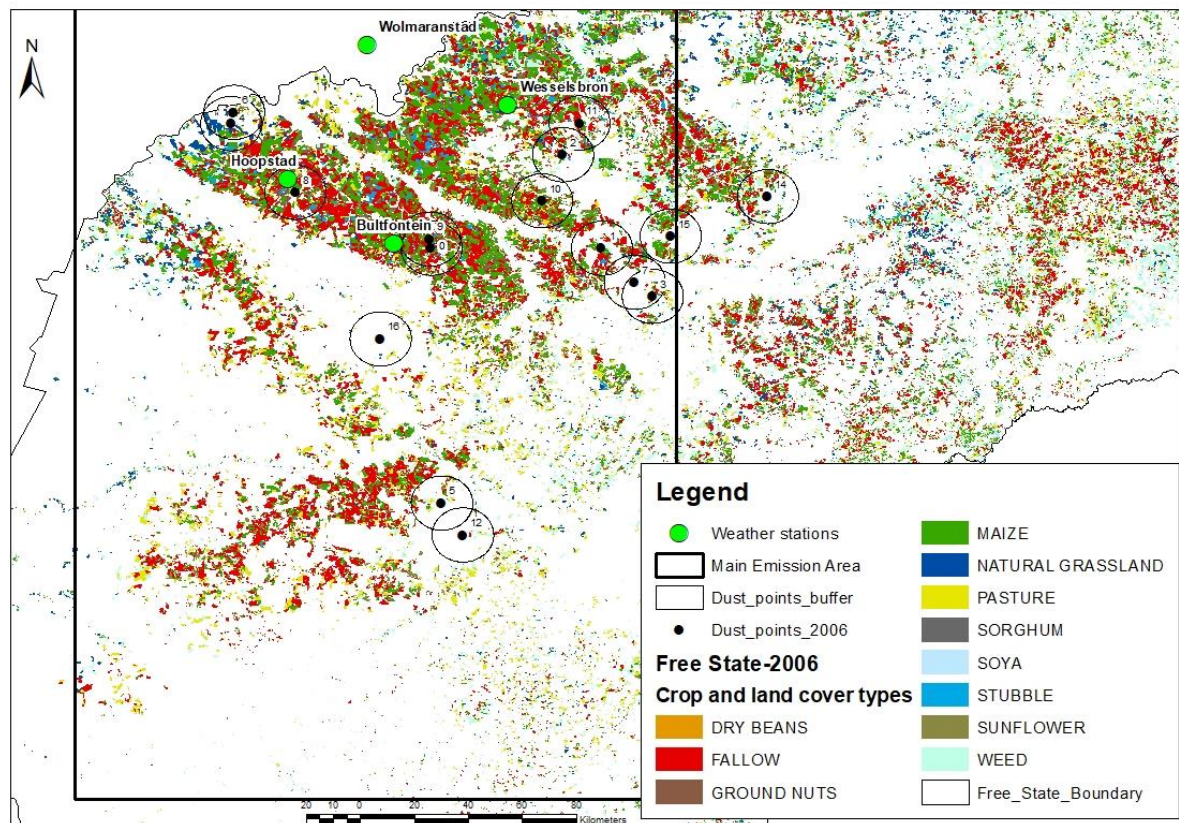


Figure 2.12: Crop and land cover spatial variation, dust points and weather stations in 2006 (wet year) focused into the western part of Free State. The square boarder line demarcates the main dust emission area. 10 km buffer around each dust source was created to identify crop and land cover types around each dust source. Data extracted from Department of Agriculture, Forestry and Fisheries database.



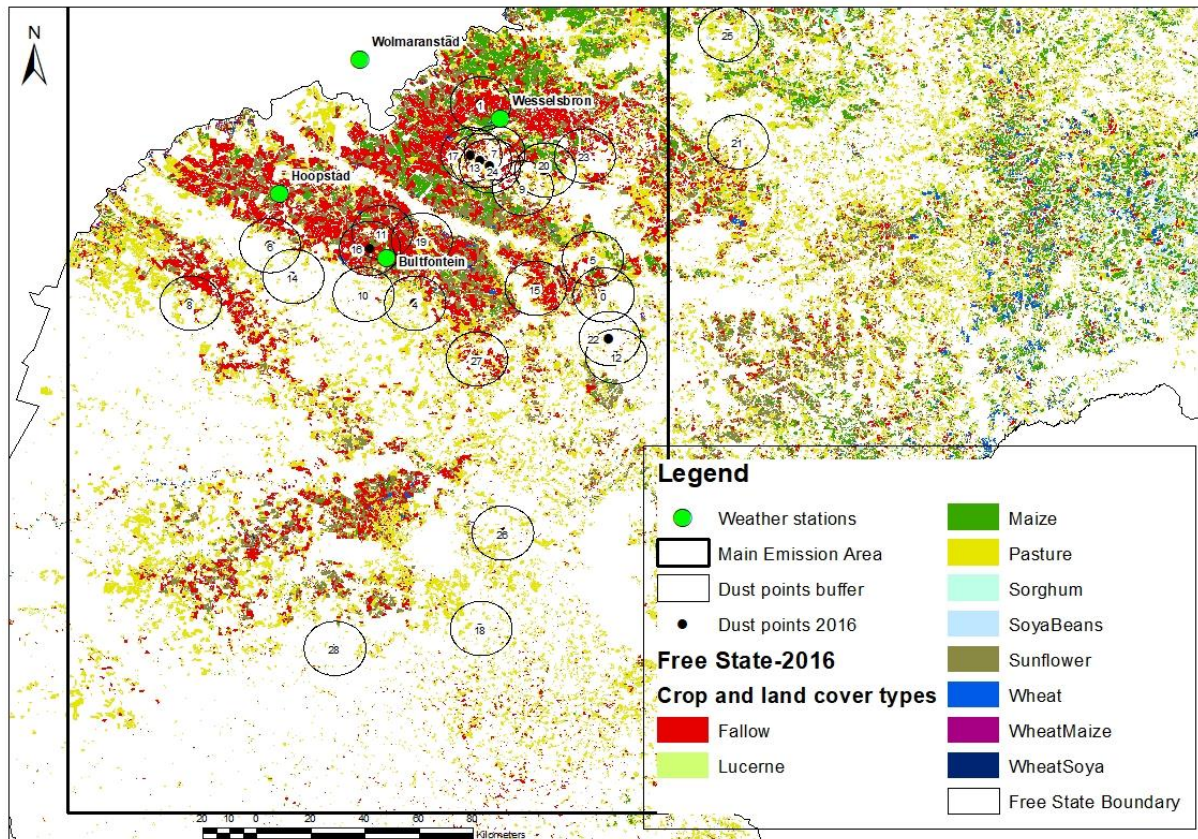


Figure 2.13: Crop and land cover spatial variation, dust points and weather stations in 2016 (dry year) focused into the western part of Free State. The square boarder line demarcates the main dust emission area. 10 km buffer around each dust source was created to identify crop and land cover types around each dust source. Data extracted from Department of Agriculture, Forestry and Fisheries database.

Table 2.3 presents the summary of crop and land cover amount around dust sources within 10 km buffer. The years 2006 and 2016 are used as examples to show under which crop and land cover does dust mostly occurs in wet and dry years. These years are chosen to represent wet and dry years. In 2006 17 dust events were recorded and in 2016, 29 dust events were recorded. From each year only 10 dust sources are presented; these number of dust sources are suitable to demonstrate the trend in crop and land cover types around each dust source. According to the data presented in Tables 2.2 and 2.3 in 2006 fallow land followed by maize were the dominating crop and land cover types e.g., dust source 20060829 was covered by 11533 ha of fallow land and 10795 ha of maize and dust source 20060925 was covered by 1286 ha of fallow land and 840 ha of maize. In 2016 fallow land followed by maize and pasture interchangeable

were the dominating crop cover types (i.e., dust source 20160803 was covered by 16811 ha of fallow land and 6159 ha of maize and dust source 20160915 was covered by 7737 ha of fallow land and 4599 ha of pasture). Interestingly natural grassland was not present around dust sources in 2016. This means in Free State over 10 years period the areas that were covered with natural grassland had been converted to cultivated land and some of the land was later left fallow in 2015-2016 when severe drought occurred, thus fallow land kept on expanding. MODIS EVI results support this argument as the results indicate that farmers did not plough in 2016; vegetation cover was very low and SPEI data supports that there was a severe drought during this year.

Table 2.3: Spatial detail of how big each crop and land cover type around a 10 km buffer around dust sources in 2006. Data extracted from Department of Agriculture, Forestry and Fisheries database.

| Dust sources | Maize (ha) | Pasture (ha) | Natural grassland (ha) | Fallow land (ha) |
|--------------|------------|--------------|------------------------|------------------|
| 20060829     | 10795      | 928          | 225                    | 11533            |
| 20060829     | 4194       | 313          | 216                    | 7843             |
| 20060829     | 3422       | 1012         | 415                    | 4521             |
| 20060925     | 840        | 1152         | 584                    | 1286             |
| 20060925     | 2419       | 1579         | 4844                   | 1718             |
| 20061110     | 927        | 1000         | 44                     | 1555             |
| 20061110     | 2103       | 962          | 3653                   | 969              |
| 20061110     | 1448       | 594          | 357                    | 3410             |
| 20061203     | 5747       | 1950         | 258                    | 11782            |
| 20061203     | 1093627    | 943          | 181                    | 12753            |

Table 2.4: Spatial detail of how big each crop and land cover type around a 10 km buffer around dust sources in 2016. Data extracted from Department of Agriculture, Forestry and Fisheries database.

| Dust sources | Maize (ha) | Pasture (ha) | Fallow land (ha) |
|--------------|------------|--------------|------------------|
| 20160106     | 1428       | 5088         | 4015             |
| 20160803     | 6159       | 2935         | 16811            |
| 20160803     | 2278       | 8376         | 1098             |
| 20160803     | 6953       | 3307         | 484              |
| 20160905     | 423        | 8390         | 3797             |
| 20160905     | 2957       | 7475         | 5859             |
| 20160915     | 142        | 3895         | 4589             |
| 20160915     | 3066       | 4599         | 7737             |
| 20160926     | 56         | 5843         | 5960             |
| 20161011     | 2403       | 4982         | 5846             |

## 2.7.5: Total percentage of crop and land cover around each dust event in Free State

Figure 2.14 presents the total percentage of crop and land cover around each dust event. A meaningful crop and land cover percentage was obtained from different dust sources within each year and across all the other years. The area around some dust sources had a total of 90% crop and land cover and the area around other dust sources had a total crop and land cover less than 10 %, for example dust source 17 of 2015-2016 and dust source 28 of 2016. Regardless of the total crop and land cover percentage dust source areas were dominated by different crop and land cover types as illustrated in Figure 2.11 and appendix 2.5 to 2.10 for instance, dust source 1 of 2007 had a total crop and land cover of 90% and was dominated by maize (71%), whereas dust source 11 of 2016 had a total crop and land cover of 89 % and was dominated by fallow land (66%). Therefore, the percentage of crop and land cover does not necessary determines whether the area is vulnerable or not to dust, however it is the type of crop and land cover that determines the vulnerability of an area to dust.

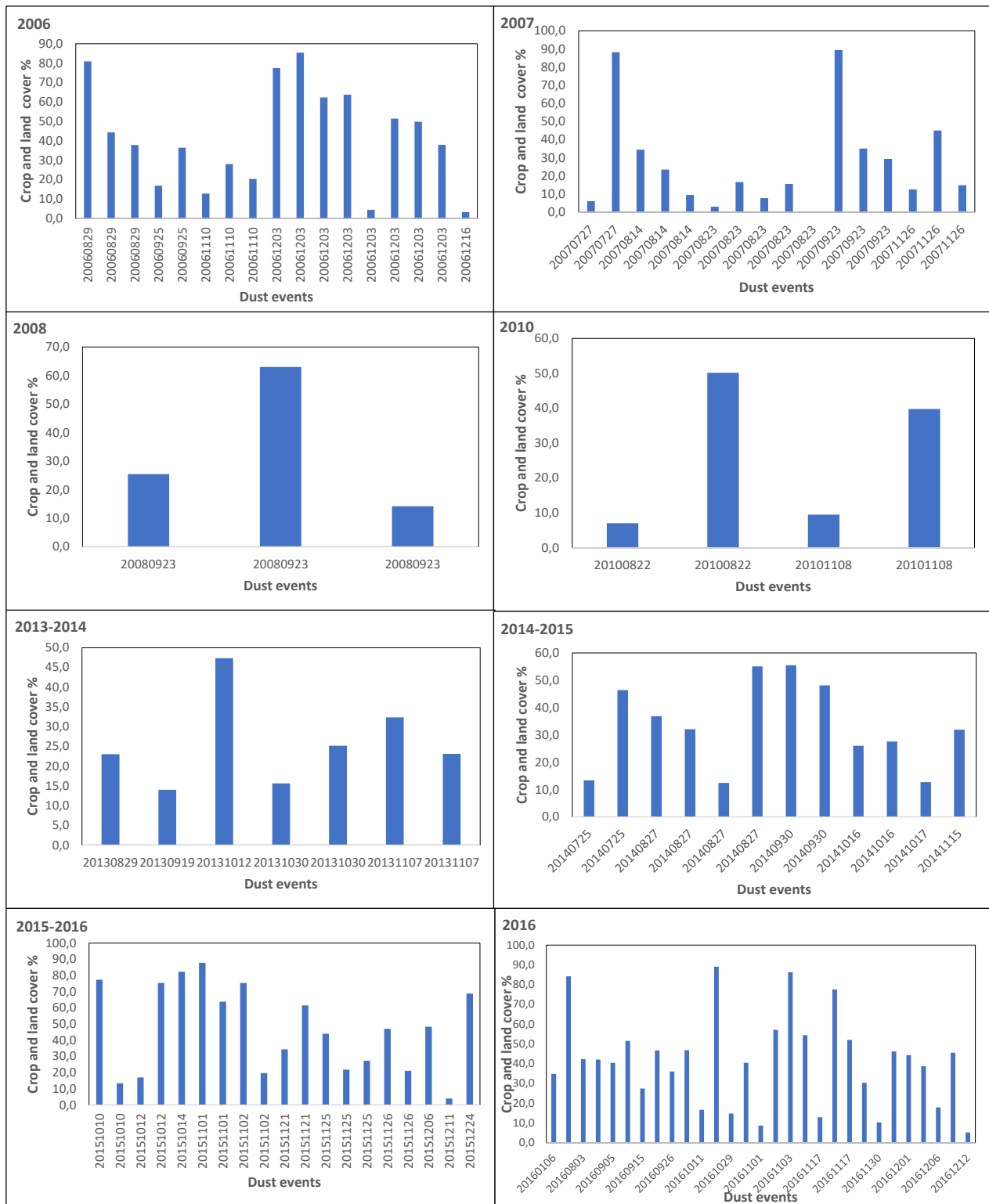


Figure 2.14: Total percentage of crop and land cover around each dust event with a 10 km radius from 2006-2016. Data extracted from Department of Agriculture, Forestry and Fisheries database.



### **2.7.6: Dust sources area composition**

The variation of crop and land cover types in the dust emission area or around dust sources from 2006-2016 was further investigated. This was done with the purpose of identifying under which crop and land cover types are dust events likely to occur. Figure 2.15 shows different crop and land cover types that were present and the number of hectares they covered in Free State dust source areas from 2006-2016 and Appendix 2.5 to 2.10 shows the crops and land cover that were present within a 10 km radius buffer of each dust source. It is apparent from Figure 2.15 that fallow land has increased from 2006-2016; in 2006 there were 72008 ha of fallow land and in 2016 there were 182046 ha of fallow land, therefore fallow land has increased by 110038 ha since 2006 around dust source areas. Maize and pasture are also another dominating crop and land cover types found around dust emission area. There are fluctuations in the number of hectares covered by maize around dust sources with some increase and decrease in different years, however maize has decreased from 67832 ha in 2006 to 46935 ha in 2016. Hectares of pasture are also fluctuating over the years, but generally pasture had increased from 17793 ha in 2006 to 136391 ha in 2016, an increase is of approximately 118598 ha. Other crop and land cover types are also present but their variation over the years is not significant. It is therefore apparent that dust mostly occurs in areas covered by fallow land, maize, and pasture.

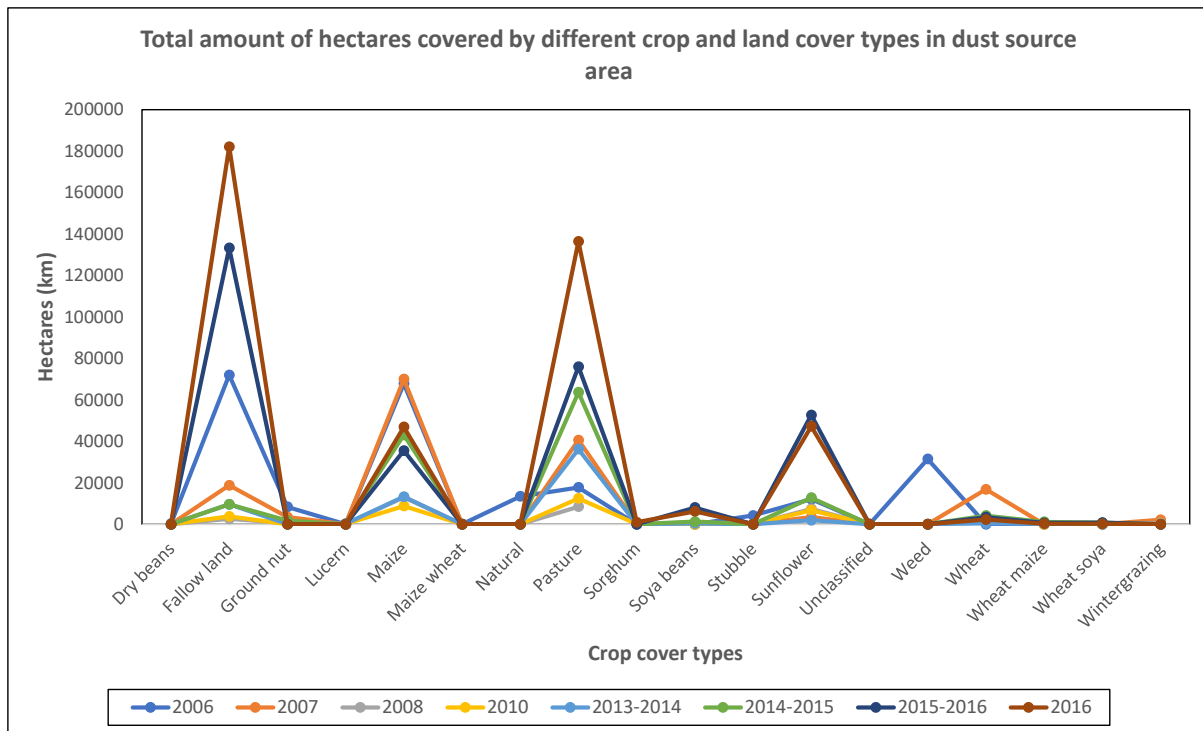


Figure 2.15: Total amount of hectares covered by different crop and land cover types in dust source areas in Free State from 2006-2016. Fallow land, maize and pasture covered most of the land compared to other crop types.

## **2.8 Discussion**

### **2.8.1 Spatial and temporal changes of LC and their impact in dust production**

The changes in Free State LC or LU were examined. LC or LU varies in different locations depending on the interest of people using the land. According to the 2000 and 2013-2014 LC maps grassland remained the most dominant LC in Free State over 13 years even though it has decreased from 2000 to 2013-2014. Cultivated land has increased over this period even though its spatial extent is still relatively lower than of grassland. However, it is not evident that these are real LC changes. It is possible that the changes observed are differences in data products or error in data products rather than the actual changes in LC. Misclassification of LC may be a huge problem that results to errors in detecting the changes in LC (Schoeman, Newby, Thompson, & Van den Berg, 2010). Significant LC changes in this region took place ages ago, when European farmers colonized the area (Reitz, 1929). Therefore, the changes that are currently illustrated by LC maps occurred a while ago even though the maps might be showing an ongoing change, but mostly they illustrate where a certain LC dominates.

Increase in cultivated lands has been noted by other studies such as (Costa, Botta, & Cardille, 2003; Falcucci, Maiorano, & Boitani, 2007; Popovici, Bălteanu, & Kucsicsa, 2013; Tekle & Hedlund, 2000), who conducted a similar research to the present study and their findings revealed that the conversion of rangeland to agricultural land has become a major land-use change which has led to more agricultural practices and associated soil loss. Over the past few year's rangelands have been converted to cultivated land with the purpose of meeting human needs. Economy has become the major driver of converting grassland to cropland (Rashford, Walker, & Bastian, 2010). If agricultural demands continue to grow grassland conversion will further increase. Free State Province is one of the regions in South Africa whereby substantial amount of land has been converted from grassland to cultivated land. This region is known for producing thousand tons of maize to supply South Africa and other parts of Africa, to meet the food demand that is escalating everyday due to increase in human population. This demand therefore put pressure on the land; meaning a significant amount of land must be converted to cultivated land for agricultural use. Rezaei et al., (2016) also investigated the impact of LC/LU change on wind erosion. The results showed that the potential of soil erosion has increased with the increase of the area of agricultural practices. This has been observed in Free State from

2000- present (Figure 2.1 and 2.2), as a substantial amount of land is being used for agricultural purposes.

### **2.8.2 Role of vegetation in the occurrence of dust**

Land needs to be covered by a good vegetation for it not to be vulnerable to erosion. This study found that vegetation plays a significant role in the occurrence of dust. The sparse vegetation was observed to correspond with dust events in Free State. Zou and Zhai, (2004) conducted a study in the northern China to determine the relationship between vegetation coverage and spring dust storms. The results showed that poor vegetation coverage in Northern China is a vital factor for the common occurrence of spring dust storms. Moreover, vegetation cover plays a central role in interannual variations of dust storms. A negative correlation was noted between vegetation coverage and incidence of dust storms. When vegetation decreases the incidence of dust storms increases vice versa. It is apparent that the results of the current study match with the results of the study by (Zou & Zhai, 2004), which provides confidence that vegetation plays a significant role in the occurrence of dust.

Vegetation cover in this study was quantified in a point format; basically, vegetation amount was only extracted for the MODIS pixel where each dust source point was observed. The present study found this analysis not adequate to draw proper conclusions about the relationship between vegetation and occurrence of dust in Free State. Therefore, findings from (Eckardt et al., 2020) who investigated at the bigger scale the role of vegetation in the occurrence of dust in Free State were adopted. Eckardt et al., (2020) noted that vegetation is certainly a vital factor for the occurrence of dust and further shown that it is not only vegetation that plays a role in the occurrence of dust but also factors such as rainfall, temperature, humidity, and wind speed. Dust emission was found to coincide with maximum hourly average wind speed, decrease in rainfall, increase in temperatures, and decrease in relative humidity. Rezaei et al., (2016) support this argument and states that high evapotranspiration and low rainfall have a high potential of resulting to low vegetation cover which is thus susceptible to wind erosion. The combination of these factors is found to contribute significantly to the occurrence of dust in Free State Province.

### **2.8.3 Role of crop and land cover type in the occurrence of dust**

Findings reported that fallow land, maize, and pasture are the major dominant land cover and crops in Free State dust emission area. Cultivated land in Free State has been mainly used for maize production (Figure 2.11). After harvesting the maize crops, farmers graze their livestock on the crop residues. However, some grassland particular the ones in Lixisols and Calcisols are mainly used for grazing and not cultivation. The farmers have been successfully using the land for these purposes. Now because we are faced with climate variability, we have what is called a good and a bad year. A good year is characterised by moderate rainfall; amount of rainfall enough to commence with ploughing and not extreme temperatures. A bad year is characterised by below average rainfall, late onset and early cessation of rainfall and extremely high temperatures. The problem then arises when the area has a bad year, during bad years the farmers normally choose to leave the land fallow for that specific year to avoid crop failure while allowing soil to store relative amount of water to use in the following year. However, leaving the land fallow exposes the land to soil erosion, and wind erosion. This is evident from this study as fallow land was dominating especially in 2015 and 2016 years which had more dust events. Cho et al., (2015) investigation relatively agrees with the present study as the research conducted in Asia illustrate that excessive bare land results to soil loss. Bajocco et al., (2012) additionally noted that besides soil erosion intense agriculture has a potential of causing soil sealing and soil compaction. Rezaei et al., (2016) further add that high evapotranspiration and low rainfall may result to low vegetation cover which is susceptible to wind erosion. Moreover, excessive grazing of pasture by livestock results to sparse vegetation cover, leading to soil being susceptible to erosion. The present study is also supported by (Eckardt et al., 2020) investigation which found that dust events are associated with severe drought, low rainfall, low vegetation cover and high wind speed. Therefore, land needs to be properly managed to prevent or minimize the negative environmental effects.

Soils tend to become loose when continuously ploughed, losing their structure and nutrient content thus they easily become eroded. During soil erosion dust occurs and it has been observed to be a major environmental problem in Free State agricultural lands. Wiggs and Holmes, (2011), were the first to quantify the degree of wind erosion on agricultural soils in Free State. Dust has been observed to mainly occur in cultivated land and the events are becoming frequent over the years as the land is moving towards cultivated land. Dust events are mostly observed when the land is left fallow and after harvesting crops. Wiggs and Holmes,

(2011) rather agree to this as their study indicated that significant quantities of dust are mobilized particular during the months of September and October, of which in Free State this period corresponds to post harvesting. After harvesting some farmers leave stubbles and graze animals which in turn leave the land bare if moderate to intense grazing applied. In some instances, farmers harvest and leave the land completely bare. Due to these land management options; the agricultural lands of Free State are prone to dust and thus regarded as major dust sources.

Changing or improving these land management can be the solution to Free State land degradation. According to the results of this study it is evident that there has been an increase in cultivated land in Free State (Figure 2.1 and 2.2) with maize, pasture and fallow land being the dominating crop and land cover types (Figure 2.15 and appendix 2.5-2.10). Some evidence shows that Free State farmers are aware of this environmental issue and doing their best to mitigate it while also trying to meet the demand of the economy. As economic demand is putting pressure on the environment, grasslands with relatively high-quality land for agricultural production are still more likely to be converted to cultivated land (Rashford et al., 2010). Phillips, (2018) state that farmers from Free State adopted the American dry-farming practices after World War 2 to combat soil erosion. Few of these land management strategies that Free State farmers have adopted to combat soil loss include changing from conventional till to no till, leaving crop residues after harvesting and planting winter crops after harvesting the summer crops. These strategies were successfully used during the Dust Bowl Era in United States. Any form of vegetation cover acts as a windbreaker and thus preventing the soil from eroding. According to Wiggs & Holmes, (2011) surface roughness plays a significant role in controlling erosion threshold. Leaving the crops residues becomes less effective if farmers at a later stage graze on the crop residues. Also, the continuous disturbance of soil by ploughing crops after the other results into soil losing its nutrients and storing relatively less amount of carbon. These results are supported by Jiao et al., (2009), who's work showed that converting grassland to cropland has made soil organic carbon to decrease more especial in the 0-30 cm soil depths.

Therefore, the best strategy according to results of the present study and other studies would be converting the cultivated land back to native grassland. Rezaei et al., (2016) also recommended that rangelands be conserved from overgrazing and converting to low-income agricultural lands. Grassland have been found by present study and other studies to have a good impact on the ecosystem as they store relatively vast amount of carbon and providing the soil

with high nutrient content. Jiao et al., (2009) support this view that converting cropland to grassland will result to more carbon being stored and soil will have high nutrient content. Having grassland as a dominating LC is beneficial for the ecosystem as less dust will occur and there will be less carbon in the atmosphere. In summary, better knowledge and improved understanding of the processes that results in LC/ LU change is very crucial to promote a sustainable land management system for present and future generation.

## **2.9 Conclusion**

To achieve the first aim of the study which was to ascertain whether LC is shifting from grassland towards cultivated land and causing dust three objectives were derived. The first objective in this chapter was to determine the spatial and temporal changes of LC in Free State. The 2000 and 2013-2014 land cover maps derived from Agricultural Research Council were analysed using ArcMap. Based on the results I obtained, there is an increase in cultivated land from 2000 and 2013 - 2014 but its spatial extent still does not exceed grassland. Cultivated land has increased by approximately 26 % and grassland has decreased by 22 %. According to the literature several studies have also noted that cultivated land increases or remain unchanged in semi-arid and arid regions and the change is mainly due to economic demand. These findings rather match with the findings of the present study; therefore, I concluded that cultivated land is becoming a dominant LC in dryland areas. The 2018 and 2020 national land cover maps were not used in this study due to the time frame of the study (2018-2021), however the study recommend them to be used in future studies.

The second objective was to determine the role of vegetation in the occurrence of dust. To answer this objective MODIS EVI data for the sites of the start of dust was used. Based on the results and those of other studies it was apparent that vegetation plays a significant role on the occurrence of dust. This was evident because around most dust sources there was sparse vegetation; EVI was ranging between 0 and 0.18 which is a clear indication of poor vegetation. Sparse vegetation is directly proportional to dust production; the sparser the vegetation, the more dust events become. Findings also illustrated that dust mainly occur in cultivated land and the events are becoming prominent over the years (2015 and 2016). Therefore, cultivated, and fallow land were found to be the major sources of dust and the events are becoming frequent as fallow lands are observed to increase over the years. Farmers are abandoning the

cultivated lands due to changes in climate; rainfall is observed to decrease and temperatures to increase. The MODIS EVI data was also compared with the weather data for the sites of the start of dust to determine if weather patterns have any role in the occurrence of dust. Based on the results it was observed that dust events correspond with low rainfall, high temperature and high wind speed periods. Several other studies have also found that vegetation is a vital factor for the occurrence of dust, however factors like rainfall, temperature, humidity, and wind speed also affect the occurrence of dust. The results of the present study correspond with other research findings, and from these findings it was concluded that vegetation plays a significant role in the occurrence of dust, however it is not the only factor.

Investigation was then narrowed down to assess exactly the dominating LC and LU around each dust source or in the dust emission area. Now that it was clear that vegetation plays a significant role in dust production, the study wished to understand under which crops and land cover types are we likely to get dust. To answer this investigation crop and land cover data obtained from Department of Agriculture, Forestry and Fisheries was used. The results showed that each dust source is likely to be covered by plus minus nine crops and land cover types, but maize, fallow and pasture lands always dominate around each dust source. Some dust events are dominated by all three mentioned crop and land cover types, some are dominated by one of them but generally around each dust source one of the three crop and land cover types is always found dominating. The reason these three crop and land cover types results in dust occurrence is because i) during the period of high winds (Aug - Nov) maize is already harvested and land is either left bare or with crop residues which are later grazed by livestock making the area susceptible to dust, ii) when area is covered by pasture and there is overgrazing, vegetation becomes sparse thus resulting to dust and iii) when the land is left fallow with no wind breaks the soil particles can easy become eroded when high wind occurs. Other studies have found that excessive bare land results to more dust and these findings rather match with the findings of the present study, as many dust sources were found to correspond with fallow land. Based on the results, it was concluded that surface roughness plays a vital role in controlling soil erosion and the crop and land cover type is the major identifier of the areas vulnerable to dust. Fallow land is identified as the hotspot of dust.



### ***Study limitations***

The main limitation to the study was the quality of the 2000 and 2013/2014 national land cover maps. It is possible that the changes observed are differences in data products or error in data products rather than the actual changes in land cover. The 1990, 2018 and 2020 national land cover maps were not used because the study was only interested in the changes that occurred from 2006 – 2016. However, the study recommends future studies to use them for long term variation in land cover types.

## **Chapter 3: Climate constraints and mitigations to Free State crop production**

### **3.1 Significance of the chapter**

The present chapter is interested to investigate rainfall variation in Free State. Understanding the shift on the onset and cessation of rainfall is important because it will help farmers to choose the right cultivar suitable for a location or region. In other parts of the world studies have been conducted that indicates that farmers are interested in knowing the dates on which they can start planting and to understand the risks of crop failure (Ati, Stigter, & Oladipo, 2002). The onset of rainfall has been viewed by farmers as an important factor that contributes to ploughing decisions. Climate variability increases the uncertainty of dates for onset and cessation of rain, length of rain season and seasonality of rainfall. Moreover, it is crucial to understand temperature patterns as they also play a significant role in crop production. Hoffman et al., (2011), proved that an increase in temperatures and decrease in rainfall might result in a decrease in plant available moisture. Monitoring minimum temperatures to establish when the frost occurs is important because if frost occurs during the critical plant growth stages there is a high possibility of crop failure. Therefore, it is vital to monitor temperature patterns to avoid or prevent crop failure. It is also crucial to monitor the wind speed of an area to better understand the factors that contributes to windiness and how windiness affects agricultural land. This chapter wishes to contribute to the knowledge of climate constraints and limitations to crop production in Free State. To achieve this the chapter will first look at the onset of rainfall, timing, and drought in FS. It will also investigate the impact of temperature and frost on crop production and lastly the effect of wind on the occurrence of dust in FS.

### **3.2 Aim**

To determine the climate constraints, and mitigations to Free State crop production.

### 3.3 Objectives

- To determine drought amount, timing, and onset in western Free State.
- To determine temperature and frost variation and how they affect crop production.
- To determine the wind effect to the occurrence of dust in western Free State.

### 3.4 Background to the study

Climate change is an unpredictable and urgent global challenge (Renita & Anindita, 2017). The impacts of climate change focusing on drought are protuberant worldwide, particularly in drylands where its adverse effects are intensified by high rainfall variability coupled with high temperatures (Kgosikoma, Lekota, & Kgosikoma, 2018). According to Kgosikoma et al., (2018) climate change threatens agricultural productivity through increased temperatures, changes in precipitation patterns and increased occurrence of extreme weather conditions, the appearance of new crop and livestock pests, inadequate supply of irrigation water and increased severity of soil erosion. According to Engelbrecht et al., (2015), both Global Climate Models (GCMs) and Regional Climate Models (RCMs) have projected a drastic increase in temperature over Africa under low mitigation in future. Engelbrecht et al., (2015), further stated that the impact of increased temperatures in agriculture and biodiversity sectors may be meaningful regardless of rainfall changes. Observations indicates that temperatures are rapidly increasing in the Southern Africa at 1.5 to 2 times the global rate of temperature increase. The rate has been observed to be particular high over the period of 1961-2010 and trends of temperature as high as a 2 to 3.6°C increase per century have been recorded (Engelbrecht et al., 2015).

Moreover, a 4-7°C increase in temperature is projected to occur if low mitigation measures are applied over the western interior regions of Southern Africa (Engelbrecht et al., 2015). Additionally, due to enhanced anthropogenic activities it has been observed that the Southern African region will become generally drier. These regional changes might have several negative impacts. Those impacts will be on; (i) agriculture; whereby maize crop yield would be reduced due to high temperatures and inadequate soil moisture, (ii) livestock production; mortality rate in cattle is subjected to be high due to repressive temperatures; (iii) water security

due to low rainfall and high evaporative demand and (iv) human health through harsh temperatures (Janowlak, 1987).

Considerable research has been done on the regional climatic trends. Davis et al., (2016) investigated the current trends in the climate of Namaqualand of South Africa and interestingly found that temperatures have increased; the minimum temperatures were observed to have increased by 1.4 °C (Figure 3.1) and maximum temperatures by 1.1 °C over the last century. Evapotranspiration has also significantly increased along the coastline by up to 30 mm especially in spring and summer. However, Davis et al., (2016) found no substantial change in annual totals, frequency or intensity of rainfall events, only the spatial variability was detected across the region. Even though there was no remarkable change in rainfall; increase in temperature and evapotranspiration pose a meaningful change in water availability as evaporative demand tends to increase with increased temperatures and that has an impact in agriculture.

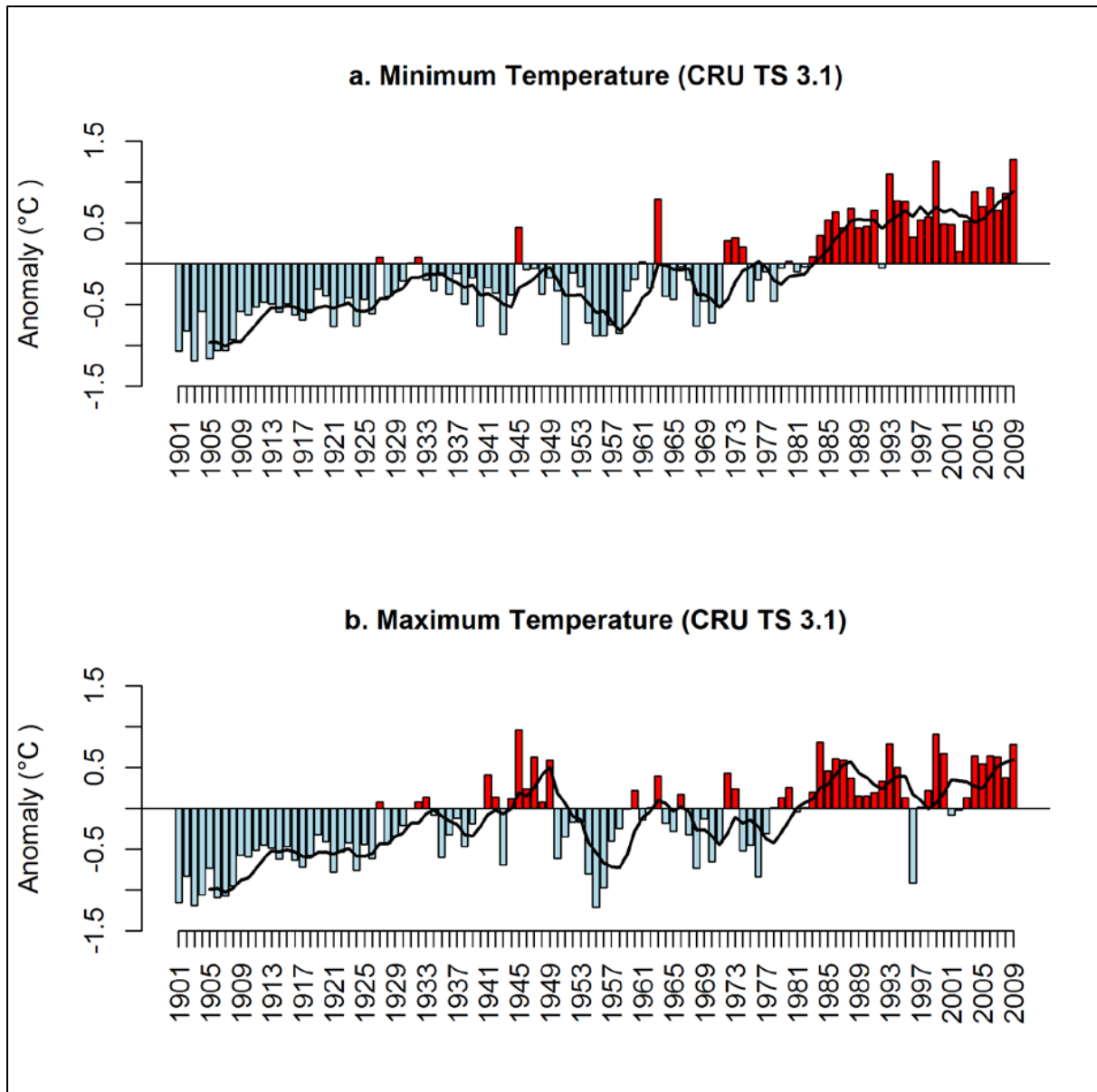


Figure 3.1: Annual minimum (a) and maximum (b) temperature anomalies (°C) for Namaqualand (1901–2009) based on the CRU TS 3.1 data set. Positive (red) and negative (blue) anomalies in temperature with respect to the long-term average climatology (1961–1990 mean). The black line shows the 5-year moving average (Davis et al., 2016).

Furthermore, in the semi-arid region's rainfall has been observed as the key driver of vegetation functioning and productivity (Harmse, Du Toit, Swanepoel, & Gerber, 2020). Rainfall varies significantly with below and above-averages. Based on future projections, a decrease in rainfall in South African is predicted. Under low mitigation the decreases in rainfall are associated with a poleward displacement of the westerlies and frontal systems. Low rainfall is subjected to put more stress predominantly on rainfed agriculture. Harmse et al., (2020), argue that in agricultural sector below-average rainfall limits food availability for livestock in the short term and impact agricultural productivity through induced mortality of palatable perennial plant species in the long term. The projected reduction in rainfall will come with delayed onset of the rainy season and an earlier cessation, the number of dry days outside the rainy season increases and the rainy season itself shortens (Janowlak, 1987).

Due to this semi-arid and arid region are estimated to increase by 5-8 % affecting several issues such as vegetation and hydrology. Landman et al., (2018) stated that adequate soil moisture is essential in order to produce high crop yields and other studies indicated that soil moisture might be lacking in future due to increased temperatures and notwithstanding rainfall changes. Landman et al., (2018) observed that for maize yield to adapt in climate change the maize would need to have high tolerance of maximum temperatures or a change in the varieties of maize growth.

Rainfall has a significant spatial and temporal variation and plays a huge impact on agricultural activities (M. E. Moeletsi & Walker, 2012). Hu et al., (2019), knowledge on the spatial and temporal changes in the rain season onset contributes a meaningful role in informing agricultural and water security planning and also seasonal variability of rainfall is important for agriculture (Dunning, Black, & Allan, 2016). It is therefore important to study the probability of the onset, cessation and length of rain period and their inter-relationships in order to assist in planning of dryland farming activities (M. E. Moeletsi & Walker, 2012). Moeletsi et al., (2010) argue that early onset of rainfall allows the farmers to plough land and plant earlier and benefit from the lower evaporative demand. Moreover, Moeletsi & Walker, (2012b) state that later onsets can cause the plant critical stages that are sensitive to water stress to be aligned with months of lower rainfall and high evaporative demand.

The combination of the above-mentioned weather factors (rainfall, and temperature) depending on how they affected the area might result into drought. For instance, when rainfall decreases to below average for a long time, temperature increasing to a point where evaporative demand

is greater than water infiltrating the soil or plants the area might be subjected to drought. Masupha & Moeletsi, (2017) defined drought as the consequence of precipitation that continue to occur below average over an area, generally within a season or more and is often associated with climatic factors such as high temperatures, high winds and low relative humidity. Sonawane, (2016) add that drought is the most widespread hydro-metrological syndrome of prolonged period of water scarcity and has direct impact on natural resources, environment and on people. There are four types of droughts namely, agricultural, meteorological, hydrologic, and socio-economic drought.

Agricultural drought is defined as a decrease in the availability of water below the ideal level compulsory for a crop during each different growth stage, which then leads to compromised growth and reduced harvests (Bahta, Jordaan, & Muyambo, 2016). Meteorological drought is a period whereby several days with precipitation are below the usual average: insufficient precipitation or no rainfall at all. Hydrologic drought focus on the effects of dry spells on surface or subsurface hydrology, rather than on the meteorological explanation of the events (Panagoulia & Dimou, 1998). Lastly Panagoulia & Dimou, (1998) state that socio-economic drought is when the supply and demand of the economy cannot be met.

### **3.5 Literature review**

Agricultural activities are strongly influenced by rainfall which differs significantly on temporal and spatial basis. According to Dunning et al., (2016), distinction in seasonal cycle of African rainfall is very important for agriculture. Studies have shown that understanding rainfall variability is crucial. Moeletsi & Walker, (2012b) noted that to help in development of farming activities, it is vital to establish the probability levels of the onset and cessation of rains and the length of rainy period. When farmers are sound informed about the length and probability dates of the onset and cessation of the rainy season they can invest in resources appropriate for those conditions (M. E. Moeletsi & Walker, 2012). It is therefore important to investigate how rainfall and other weather factors (temperature and wind) affects agricultural production. Studies that predict the likely effect of climate change on agricultural production are summarized below.

### **3.5.1 Likely impact of climate change on agricultural activities**

Rainfall is a crucial factor affecting agricultural production; however, it is not the only factor. A study by Ontel & Vladut, (2015), investigated the impact of drought on the productivity of agricultural crops with the Oitenia Plain, Romania at various time scales. Data was acquired from the Agro-databases, which contains the productions of the winter wheat, maize, and sunflower for the period of 1971-2013. Rainfall amount and temperature recorded at six meteorological stations represented meteorological elements that were used (Ontel & Vladut, 2015). The evaluation of the drought variability phenomenon at different time scale indicated that the frequency of dry years was higher from 1983-2002. The upward trends of air temperatures determined the intensification of dry periods and increased the demand for water in agriculture. It was concluded that drought is the most important climatic factor that influence crop growth and yield.

Long-term analysis of rainfall is vital to better improve crop production. The productivity of vegetation and how it functions in semi-arid regions is mainly driven by rainfall (Harmse et al., 2020). Harmse et al., (2020) studied the long-term trend of rainfall in the Upper Karoo of South Africa. This study analysed farm records from the past eight decades at eight sites in the Upper Karoo. Harmse et al., (2020) described the aim of the study as to provide detailed and comparable descriptions to generate a more general understanding of rainfall at a spatial scale over this entire bioregion and to assess recent farming conditions within a historical rainfall context. The results presented a progressively rainfall trend increase of  $\sim 10$  mm per decade in the Upper Karoo from mid-1930's to 2018. According to SPI the period from 1989 to 2018 (30-years) was mostly characterised by above-average rainfall. It was apparent that all the dry cycles were followed by wet cycles – and often extremely wet cycles. The study thus concluded that farming conditions of nowadays are more favourable compared to historical rainfall recorded before the year 1989.

Moeletsi & Walker, (2012b) state that Free State agricultural production is mainly affected by high climate variability which causes the dates for the onset and cessation of rains, length of rainy season and seasonal rainfall to be highly uncertain. This knowledge has thus driven these researchers to investigate rainy season characteristics in Free State. Data was acquired from 309 stations that are in Free State, South Africa and daily rainfall was analysed for a period of



58 years from 1950 to 2008. The onset and cessation of rain was determined using cumulative rainfall over consecutive decades and cumulative rainfall over 1 decade (M. E. Moeletsi & Walker, 2012). Moreover, to evaluate the probability of onset failure and rainy season duration of less than 50, 100, 120 and 140 day, Moeletsi & Walker, (2012b) used rainbow statistical software. The results indicated that there is large spatial variance for onset of rain while there is small variance for cessation over Free State. Furthermore, results illustrated that there is an east to west movement of onsets while the duration of rainy season and seasonal rainfall have also increased from west to east.

Temperature variation is another factor that has been observed to have a significant impact in agricultural production over the years. Janowlak, (1987) conducted a study where they predicted the seasonal and regional climate projections for Southern Africa using weather data (temperature and rainfall). The results indicated that over the last five decades temperature has been increasing rapidly over Southern Africa. Moreover, it was observed that in future the Southern Africa is anticipated to become mostly drier under low mitigation measures. These changes will thus leave little room for adaptation in a region that is already characterised as dry and hot. The changes will have an impact on crop and livestock farming and vegetation cover (Janowlak, 1987). Therefore, skilful seasonal forecast may become a progressively significant adaptation tool in Southern Africa.

Temperature and rainfall are always studied together and have been found as main factors that affect crop production worldwide. A study by Bannayan et al., (2011) investigated the role played by precipitation, temperature and three climate indices (Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and Nino) in historically observed rainfed crop yields of both barley and wheat in the northeast of Iran from 1983-2005. The results discovered that there are variations in the association between crop yield and climatic factors at different locations. Crop yields were proven to be determined and limited by maximum temperatures as variation in temperature caused discrepancy in crop yields. In the north parts of Iran, Nino showed a clear association trend with crop yields and in central parts NAO provided a solid basis for the relationship between crop yields and climate factors. Therefore, it is evident that precipitation and temperatures play a meaningful role in agricultural productivity.

Climate change focusing on rainfall and temperature is a serious problem for farmers, however there is little awareness of this amongst farmers (Renita & Anindita 2017). Renita & Anindita, (2017) investigated the local knowledge of farmers perception towards climate change and analysed farmers intention towards climate change adaptation. The primary data was obtained by interview and questionnaires in three farmers groups. The secondary data was obtained from government of Indonesia. Descriptive statistics was used to analyse data. Structural equation modelling partial least square was used to generate information regarding farmers behaviour towards climate change.

The results indicated that according to 57.5 % of respondent's temperature and the intensity of rainy season were meaningfully changing. Temperature was observed to be getting higher according to 40 % respondents. Furthermore, deforestation or logging was found to be a factor driving climate change by 65 % of respondents. However, according to 17.5 % of respondent's factories caused climate change. The respondents added that impact of climate change cause increase in pests, and diseases that attach paddy crops and thus meaningfully decrease land productivity. Climate change is therefore a serious threat to farmers, and they should find ways to adapt to it to mitigate the damages it causes on agricultural productivity.

A study by Kgosikoma et al., (2018) also analysed the smallholder farmers perceptions on climate change and its stressors, their adaptation strategies and factors that influence their adaptation to climate change. The research was conducted in Kweneng district, located in the southeastern part of Botswana in 2014. The targeted population was Kweneng district subsistence or smallholder farmers who were highly vulnerable to drought, a key stressor of climate change. To obtain a representative sample from three subdistricts in the district a multi-stage sampling was used. A structured questionnaire was used to collect data by using face-to-face interviews.

The results showed that according to farmers the mean annual temperatures and the number of hot days has increased and the mean annual rainfall and the number of rainfall days over the past 10 years have decreased. These changes have resulted in certain adaptation strategies which included changes in planting dates for crops in line with shifts in rainfall season onset, changes in crop varieties planted, changes in the use of chemical fertilizers, implementation of soil conservation technique and irrigation (Kgosikoma et al., 2018). Given the significance of knowledge about climate change and adaptation, the study then recommended that government

should implement programs that will help increase access to information on climate change and appropriate adaptive strategies.

Moreover, the agricultural sector is physically and economically vulnerable to climate change. Gbetibouo & Hassan, (2005), measured the economic impacts of climate change on major South African field crops. A Ricardian model was used to measure the impacts of climate change and to analyse the potential future impacts of further changes in climate. To capture the farmer-adapted responses to climate variations, a regression of farm net revenue on climate, soil and other socio-economic variables was conducted. The analysis was based on agricultural data for seven field crops (maize, wheat, sorghum, sugarcane, groundnut, sunflower, and soybean), climate and edaphic data across 300 districts in South Africa. The results indicated that the production of field crops is more sensitive to marginal changes in temperature as compared to changes in precipitation. The net revenue was positively affected by rise in temperatures and was negatively affected by reduction in rainfall. The importance of season and location in dealing with climate change was also highlighted, showing that the spatial distribution of climate change impact and consequently needed adaptations will not be uniform across different regions of South Africa. The results of climate change scenarios indicated many impacts that would require a very district shift in farming practices and patterns in different regions. They include major shifts in crop calendars and growing seasons, switching between crops to the possibility of complete disappearance of some field crops for some regions.

Davis et al., (2016) conducted a study which investigated recent trends in Climate of Namaqualand. Weather factors such as temperature, rainfall and evapotranspiration were analysed. A high-resolution ( $0.5^{\circ} \times 0.5^{\circ}$ ) gridded monthly data set provided by the CRU TS 3.129 was used to analyse the spatial trends in temperature and rainfall for the period 1901–2009 (Davis et al., 2016). The results indicated that temperature have increased; minimum temperatures by  $1.4^{\circ}\text{C}$  per decade and maximum by  $1.1^{\circ}\text{C}$ . There was no substantial change in annual totals of the frequency or intensity of rainfall events, however spatial variability was observed across the region. Furthermore, there was a notable increase of up to 30 mm per decade in evapotranspiration along the coastline, which was mostly remarkable in spring and summer. Even though there was no distinguished change in rainfall, an increase in temperature and ET poses a meaningful challenge for water availability as evaporative demand will increase with increased temperatures. Additionally, Davis et al., (2016) argued that continued increase in temperature for the region has extensive implications for livestock heat stress as well as for

other agricultural sectors. The summarized articles have brought an insight about how climate change affects agricultural production and the methods used to investigate the issue. The above reviewed literature has highlighted studies that have been done and identify the gaps in knowledge. The literature has also demonstrated the suitable methods to answer similar research questions and those methods have been adopted in the present study.

### 3.6 Methodology

#### 3.6.1 Data collection

The aim of this chapter was to determine the climate constraints, and mitigations to Free State crop production. The type of data that was used to achieve this investigation was for objective one ARC rainfall data, CHIRPS data and SPEI data and ARC temperature data for objective two. Objective three used ARC wind speed data, ERA5 wind speed data and ARC Evapotranspiration data (Table 3.1). The study wishes to investigate how the shifting on the onset and amount of rainfall, changes in temperatures and increase in wind affect crop production in Free State. ARC weather station rainfall data, CHIRPS, and SPEI were used to determine the variation of rainfall in Free State. ARC temperature data was used to determine how warming, and frost affect crop production in Free State. ARC weather station wind speed data, ERA5 wind speed data and ARC Evapotranspiration data were used to determine the effect of wind in the occurrence of dust.

Table 3.1: Summary of data required to achieve each objective

| Types of data     | Objective 1 (Rainfall) | Objective 2 (temperature) | Objective 3 (wind) |
|-------------------|------------------------|---------------------------|--------------------|
| ARC (rainfall)    | Yes                    | No                        | No                 |
| CHIRPS            | Yes                    | No                        | No                 |
| SPEI (drought)    | Yes                    | No                        | No                 |
| ARC (temperature) | No                     | Yes                       | No                 |
| ARC (wind)        | No                     | No                        | Yes                |
| ERA5 (wind)       | No                     | No                        | Yes                |
| ARC (ET)          | No                     | No                        | Yes                |

### 3.6.1.1 Automatic weather station data

For examining the impact of rainfall, temperature, frost and wind on agricultural activities, weather data acquired from Agricultural Research Council (ARC) was used. The weather data (rainfall, temperature, wind, and ET) is recorded in a network of four recently established, scientific-grade, automatic weather stations (Table 3.2) and (Figure 3.2) (Bultfontein (located on the farm Arbeidskroon, about 20 km North West of the town of Bultfontein), Hoopstad, Wesselsbron and Wolmaranstad) in the western Free State and is available in a time series from 2003 up to present. The start date of the data varies in the four weather stations; Bultfontein (2005), Hoopstad (2003), Wesselsbron (2004) and Wolmaranstad (2007), because the weather stations were installed in different years. However, analysis for weather station data was done for the period of 2006-2016 for better comparison with dust source data, as the first dust event was observed in 2006. The ARC weather data had gaps in some years and thus gap filling undertaken. Rainfall and temperature data have been used in other studies Blignaut et al., (2009), to establish the influence of climate change on agricultural activities.

Table 3.2: Agricultural Research Council weather stations in Free State

| Station Name              | Latitude (°S) | Longitude (°E) | Altitude (m) |
|---------------------------|---------------|----------------|--------------|
| Bultfontein: Arbeidskroon | -28.15282     | 26.06358       | 1305         |
| Hoopstad: Vryheid         | -27.93911     | 25.70882       | 1313         |
| Wesselsbron: Cornelia     | -27.69107     | 26.44186       | 1288         |
| Wolmaranstad: Hartbeespan | -27.49379     | 25.97542       | 1279         |

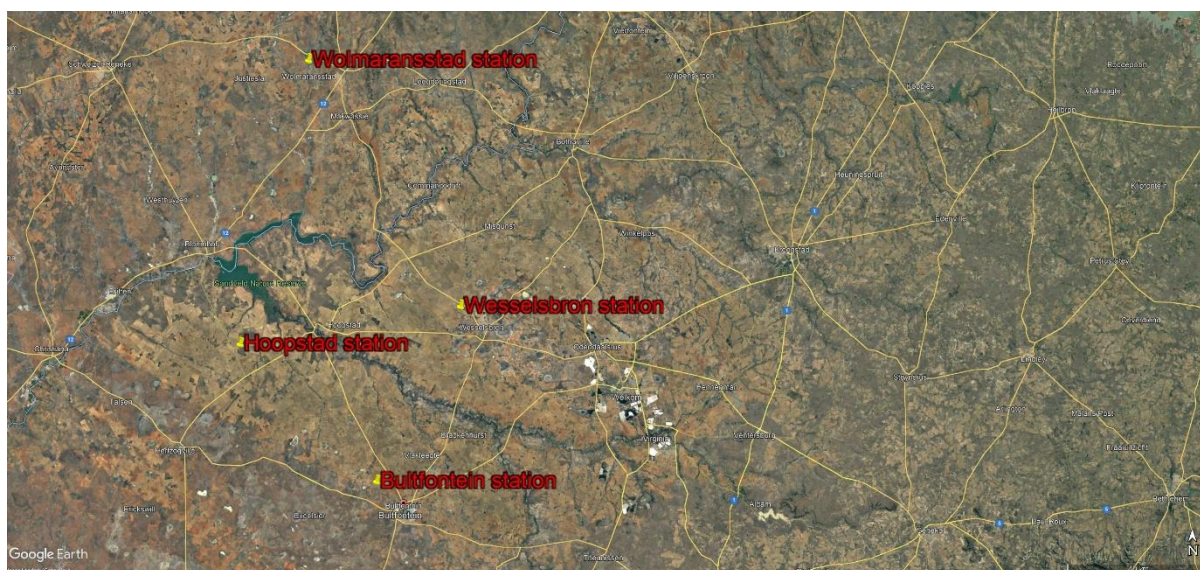


Figure 3.2: Location of Agricultural Research Council weather stations in Free State.

### 3.6.1.2 ARC rainfall data

Ground measured rainfall data was obtained from a series of four ARC weather stations. The ARC ground measured rainfall data had missing values and thus gap-filling was done using the CHIRPS data. Rainfall missing data was mainly due to malfunction of the rain gauge equipment. Therefore, a remote sensing data was used, to produce complete data series from the four ARC weather stations. Remote sensing products have an advantage of allowing record data or they always have a full record of data. CHIRPS data was extracted for each weather station using the coordinates of the weather stations. To determine the reliability of the relationship between CHIRPS and ground-measured rainfall data, a comparison of the CHIRPS data with the ground measured rainfall data from the farm Arbeidskroon (referred to as Bultfontein Weather Station in ARC database) was conducted. Generally, CHIRPS data is not significantly different from ground measured data, which makes CHIRPS data suitable to gap fill the ground measured data. However, CHIRPS did not report the very large rainfall events in June 2009 (CHIRPS = 24.26 mm and ARC 379.53 mm) and Dec 2011 (CHIRPS = 27.23 mm and ARC = 101.34 mm) which resulted in the means for the months of June using ARC data to be much higher than those calculated using CHIRPS.

### **3.6.1.3 CHIRPS data**

The CHIRPS data was extracted using a built-for-purpose Java script code in the Google Earth Engine (<https://code.earthengine.google.com/>) (Java script in Appendix 3.1) for the four weather stations. CHIRPS data was used to gap fill the ARC rainfall data and compared with it to determine rainfall variation in Free State. Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) was developed by the USGS. CHIRPS produce dataset on daily, pentadal and monthly precipitation at a high resolution of  $0.05^\circ$  globally (Funk et al., 2015). To produce a time series for trend analysis CHIRPS integrates satellite imagery with station data. CHIRPS has been providing data from 1981 up until present. The period of 1981-2019 was used to determine the shift on the onset of rainfall over the years. It was advantageous to use the data from 1981 to better observe the associated trends. Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis version 7 is used by CHIRPS to calibrate global Cold Cloud Duration (CCD) rainfall estimates (Funk et al., 2015).

### **3.6.1.4 Standardized Precipitation Evapotranspiration Index (SPEI)**

SPEI was used to understand the trends of drought over the years. SPEI programme was acquired from the SPEI Global Drought Monitor (<http://spei.csic.es/map/maps.html#months=1#month=5#year=2018>) accessed in July 2018. SPEI determines drought by taking into consideration both precipitation and evapotranspiration (Masupha & Moeletsi, 2017). Highest possible evapotranspiration is compared with the current water availability whereby precipitation represents the water availability and evapotranspiration signify the water demand (Masupha & Moeletsi, 2017). The SPEI is a multiscale drought index based on climatic data. The SPEI is computed using monthly or weekly precipitation as the input data (Reinert, Prill, Frank, & Zängl, 2016). The SPEI uses the monthly or weekly difference between precipitation and Potential Evapotranspiration (PET). This represents a simple climatic water balance which is calculated at different time scales to obtain the SPEI.

SPEI can be used for determining the onset, duration, and magnitude of drought conditions with respect to normal conditions in a variety of natural and managed systems such as crops, ecosystems, rivers, water resources, etc. The SPEI Global Drought Monitor offers near real-

time information about drought conditions at the global scale, with a 0.5 degrees spatial resolution and a monthly time resolution (Reinert et al., 2016). SPEI timescales between 1 and 48 months are provided. The data analysed in the present study is for SPEI time-scales 1, 3, 12 and 48. SPEI 1 focus on meteorological drought cycles, SPEI 3 emphasizes on seasonal short and medium term trends such as soil moisture that would flag agricultural drought, SPEI 12 emphasises annual moisture cycles that would flag hydrological drought conditions and SPEI 48 represents the accumulative long term decadal drought cycles (Lee & Zobeck, 2009). The dataset is updated during the first days of the following month based on the most reliable and updated sources of climatic data.

Masupha & Moeletsi, (2017) state that SPEI has an ability to combine a multi-scalar character with the capacity to include the effects of temperature variability and evapotranspiration to monitor droughts with respect to severity, duration, onset, extent, and end. The SPEI fulfils the requirements of a drought index since its multi-scalar character which enables it to be used by different scientific disciplines to detect, monitor, and analyse droughts. The SPEI allows comparison of drought severity through time and space, since it can be calculated over a wide range of climates, as can the SPI. Furthermore, Keyantash & Dracup, (2002) indicated that drought indices must be statistically robust and easily calculated and have a clear and comprehensible calculation procedure and all these requirements are met by the SPEI.

#### **3.6.1.5 ARC temperature data**

Temperature data was obtained from a series of four ARC weather stations. ARC ground measured temperature data was used to establish the impact of maximum and minimum temperatures and frost in Free State crop production. Temperature data had missing values and thus a (multiple) (non)-linear regression method was used to gap-fill the temperature data. Gap filling was done to obtain high quality synthetic data that is consistent. The main advantage of regression method is that it is not necessary to make any prior assumptions about a physical relation between variables, as compared to semi-empirical models (Moors, n.d.). Regression method was found to be the best in estimating missing variables in temperature and water vapour pressure data (Moors, n.d.). The data from the weather stations came with gaps probably due to malfunction of the weather station. A (multiple) (non)-linear regression method uses the closest station to gap fill the station with missing data. A scatter plot of both stations using the



data of the day that is followed by the day with missing data was created. Furthermore, a trendline was added on the scatter plot with the regression equation:  $y = mx + c$  and coefficient of determination ( $R^2$ ) to determine the relationship between the stations. The values on the station that is used to gap-fill the other were multiplied by the  $m$  value from the regression equation. The values obtained were then used to fill the missing hours. From the present study there are four weather stations and they have missing data in different hours, days, months, and years. Therefore, each station was able to gap fill the neighbouring station. Bultfontein station was gap filled by Hoopstad station, Hoopstad station was gap filled by Wolmaranstad station, Wesselsbron station was gap filled by Bultfontein station and lastly Wolmaranstad was gap filled by Hoopstad station.

#### **3.6.1.6 ARC and ERA5 wind data**

To determine how wind affects Free State agricultural lands and possibly contributing to dust wind speed data obtained from a series of four ARC weather stations was used. The ARC wind speed data had missing values and is in a point data format and for these reasons this data could not be solely used to investigate wind effect in Free State agricultural lands. Therefore, ERA5 wind data was also used. ERA5 wind speed data was obtained from ERA5 database using Google Earth Engine. ERA5 (Copernicus Climate Change Service, 2017) is the latest reanalysis dataset from the European Centre for Medium-range Weather Forecasts (ECMWF) (Kalverla, Duncan, Steeneveld, & Holtslag, 2019). Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. ERA5 replaces its predecessor, the ERA-Interim reanalysis (Kalverla et al., 2019). ERA5 is characterised by a finer horizontal grid of about 30 km and enhanced vertical resolution (Kalverla et al., 2019). ERA5 is available from 1979 and provides output in hourly intervals, which enables an inclusive analysis. These two datasets are in completely different formats which made them not easy to compare.

### **3.6.1.7 ARC Reference Evapotranspiration ( $ET_0$ ) data**

Reference ET was obtained from a series of four ARC weather stations in Free State. The data was compared with wind speed to determine how these factors influence or contribute to the occurrence of dust. Reference ET is the evapotranspiration rate from a reference surface, not short of water (Allen, Pereira, Raes, & Smith, 1998). The reference surface is assumed to be a grass reference crop with specific characteristics, such as crop height of 0.12 m, fixed surface resistance of  $70 \text{ s m}^{-1}$  and an albedo of 0.23. Reference ET does not consider the crop characteristics and soil factors; it is only affected by climatic parameters such as temperature, radiation, wind speed, sunshine hours and air humidity and can be computed from weather data (Allen et al., 1998). Reference ET is in a point data format which also made it difficult to compare with ERA5 wind data.

### **3.6.2 Data analysis**

Descriptive statistics such as maximum, minimum, average, standard deviation, and sum were calculated for each sample of data for the four weather stations. Coefficient of determination ( $R^2$ ) was used to determine the correlation between measured ARC rainfall and estimated CHIRPS rainfall. Excel and R studio provide data analysis tools that were used to produce the graphs. R is a system for statistical computation and graphics. It provides a programming language, high level graphics, interfaces to other languages and debugging facilities (Team, 2015). Mann-Kendall (MK) statistical test was used to determine whether measured ARC and estimated CHIRPS rainfall have a monotonic upward or downward trend. MK is a non-parametric test that is frequently used for identifying trends in hydrologic variables (YADAV et al., 2014). A chi-square statistical test was also used to determine whether the decades from the CHIRPS data are dependent or not. Testing dependence was done with the purpose of determining whether the onset of rainfall in a current decade is influenced by the previous decade. However, the limitation of this test is the fact that it cannot be applied on continuous data.

### **3.6.2.1 Examining the shift on the onset of rainfall**

CHIRPS daily data from 1981 until 2019 was extracted using Goggle Earth Engine for Bultfontein area (26.06358E, -28.15282S). The data was divided into four groups (i.e., three decades (1981-1990, 1991-2000, 2001-2010) and 9 years (2011-2019) for better analyses. According to knowledge from the Free State farmers, for them to start planting maize each year they wait until they receive approximately 15 mm of rain. Once this amount of rainfall is received, they believe that the soil is moist enough to commence with ploughing. Thus 15 mm was used as a threshold in the present study (i.e., rainfall event equal or greater than 15 mm/day was regarded as the onset of rainfall suitable for planting maize crops). For each period rainfall events that were less than 15 mm were removed or filtered and only days with rainfall equal or greater than 15 mm were kept for analysis. A pivot table was used to count the number of events that were equal or greater than 15 mm/day for each year, focusing on September-December months. Bar graphs were further plotted to show these number of events from each 10-year period. Furthermore, the Julian day in which the first 15 mm/day of rain occurred from September-December was regarded as the onset of rainy season. These days were plotted against the years with the purpose of demonstrating the trend of the onset of rainfall.

### **3.6.2.2 Temperature data**

Temperature data from ARC weather stations was used to determine the variation of temperatures in Free State and the number of frost hours per month, total number of frost hours per year, and the onset of frost. To determine the number of frost hours per month hourly temperatures that were more than 0°C were filtered and only temperatures equal or less than 0°C were kept for analysis and those hours were then counted. Frost occurs when temperatures drop to 0°C and below. Additionally, total hours with temperatures equal or less than 0°C for the whole year were obtained to determine the total number of frost hours per year. To determine the onset of frost per year minimum daily temperatures were used, and the onset of frost was regarded as the first day in a year that received a minimum temperature of 0°C or below.

### **3.6.2.3 ARC and ERA5 wind speed data**

Wind speed data was analysed with the purpose of determining whether it is becoming windier over the years. Daily and monthly maximum wind speed, daily and monthly average wind speed, monthly total wind run and monthly number of hours with wind speed greater than 6 m/s were plotted in line and bar graphs. The 6 m/s wind speed was used as a threshold because according to the literature, particles start moving when wind is 6 m/s. ERA5 wind speed data was also compared with ARC ground measured wind speed and Reference ET data.

## **3.7 Results**

### **3.7.1 Introduction**

The aim of this chapter is to determine the climate constraints, and mitigations to Free State crop production. The first set of results wishes to answer the first objective, which is to determine rainfall variation and its influence on agricultural activities. To achieve this objective ARC rainfall, CHIRPS and SPEI analysis are presented. Temperature data is further presented to answer the second objective which is to establish the impact of temperature and frost on agriculture. Lastly, ARC and ERA5 wind speed data are presented to determine how wind affects Free State agricultural land. Wind speed data is further compared with Reference ET to find their influence in the occurrence of dust.

### **3.7.2 Seasonality of rainfall**

#### **3.7.2.1 ARC rainfall data and CHIRPS data**

Figure 3.3 shows the number of days that received rainfall within a month. Some months within a year and from different years and stations had many rain days, however that does not mean a specific month had received high rainfall. The rainfall intensity might be low in a specific month with many rain days and there might be high rainfall intensity in a month with a smaller number of rain days. The plotted number of rain days includes all the values greater than zero. In Bultfontein weather station January 2006 had the highest number of rain days (25

days) as compared to all the other months within that year and between the other years. In Hoopstad weather station April 2011 had the highest number of rain days (22 days). For Wesselsbron weather station December 2011 had the highest number of rain days (23 days), whereas for Wolmaranstad weather station January 2010 and April 2011 had the highest number of rain days (20 days). Generally, the highest number of rain days in Free State range from 20-25 and these high numbers are obtained in wet months.

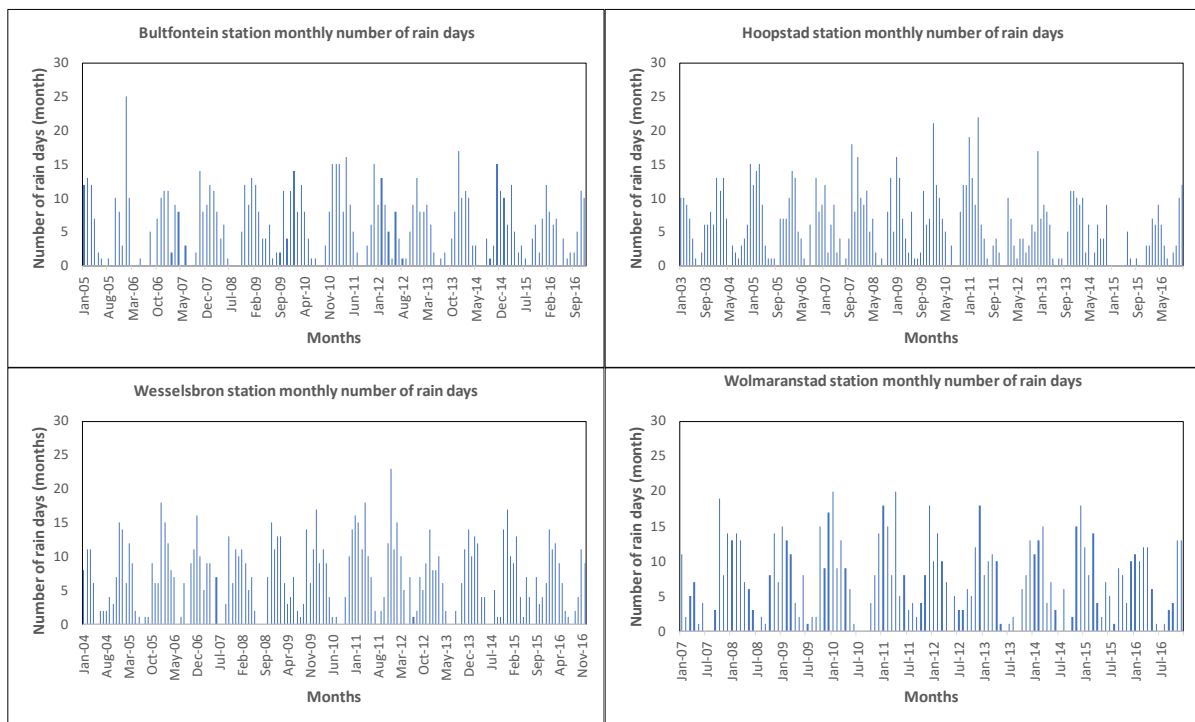


Figure 3.3: Monthly number of rain days from a series of four ARC weather stations in Free State, South Africa. Data obtained from ARC database.

Figure 3.4 shows the comparison between measured ARC annual rainfall and estimated CHIRPS annual rainfall. The results of the coefficient of determination ( $R^2$ ) for the comparison of the measured ARC annual rainfall and the estimated CHIRPS annual rainfall are positive in all the stations. The  $R^2$  values range from 0.078 in Wesselsbron to the highest of 0.675 in Wolmaranstad. Based on the  $R^2$  values for three station (Bultfontein = 0.217, Hoopstad = 0.334 and Wesselsbron = 0.078) there is a positive poor relationship between the measured rainfall

and the estimated rainfall. However, there is a positive strong relationship between measured annual rainfall and estimated rainfall in Wolmaranstad station.

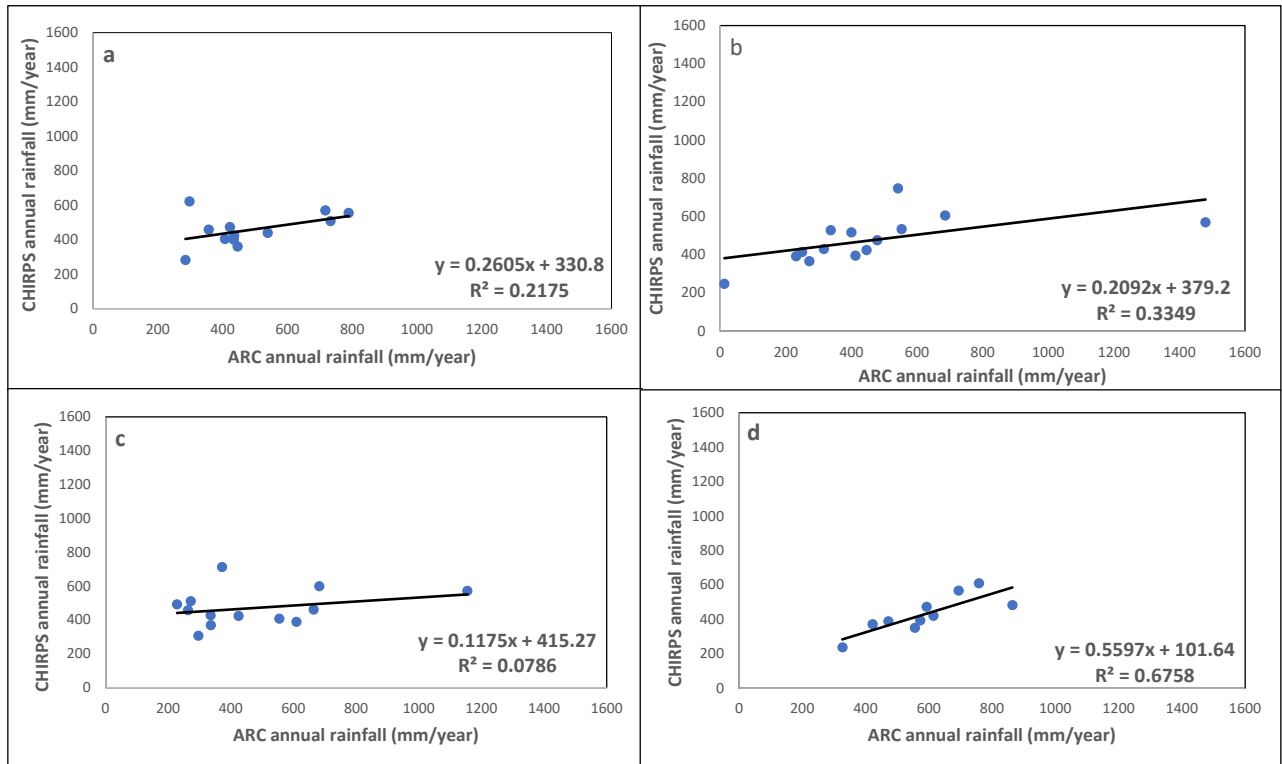


Figure 3.4: Comparison between measured ARC annual rainfall and estimated CHIRPS annual rainfall for (a) Bultfontein, (b) Hoopstad, (c) Wesselsbron and (d) Wolmaranstad.

Figure 3.5 indicates the total annual rainfall variation from CHIRPS and a series of four ARC weather stations in Free State, South Africa. From the ARC weather station data there is a variation of rainfall from year to year in the four stations with total rainfall amount received in 2005 of 357 mm/year and 408 mm/year in 2016 in Bultfontein station. Rainfall has increased in Bultfontein by approximately 51 mm/year from 2005 to 2016. From Hoopstad station the total rainfall amount received in 2003 was 231 mm/year and 249 mm/year in 2016. Rainfall has slightly increased by 18 mm/year from 2003 to 2016. 2015 was excluded from analysis due to the station being dysfunctional. From Wesselsbron station rainfall has increased by 282

mm/year from 2004 (272 mm/year) to 2016 (554 mm/year). From Wolmaranstad station rainfall has decreased by 20 mm/year from 2007 (593 mm/year) to 2016 (573 mm/year). The stations data does not start in the same year which makes the comparison a bit biased. Generally, a similar trend is observed from all stations; a year with relatively low or high rainfall in one station is observed to be similar in the rest of the stations. However, a sharp peak in rainfall amount in 2009 is observed from two stations (Hoopstad and Wesselsbron) where the rainfall recorded from each station in 2009 was 1479.43 mm/year and 1155.10 mm/year respectively. In 2009 South Africa recorded a flooding event that affected most Provinces including Free State Govindasamy, (2011) , however the floods did not hit the whole of Free State as evident from the rainfall data.

According to CHIRPS data there is a slight decrease in Free State rainfall. From Bultfontein station CHIRPS observed a decrease of 54 mm/ year from 2005 to 2016. From Hoopstad an increase of 22 mm/year from 2003 to 2016 was observed. From Wesselsbron a decrease of 104 mm/year was observed and from Wolmaranstad a decrease of 79 mm/year was observed. CHIRPS did not record the flood event observed from the ARC weather station data. According to ARC rainfall data Free State rainfall has slightly increased, whereas CHIRPS has observed a slight decrease. Average annual for CHIRPS shows a decrease in rainfall and average annual for ARC data shows a slight increase in rainfall. Generally, Free State is getting dry over the years as most years have experienced a decrease in rainfall amount. ARC and CHIRPS are different data sets which makes them difficult to compare.

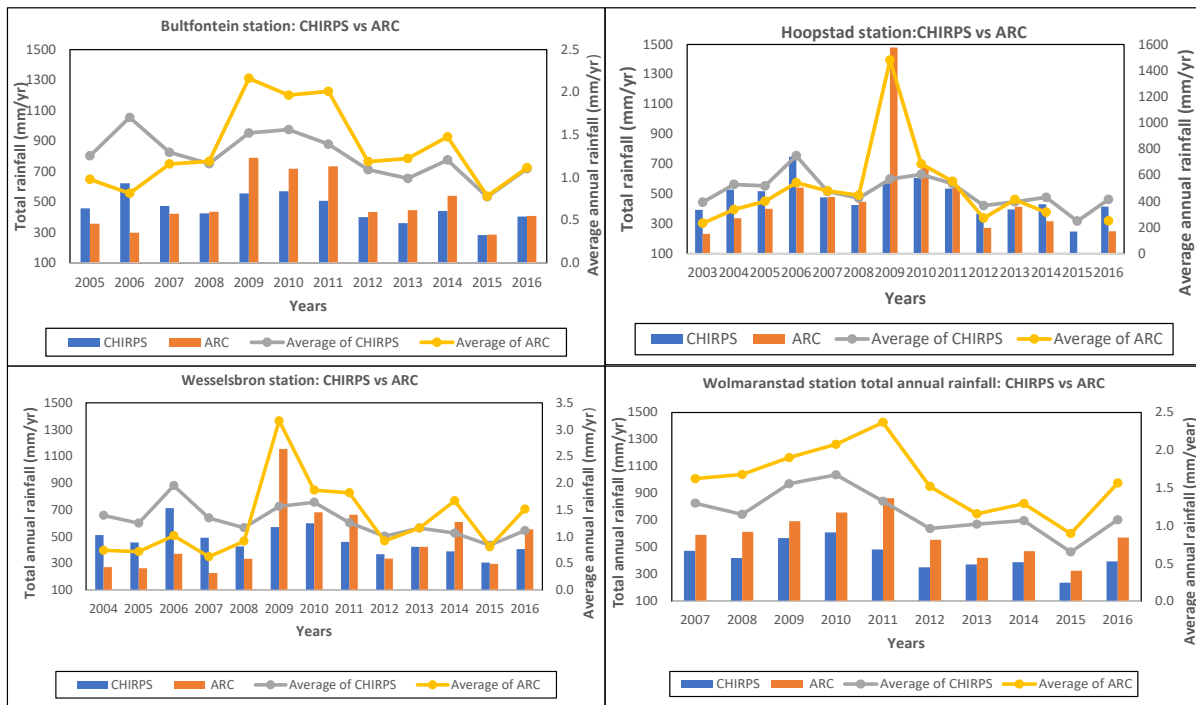


Figure 3.5: Total annual and average rainfall from CHIRPS and a series of four ARC weather stations in Free State, South Africa. The grey line is the annual average for CHIRPS and orange line is the annual average for ARC.

Table 3.3 present the descriptive statistics of measured ARC rainfall, estimated CHIRPS rainfall and Mann-Kendall test results. The minimum rainfall in ARC ranges between 231 – 327 mm/ year and maximum rainfall ranges between 789 – 1479 mm/year in the four weather stations (Table 3.3). The mean ranges between 458 – 587 mm/year and standard deviation ranges between 159 – 337 mm/year. The minimum rainfall in CHIRPS ranges between 228 – 306 mm/ year and maximum rainfall ranges between 611 – 748 mm/year in the four weather stations (Table 3.3). The mean ranges between 430 – 475 mm/year and standard deviation ranges between 95 – 122 mm/year. The standard deviations are relatively high for all the stations both from ARC and CHIRPS rainfall. This indicates that a wide range of values were observed from all the stations.

Mann- Kendall (MK) test was used to determine whether there is a monotonic upward or downward trend in ARC and CHIRPS rainfall from the four weather stations (Table 3.3). Null hypothesis ( $H_0$ ) states that there is no trend in the series and alternative hypothesis ( $H_1$ ) states that there is a trend in the series. Using the 0.05 significance level alpha, when the calculated



p-value is greater than alpha we do not reject the null hypothesis and when p-value is lower than alpha, we reject the null hypothesis. The calculated p-value for ARC rainfall was greater than alpha in all the stations, thus null hypothesis was not rejected. It can therefore be concluded that there is no constant increase or decrease trend in ARC rainfall (Appendix 3.2). The calculated p-value for CHIRPS rainfall was greater than alpha in Hoopstad and Wolmaranstad, therefore null hypothesis was not rejected. However, the calculated p-value for CHIRPS rainfall in Bultfontein and Wesselsbron was less than alpha, therefore null hypothesis was rejected. This indicates that there is a consistently decreasing trend in Bultfontein and Wesselsbron CHIRPS rainfall (Appendix 3.3). Moreover, when the calculated S value is positive that means there is an increasing trend and when it is negative there is a decreasing trend. Based on the calculated S for ARC rainfall Bultfontein and Wesselsbron have an increasing trend of rainfall, whereas Hoopstad and Wolmaranstad have a decreasing trend. The calculated S for CHIRPS rainfall shows a decreasing trend of rainfall in all the stations. This ascertains that rainfall is decreasing over the years.

Table 3.3: Descriptive statistics of annual ARC and annual CHIRPS rainfall in a series of four weather stations

| Stations     | ARC rainfall (mm/year)    |         |      |                | M-K test |     |
|--------------|---------------------------|---------|------|----------------|----------|-----|
|              | Minimum                   | Maximum | Mean | Std. deviation | p-value  | S   |
| Bultfontein  | 285                       | 789     | 489  | 170            | 0.84     | 4   |
| Hoopstad     | 231                       | 1479    | 492  | 325            | 0.51     | -13 |
| Wesselsbron  | 228                       | 1155    | 476  | 258            | 0.30     | 18  |
| Wolmaranstad | 327                       | 864     | 587  | 159            | 0.21     | -15 |
| Stations     | CHIRPS rainfall (mm/year) |         |      |                | M-K test |     |
|              | Minimum                   | Maximum | Mean | Std. deviation | p-value  | S   |
| Bultfontein  | 282                       | 622     | 458  | 95             | 0.05     | -30 |
| Hoopstad     | 248                       | 748     | 475  | 122            | 0.19     | -25 |
| Wesselsbron  | 306                       | 713     | 471  | 108            | 0.02     | -40 |
| Wolmaranstad | 238                       | 611     | 430  | 108            | 0.15     | -17 |

There is a considerable variation of anomalies from year to year within each weather station and from different weather stations (Figure 3.6). For some years there is a noticeable increase in the below normal average rainfall (negative anomaly) and in some years there is an increase in the above normal average rainfall (positive anomaly). These results correspond with MK test results; a year with positive rainfall anomaly also shows an upward trend in MK results

(appendix 3.2 and 3.3) vice versa. 2009 generally had a positive anomaly from all the stations and from the ARC data there is a huge variation between the normal average rainfall for Free State and the rainfall received in this year. This huge variation is certainly due to the flood event that occurred in this year. Negative rainfall anomaly indicates that rainfall in that year was below average and positive rainfall anomaly means that rainfall was above average in that specific year. CHIRPS is closely related to ground measured rainfall data. Interestingly CHIRPS did not record the flooding event that took place in 2009. In comparison, it is apparent that CHIRPS slightly underestimated rainfall in some years, even though in most years the observations are more similar. This may be due to poor detection of rain-bearing clouds.

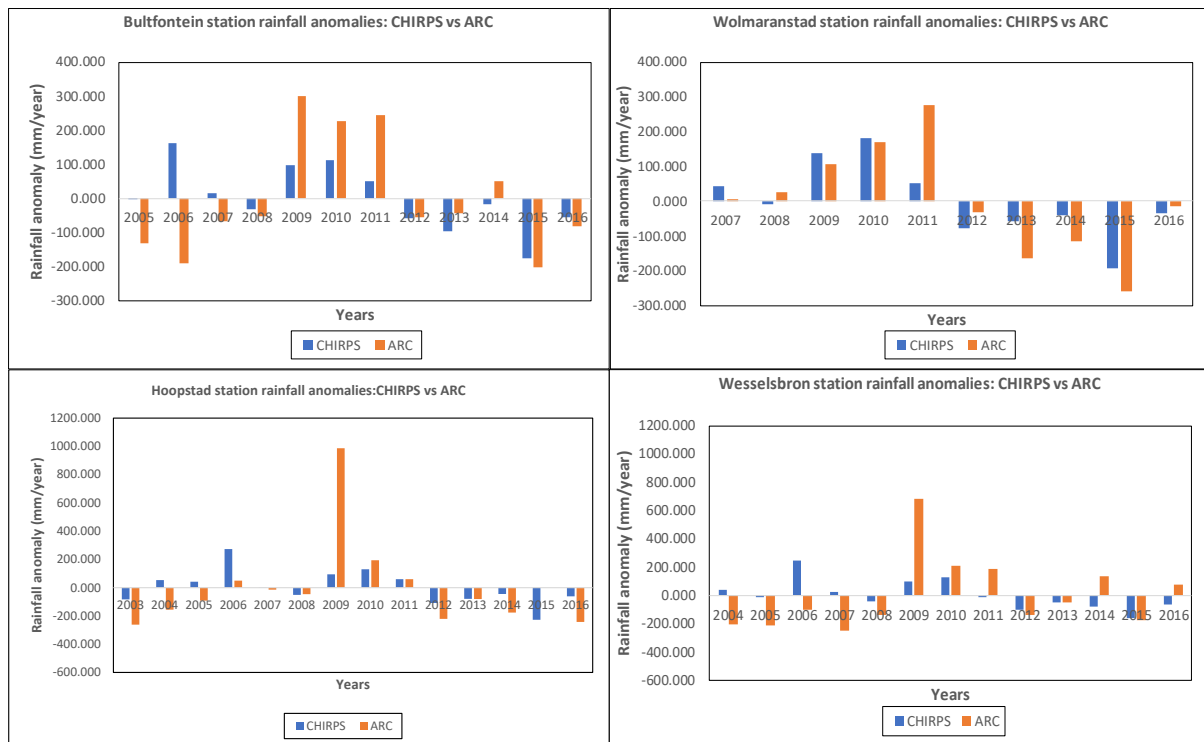


Figure 3.6: Rainfall anomalies from CHIRPS a series of four ARC weather stations in Free State, South Africa.

According to Figure 3.7 there is a meaningful rainfall variation within a year. The year 2007 was chosen for better comparison between the four stations because that is the year available between all the stations and the rest of the years are on the appendix. It is evident from Figure

3.7 and Appendix 3.4-3.7 that rainfall increases from October to February in most years and decrease from June to September. However, there is also evidence that in some year's rainfall occurred late (e.g., 2011 in all four stations as shown in the Appendix 3.4-3.7), with the first rainfall that is adequate to make the soil moisture being received in November. Free State is characterised by warm wet summer and cold dry winter, hence high rainfall is observed in summer and low rainfall in winter. The same trend is observed in all four weather stations. Hoopstad station generally receives lower rainfall as compared to other stations even though the trend is similar and Wolmaranstad station mostly receives higher rainfall than other stations.

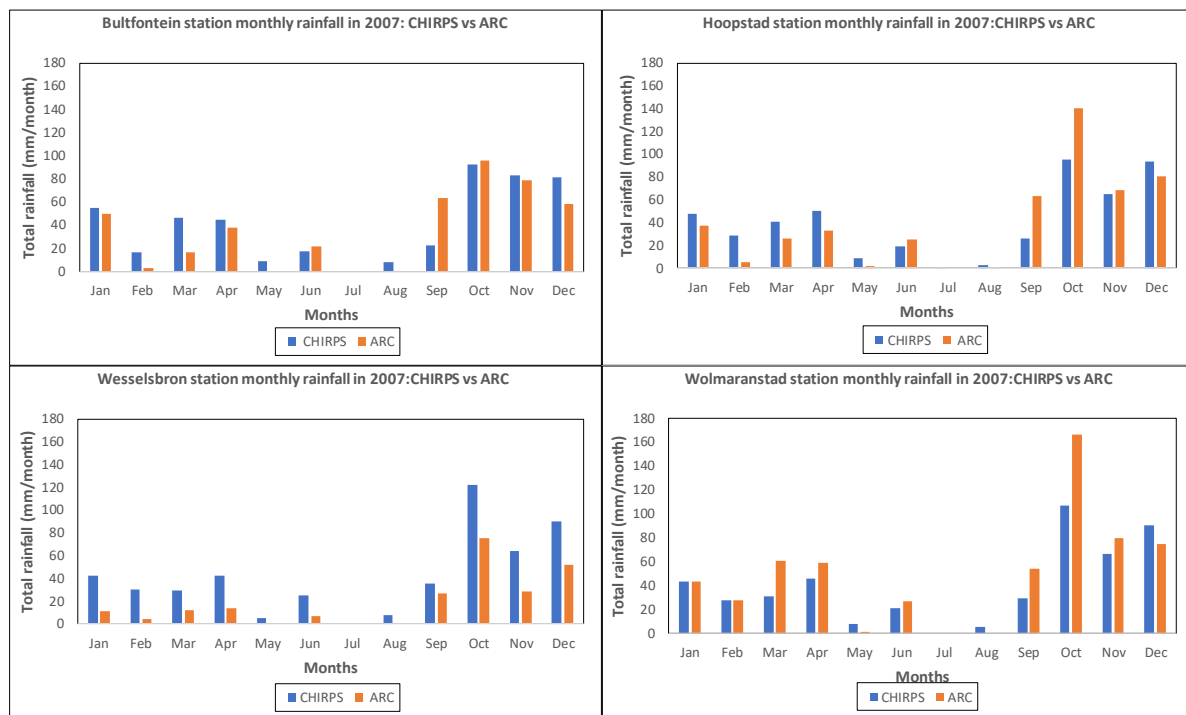


Figure 3.7: Total monthly rainfall from CHIRPS and a series of four ARC weather stations in Free State, South Africa

The maximum rainfall for 2007 in ARC rainfall ranges between 75 – 167 mm/ month and minimum rainfall is 0 mm/month in the four weather stations (Table 3.4). The average ranges between 19 – 49 mm/month and standard deviation ranges between 23 – 47 mm/month. The standard deviations are relatively high for all the stations, with the least one being 23

mm/month in Wesselsbron. This indicates that a wide range of values were observed from all the stations. The maximum rainfall in CHIRPS rainfall ranges between 92 – 122 mm/month and minimum rainfall was 0 mm/month for all the stations in 2007. The average ranges between 39 – 41 mm/month and standard deviation ranges between 32 – 36 mm/month. The standard deviations are high for all the stations, which means a wide range of values were observed in all the stations. Table 3.4 generally shows that there is a variation between ARC rainfall and CHIRPS rainfall.

Table 3.4: Descriptive statistics of CHIRPS and ARC rainfall in 2007 in a series of four weather stations

| CHIRPS rainfall in 2007 |                    |                    |                    |                               |
|-------------------------|--------------------|--------------------|--------------------|-------------------------------|
|                         | Maximum (mm/month) | Minimum (mm/month) | Average (mm/month) | Standard deviation (mm/month) |
| Bultfontein             | 92                 | 0                  | 39                 | 32                            |
| Hoopstad                | 95                 | 0                  | 40                 | 32                            |
| Wesselsbron             | 122                | 0                  | 41                 | 36                            |
| Wolmaranstad            | 107                | 0                  | 39                 | 33                            |
| ARC rainfall in 2007    |                    |                    |                    |                               |
| Bultfontein             | 96                 | 0                  | 35                 | 34                            |
| Hoopstad                | 140                | 0                  | 40                 | 42                            |
| Wesselsbron             | 75                 | 0                  | 19                 | 23                            |
| Wolmaranstad            | 167                | 0                  | 49                 | 47                            |

### 3.7.3 Drought

Figure 3.8 to 3.11 indicates SPEI in Bultfontein, Hoopstad, Wesselsbron and Wolmaranstad stations. From the Figures it is apparent that there was a wet and a dry cycle from 1950 up until present. It is notable that there was a severe drought in some years such as 1951, 1962, 1982, 1989, 1995, 2005, 2012, 2014 and 2016 from all the stations. Several other studies Bahta et al., (2016); Baudoin et al., (2017); Masupha & Moeletsi, (2017); Rouault & Richard, (2003) also noted these drought patterns in other regions of South Africa. The severe drought events match with the rainfall data. According to the ARC rainfall data 2005, 2012, 2015 and 2016 (Figure 3.6) received rainfalls that were below average and there was notable increase in temperatures during these years.

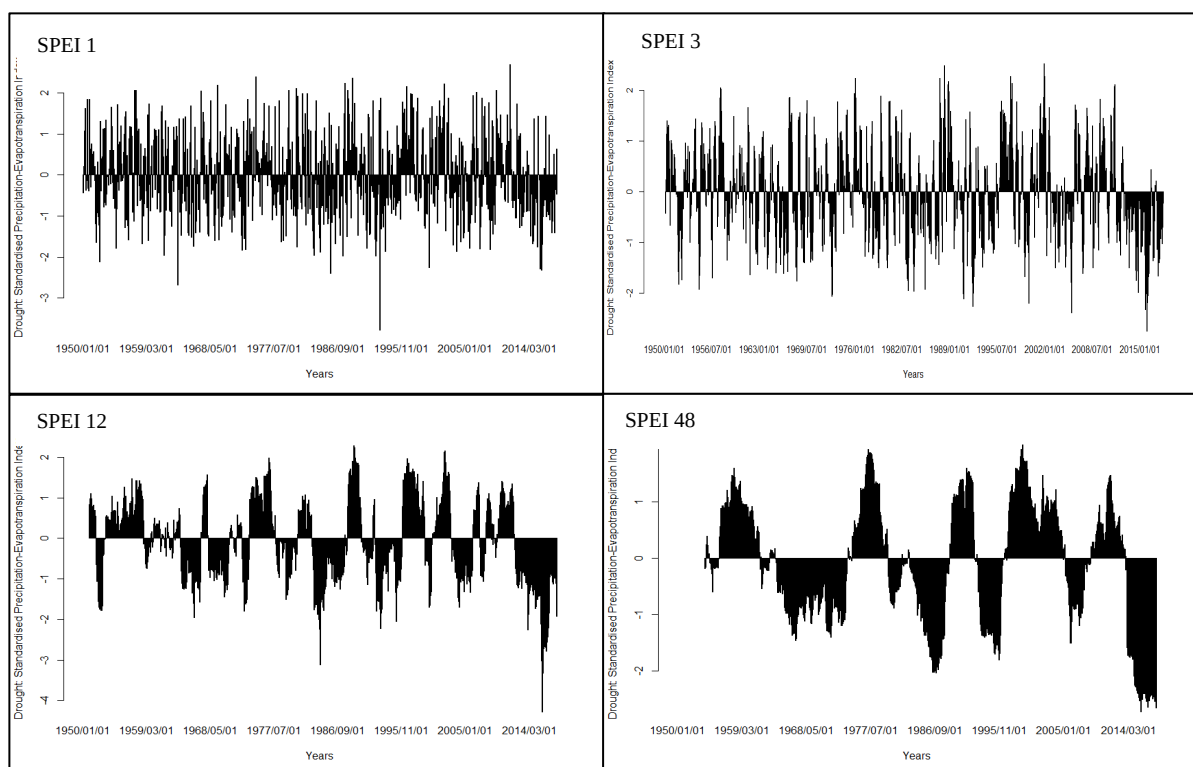


Figure 3.8: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 3, bottom left = SPEI 12 and bottom right = SPEI 48 in Bultfontein. Graphs showing years with no drought to years with severe drought.

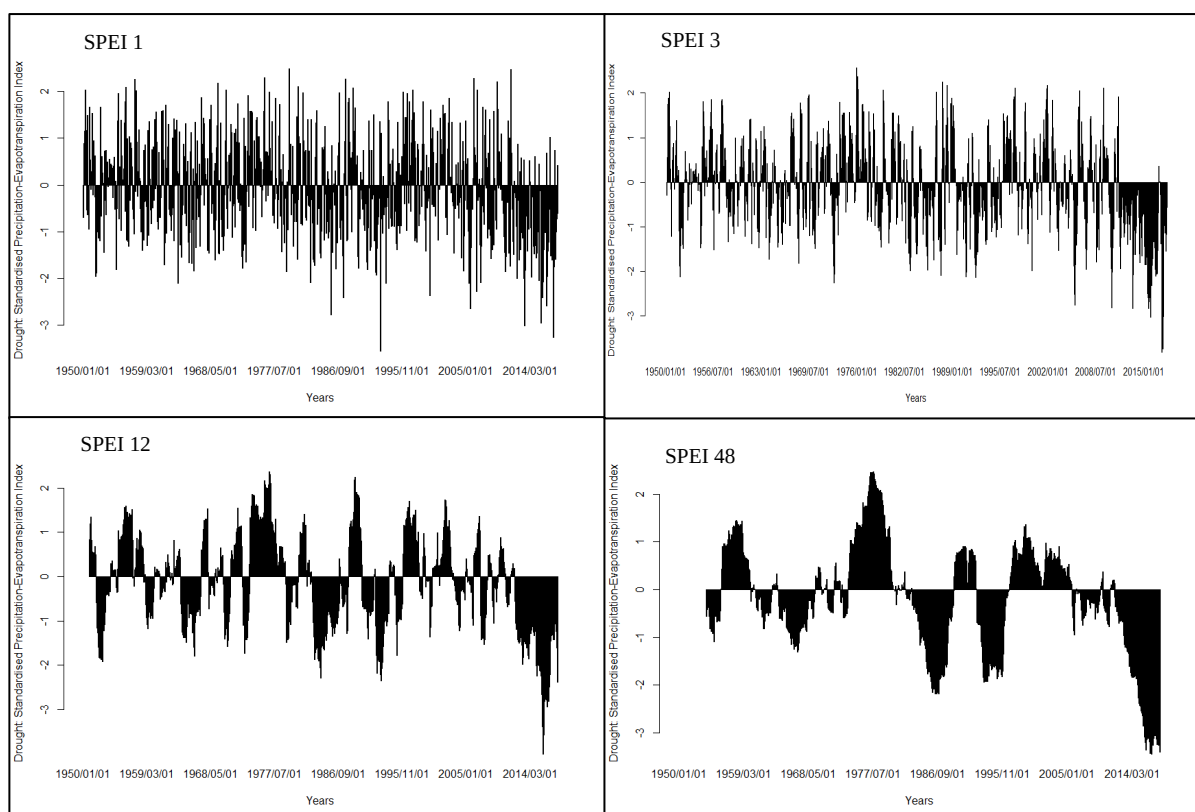


Figure 3.9: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 3, bottom left = SPEI 12 and bottom right = SPEI 48 in Hoopstad. Graphs showing years with no drought to years with severe drought.

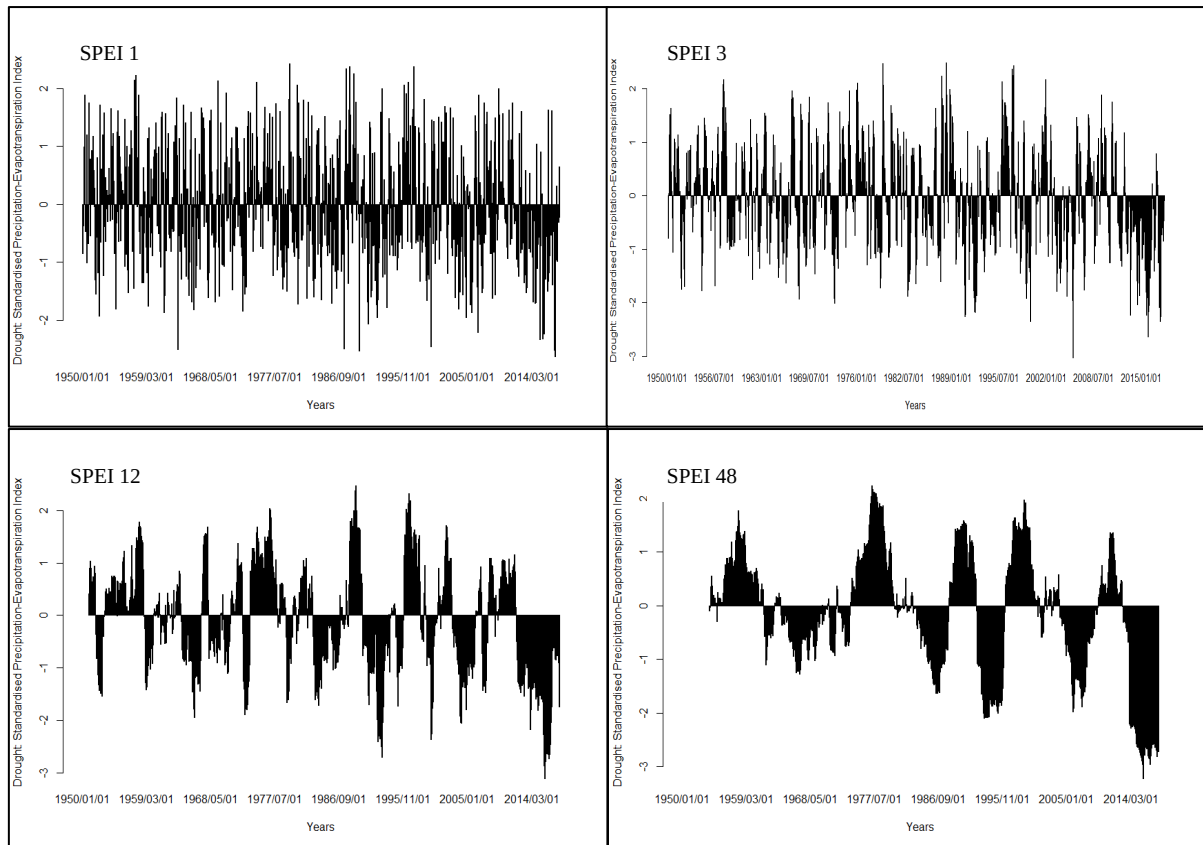


Figure 3.10: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 3, bottom left = SPEI 12 and bottom RIGHT = SPEI 48 in Wesselsbron. Graphs showing years with no drought to years with severe drought.

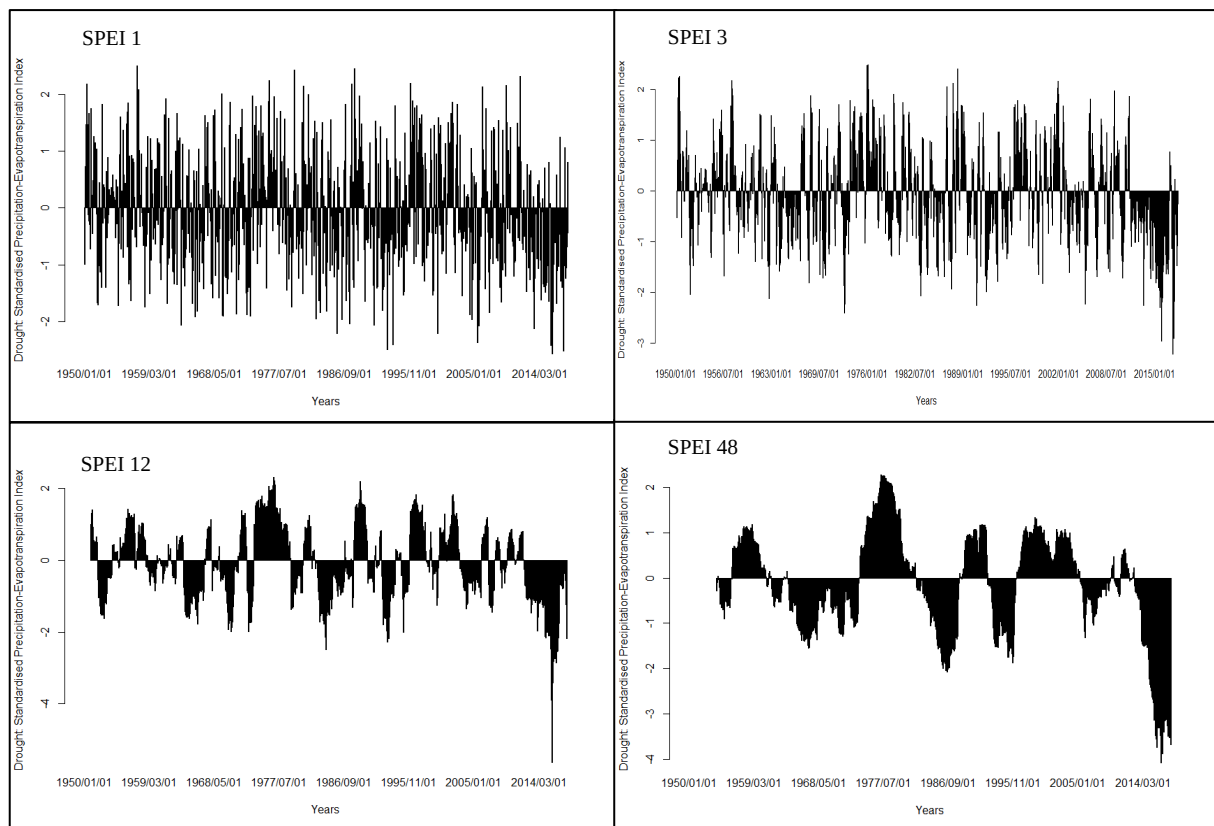


Figure 3.11: Standardised Precipitation Evapotranspiration Index (top left= SPEI 1, top right = SPEI 12, and bottom left = SPEI 48 in Wolmaranstad. Graphs showing years with no drought to years with severe drought.

### 3.7.4 Timing of rain

#### 3.7.4.1 The shift on the onset of rainfall in Free State

##### *Onset of rainfall in September*

Number of rainfall events greater or equal to 15 mm/ day for the period (1981-2019) during summer period in a series of four weather stations in Free State (Figure 3.12), were analysed with the purpose of examining the shift on the onset of rainfall. The rainfall season in Free State starts in September/ October and ends in March/ April (Moeletsi, 2010). This study is interested on the months September to December because maize crops are likely to be planted during this period. In Bultfontein from the first 10-year period (1981-1990) (Appendix 3.8), it is evident that the onset of rainfall suitable for the start of ploughing is shifting. There were



only four years that received this minimum rainfall amount in September from 1981-1990 and the events were significantly low (1981=1, 1986 = 1, 1987= 2 and 1988 = 1). From 1991-2000 (Appendix 3.9) there were no rainfall events greater or equal to 15 mm/ day in September. From 2001-2010 (Appendix 3.10) there were two rainfall events greater or equal to 15 mm/ day in September (2001 = 1, and 2007 = 1). From 2011-2019 (Appendix 3.11) there were no rainfall events greater or equal to 15 mm/ day in September. In Hoopstad from 1981-1990 (Appendix 3.12) only two years received the minimal rainfall amount in September and the events were significantly low (1986=1, and 1988 = 1). From 1991-2000 (Appendix 3.13) the 15 mm/ day of rainfall was only received in 1991 and it was only one event. From 2001-2010 (Appendix 3.14) there was no rainfall event greater or equal to 15 mm/day in September. Moreover, the period 2011-2019 (Appendix 3.15) also did not have the rainfall event greater or equal to 15 mm/day in September.

In Wesselsbron from 1981-1990 (Appendix 3.16) there were only two years (1987 = 2 events and 1988 = 1 event) that received the minimal rainfall amount in September. From 1991-2000 (Appendix 3.17) there was only one rainfall event greater or equal to 15 mm/ day in September and it occurred in 1998. From 2001-2010 (Appendix 3.18) there were two rainfall events greater or equal to 15 mm/ day in September (2001 = 1 and 2007 = 1). From 2011-2019 (Appendix 3.19) there was one rainfall event greater or equal to 15 mm/ day in September 2016. In Wolmaranstad there was only one year (1987) that received 15 mm/day in September from 1981-1990 (Appendix 3.20). From 1991-2000 (Appendix 3.21) there were no rainfall events greater or equal to 15 mm/ day in September. From 2001-2010 (Appendix 3.22) there was one rainfall event greater or equal to 15 mm/ day in September (2007 = 1). From 2011-2019 (Appendix 3.23) there was one year (2012) that received the rainfall event greater or equal to 15 mm/ day in September.

### ***Onset of rainfall in October***

According to Figure 3.12 in October of 1981-1990 five years received the 15 mm of rainfall (1982 = 1, 1984 = 1, 1985 = 1, 1986 = 1 and 1988 = 3) in Bultfontein. From 1991-2000 four years received the 15 mm of rainfall (1991 = 4, 1993 = 1, 1995 = 1, and 1999 = 2). From 2001-2010 there were two rainfall events greater or equal to 15 mm/ day in October (2008 = 1 and 2009 = 1). From 2011-2019 there were two rainfall events greater or equal to 15 mm/ day in October (2012 = 1, and 2018 = 1). In Hoopstad from 1981-1990 six years received the 15 mm

of rainfall (1982 = 2, 1983 = 1, 1984 = 1, 1985 = 1, 1986 = 1 and 1988 = 2) in October. From 1991-2000 two years received this minimal rainfall (1991 and 1999) and both years only received two events. From 2001-2010 only 2008 had an event in October. From 2011-2019 there was no event greater or equal to 15 mm/ day in October.

In Wesselsbron from 1981-1990 seven years (1981, 1982, 1983, 1984, 1985, 1986 and 1988) received the minimum rainfall in October. From 1991-2000 six years received the 15 mm of rainfall (1991 = 1, 1992 = 1, 1993 = 3, 1994 = 1, 1995 = 2 and 1996 = 1) in October. From 2001-2010 there were three events in October (2001 = 1, 2007 = 2, and 2008 = 1). From 2011-2019 there were two events in October (2013 = 1, and 2018 = 1). In Wolmaranstad from 1981-1990 there were five years that received the 15 mm of rainfall (1982 = 2, 1984 = 1, 1985 = 1, 1986 = 2 and 1988 = 3). Furthermore, October of 1991-2000 period also had five years that received the 15 mm of rainfall (1991 = 1, 1992 = 1, 1993 = 3, 1995 = 1 and 1997 = 1). From 2001-2010 there were two rainfall events greater or equal to 15 mm/ day in October (2007 = 1 and 2008 = 1).

### ***Onset of rainfall in November***

As presented in Figure 3.13 in November of 1981-1990 seven years received the 15 mm of rainfall in Bultfontein. From 1991-2000 November had eight years that received the 15 mm of rainfall. From 2001-2010 November had eight years that received the 15 mm of rainfall with 2001 having the highest numbers of events (6). From 2011-2019 two years received the 15 mm of rainfall with 2014 having the highest numbers of events (5), and 2001 having the least (1). In Hoopstad from 1981-1990 there were six years that received the 15 mm of rainfall in November. From 1991-2000 there were also six years that received the 15 mm of rainfall. From 2001-2010 there were seven years that received the events in November. From 2011-2019 there were no rainfall events greater or equal 15 mm/ day in November.

In Wesselsbron from 1981-1990 seven years received the 15 mm/day of rainfall and the events were ranging from 1-2 in these years. From 1991-2000 November had six years that received the 15 mm of rainfall. From 2001-2010 November had six years that received the 15 mm of rainfall. From 2011-2019 November had two years that received the 15 mm of rainfall. In Wolmaranstad from 1981-1990 seven years received the 15 mm of rainfall. From 1991-2000 November had four years that received the 15 mm of rainfall. From 2001-2010 November had

five years that received the 15 mm of rainfall with 2001 having the highest numbers of events (3). From 2011-2019 two years received the 15 mm of rainfall in November.

### ***Onset of rainfall in December***

Figure 3.13 illustrates that for the first decade (1981-1990) Bultfontein had two years that received the 15 mm of rainfall in December. From 1991-2000 there were three years that received the 15 mm of rainfall in December. From 2001-2010 December had six years that received the 15 mm of rainfall. From 2011-2019 December had six years that received 15 mm/day and above of rainfall. In Hoopstad for 1981-1990 period there were six years that received the 15 mm of rainfall. For 1991-2000 decade there were six years that received the 15 mm of rainfall in December and the maximum events were 4 in 1993 and 1999. For 2001-2010 period there were seven years that received the 15 mm of rainfall in December. For 2011-2019 period six years received this rainfall amount in December (2011 = 2, 2012 = 2, 2013 = 2, 2014 = 1, 2016 = 1 and 2019 = 2).

In Wesselsbron for 1981-1990 decade seven years received the 15 mm of rainfall. For 1991-2000 period there were seven years that received the 15 mm of rainfall. For 2001-2010 decade December had seven years that received the 15 mm of rainfall. For 2011-2019 period December had four years that received 15 mm/day and above of rainfall. In Wolmaranstad for 1981-1990 decade there were seven years that received the 15 mm of rainfall in December. For 1991-2000 period December had six years that received the 15 mm of rainfall. For 2001-2010 decade there were six years that received the 15 mm of rainfall. Lastly for 2011-2019 period six years received the 15 mm of rainfall in December.

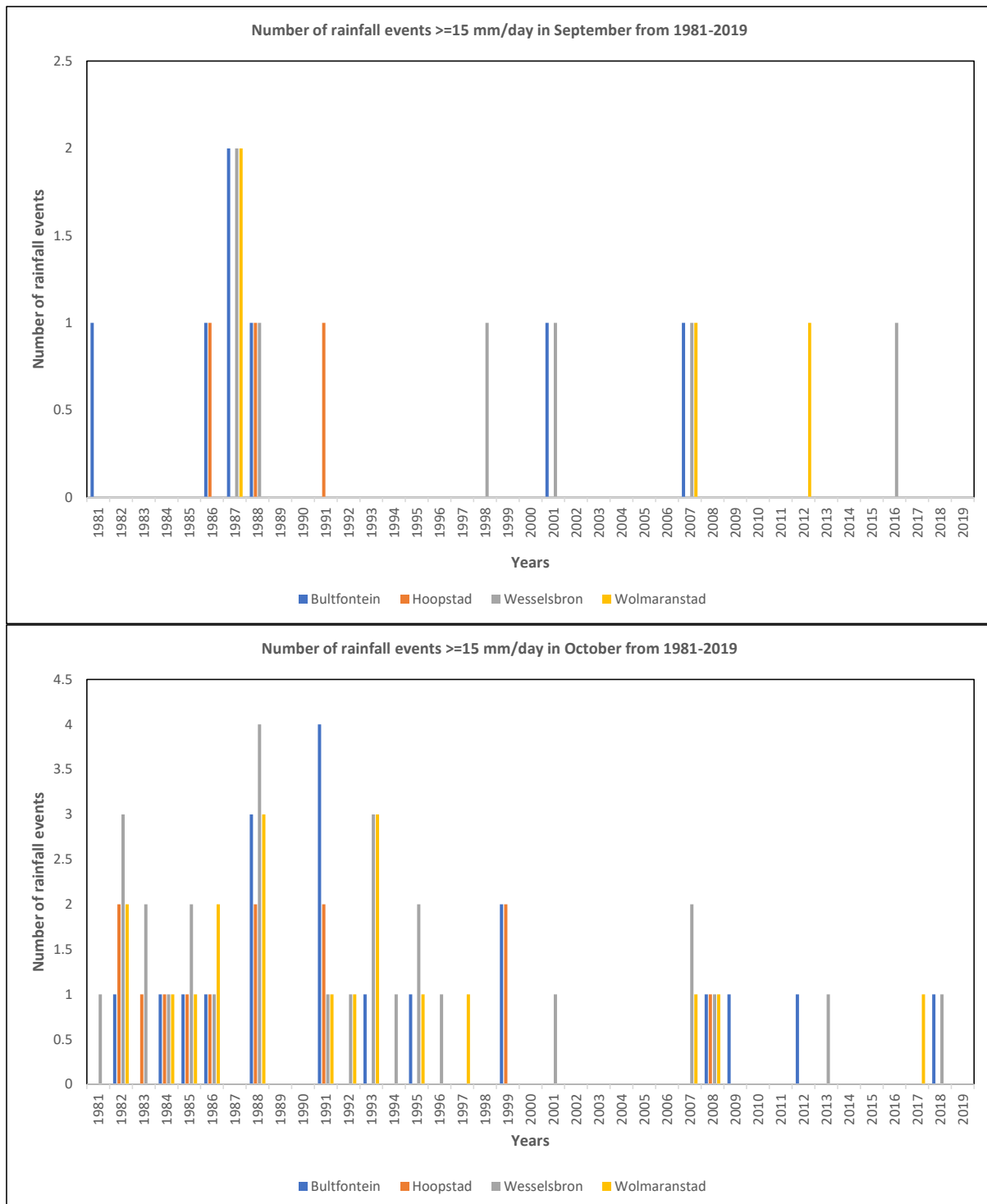


Figure 3.12: Number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations in September (top) and October (bottom), Free State (1981-2019).

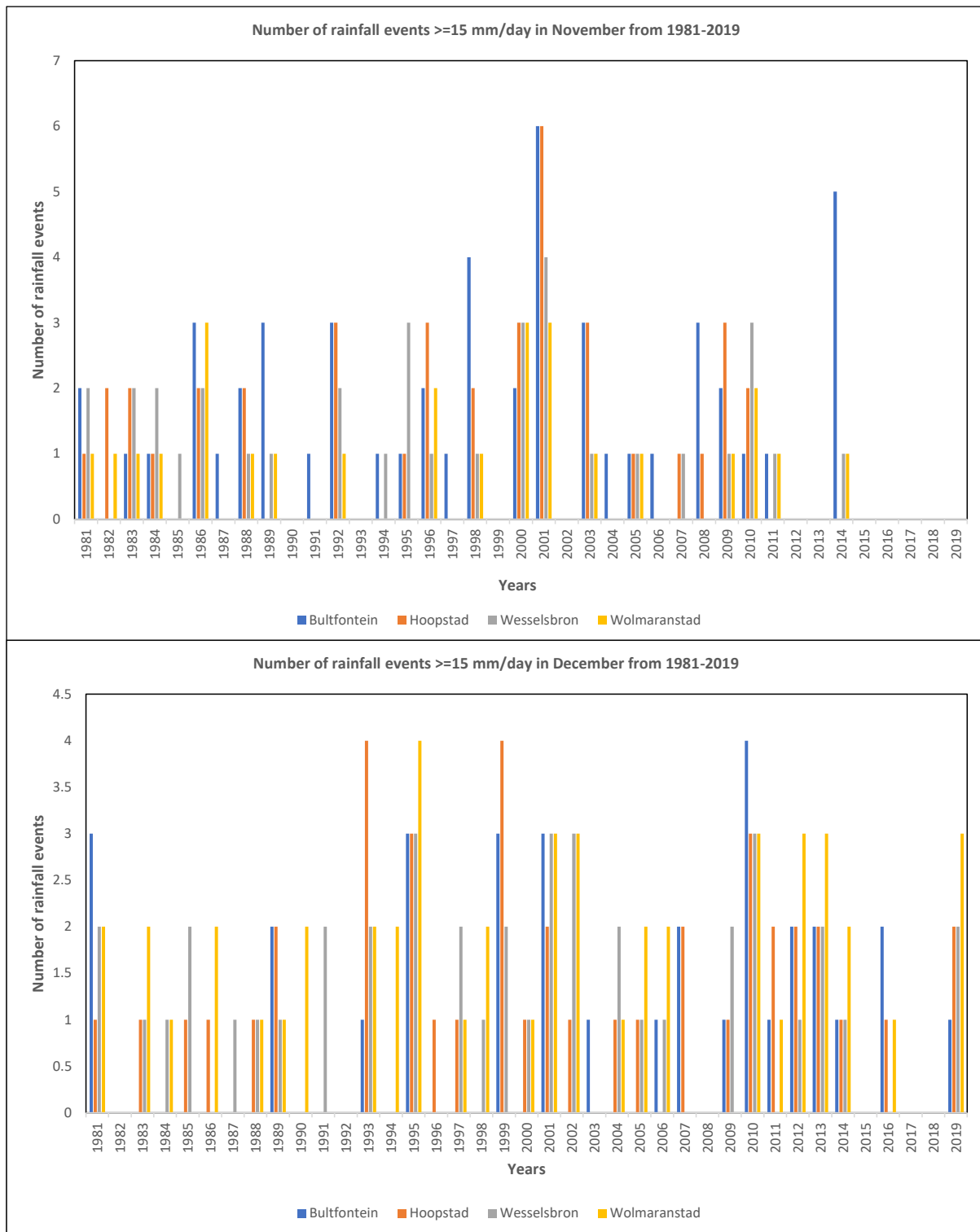


Figure 3.13: Number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations in November (top) and December (bottom), Free State (1981-2019).

Figure 3.14 and Table 3.5 further shows the total number of rainfall events that were greater or equal to 15 mm/ day. It is apparent that onset of rainfall is becoming late as high records of the rainfall event  $\geq 15$  mm/ day were recorded in November and December and the least were recorded in September. These results generally indicate that there is a meaningful shift on the onset of rainfall suitable for ploughing maize in Free State. According to the results the 15 mm of rainfall is mostly received mid-summer (November and December) (Figure 3.14). September of 1981-1990 received the highest number of events across the stations (12 events) compared to September of other decades. October of 1981-1990 received the highest number of events across the stations with the total of 28 events. November of 2001-2010 received the highest number of events across the stations (54 events) compared to other decades. December of 2001-2010 received the highest number of events across the stations (52 events) compared to other decades.

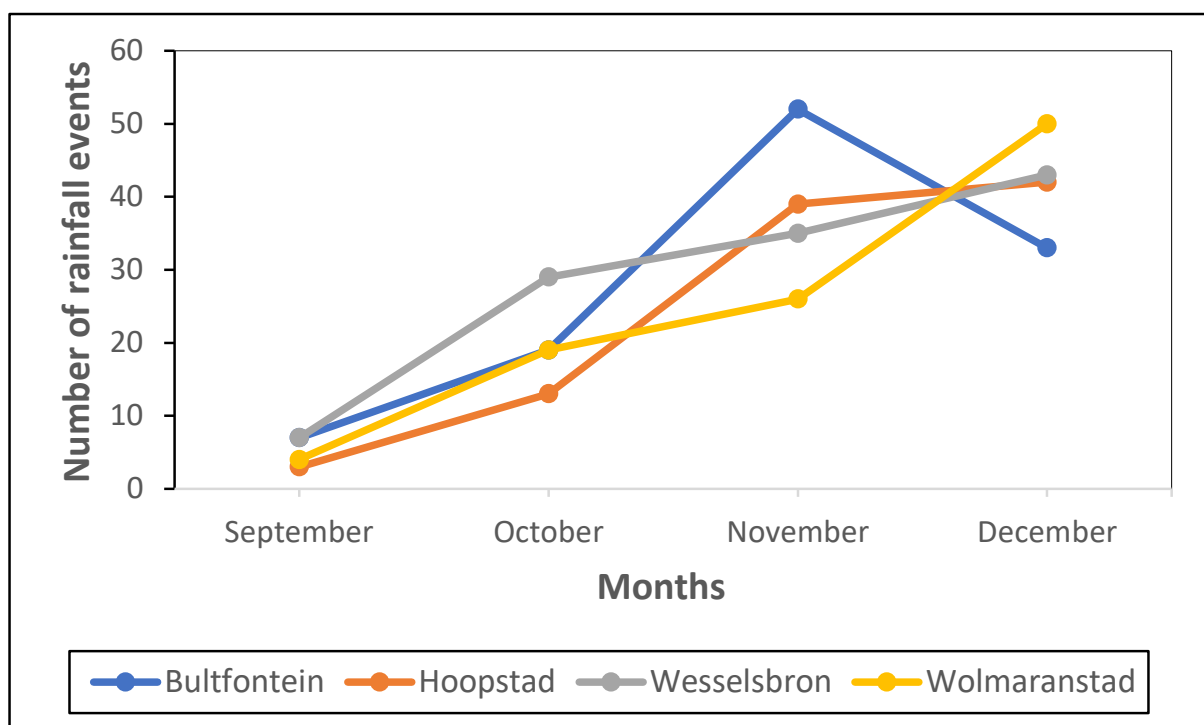


Figure 3.14: Number of rainfall events greater or equal to 15 mm/day from 1981-2019 in a series of four weather stations

Table 3.5: Total number of rainfall events greater or equal to 15 mm/ day in a series of four weather stations per decade from 1981-2019

|              | September |           |           |           | October   |           |           |           | November  |           |           |           | December  |           |           |           |         |
|--------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------|
| Stations     | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2019 | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2019 | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2019 | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2019 | Average |
| Bultfontein  | 5         | 0         | 2         | 0         | 7         | 8         | 2         | 2         | 13        | 15        | 18        | 6         | 5         | 7         | 12        | 9         | 7       |
| Hoopstad     | 2         | 1         | 0         | 0         | 8         | 4         | 1         | 0         | 10        | 12        | 17        | 0         | 7         | 14        | 11        | 10        | 6       |
| Wesselsbron  | 3         | 1         | 2         | 1         | 14        | 9         | 4         | 2         | 11        | 11        | 11        | 2         | 9         | 13        | 15        | 6         | 7       |
| Wolmaranstad | 2         | 0         | 1         | 1         | 9         | 7         | 2         | 1         | 9         | 7         | 8         | 2         | 11        | 12        | 14        | 13        | 6       |

### 3.7.4.2 Trend on the onset of rainfall from 1981-2019 in Bultfontein

Figure 3.15 shows the trend on the onset of rainfall from 1981-2019 in Bultfontein. The year with the earliest onset of rainfall was 1987 (DOY 249). The onset of rainfall shifted by approximately 105 days from 1981- 2019. There were five years that had a late onset of rainfall: 1990, 2002, 2015 and 2017; these years did not receive the 15 mm of rainfall from September until December. The onset of rainfall trend is significantly fluctuating (Appendix 3.24); some years receive early rainfall, and some receive late rainfall from this period (1981-2019). However, from the first decade (1981-1990) the onset of rainfall has shifted from occurring in DOY 252 in 1981 to DOY 311 in 1989 and became very late in 1990 as there was no 15 mm received from September-December. From 1991-2000 the onset of rainfall gradually shifted from being early 1991 (DOY 286) to late in the middle up until the end of the decade (1995 = 301, 1996 = 331, 1997 = 315, 1998 = 321, and 2000= 321). The third decade 2000-2010 started with early onset of rainfall and drastically shifted to late in 2002 and 2004 and remained late until the end of the decade. From 2011-2019 the rainfall was relatively late with 2015 and 2017 not receiving the onset at all between September and December period.

### 3.7.4.3 Trend on the onset of rainfall from 1981-2019 in Hoopstad

Figure 3.15 shows the trend on the onset of rainfall from 1981-2019 in Hoopstad. The year with the earliest onset of rainfall was 1988 (DOY 256) and 2019 had the latest onset of rainfall (DOY 363). The onset of rainfall shifted by approximately 44 days from 1981- 2019, this is a substantial period waiting for rainfall to occur before planting commences. This is evidence that rainfall is occurring late, and it is getting drier. The conditions of the onset of rainfall were

not met in:1987, 1990, 1994, 2006, 2015, 2017, 2018 (i.e., getting 15 mm/day between September and December); meaning these years were relatively dry. The onset of rainfall trend is fluctuating; however, it is observed that the rainfall is becoming late (Appendix 3.25). From 1981-1990 the onset of rainfall shifted from occurring in 319 DOY in 1981 to not meeting the conditions at all in 1990. Furthermore, from 1991- 2000 onset of rainfall shifted by 43 days: from occurring on DOY 267 in 1991 to occurring in DOY 310 in 2000. From 2001-2010 onset of rainfall occurred on DOY 311 both in 2001 and 2010 even though there were fluctuations during the 10-year period. The onset of rainfall shifted by 20 days from 2011-2019; 2011 occurred DOY 343 and 2019 occurred in DOY 363.

#### **3.7.4.4 Trend on the onset of rainfall from 1981-2019 in Wesselsbron**

Figure 3.15 indicates the trend on the onset of rainfall from 1981-2019 in Wesselsbron. The year with the earliest onset of rainfall was 1987 (DOY 249) and 1997 had the latest onset of rainfall (DOY 357). The onset of rainfall shifted by roughly 61 days from 1981- 2019, this is a large period waiting for rainfall to occur before planting commences. This is again evidence that rainfall is occurring late, and it is getting drier. The conditions of the onset of rainfall were not met in:1990, 2015 and 2017 (i.e., getting 15 mm/day between September and December); which means these years were relatively dry. The onset of rainfall trend is fluctuating; however, it is observed that the rainfall is becoming late (Appendix 3.26). From 1981-1990 the onset of rainfall shifted from occurring on DOY 281 in 1981 to not meeting the conditions at all in 1990. Furthermore, from 1991- 2000 onset of rainfall shifted by 19 days; from occurring on DOY 292 in 1991 to occurring on DOY 311 in 2000. From 2001-2010 onset of rainfall shifted by 49 days; from occurring on DOY 262 in 2001 to occurring on DOY 311 in 2010. The onset of rainfall shifted by 19 days from 2011-2019; 2011 occurred in DOY 323 and 2019 occurred in DOY 342.

#### **3.7.4.5 Trend on the onset of rainfall from 1981-2019 in Wolmaranstad**

Figure 3.15 illustrates the trend on the onset of rainfall from 1981-2019 in Wolmaranstad. The year with the earliest onset of rainfall was 1987 (DOY 249) and 2016 had the latest onset of rainfall (DOY 362). The onset of rainfall shifted by approximately 39 days from 1981- 2019,



this is a significant period waiting for rainfall to occur before planting commences. The conditions of the onset of rainfall were not met in: 1999, 2015 and 2018 (i.e., getting 15 mm/day between September and December); which means these years were relatively dry. The onset of rainfall trend is fluctuating; however, it is observed that the rainfall is becoming late (Figure 3.15 and Appendix 3.27). From 1981-1990 the onset of rainfall shifted from occurring on DOY 319 in 1981 to occurring on DOY 337 on 1990. Moreover, from 1991- 2000 onset of rainfall shifted by 18 days; from occurring on DOY 292 in 1991 to occurring on DOY 310 in 2000. From 2001-2010 onset of rainfall shifted by 13 days; from occurring on DOY 311 in 2001 to occurring on DOY 324 in 2010. The onset of rainfall shifted by 35 days from 2011-2019; 2011 occurred in DOY 323 and 2019 occurred in DOY 358.

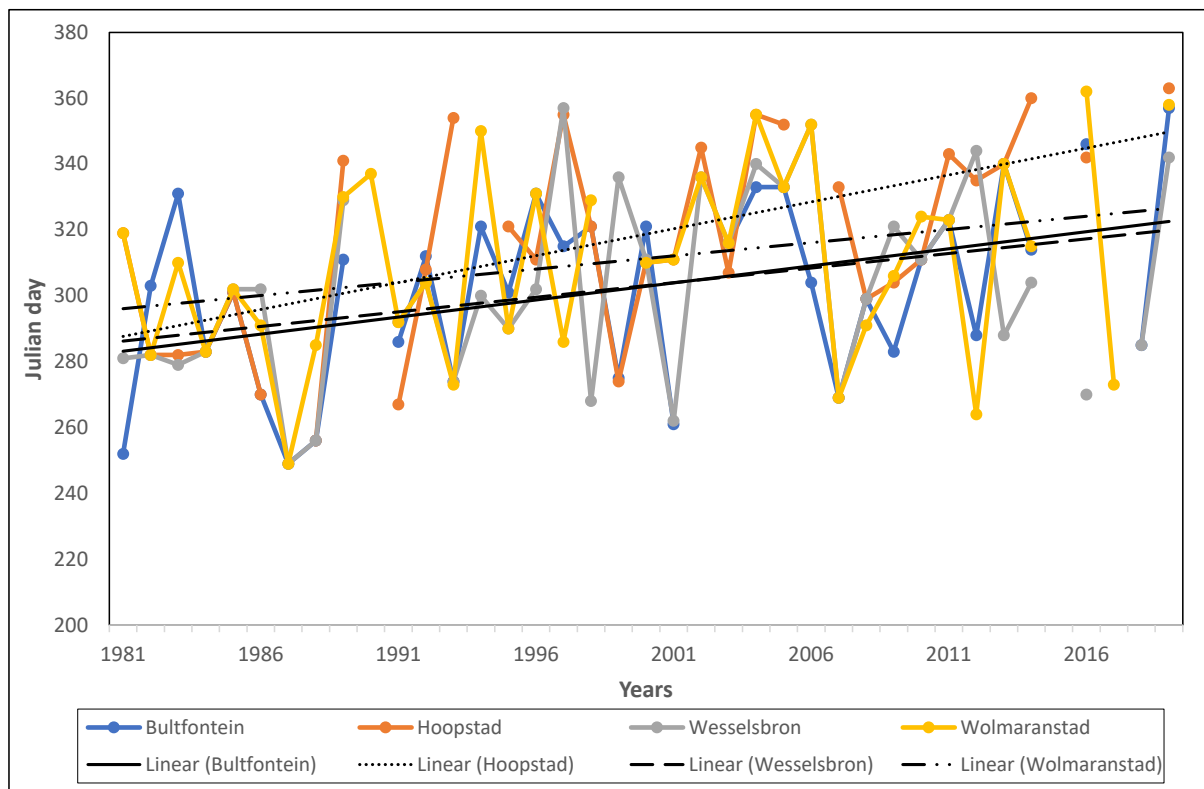


Figure 3.15: Trend on the onset of rainfall in in a series of four weather stations in Free State (1981-2019). Graph showing variation on the onset of rainfall in different years. Trendlines shows that the onset of rainfall is becoming late.

#### **3.7.4.6 Testing whether each decade is dependent on the other decade in Bultfontein**

Following a Chi-squared statistic distribution standard procedure by Toutenburg, (1992), Chi-squared statistic distribution was used to test whether each decade is dependent on the other decade. Two hypotheses were formulated for the four weather stations. Null hypothesis ( $H_0$ ) stated that the onset of rainfall of the current decade is independent on the previous decade. The alternative hypothesis ( $H_1$ ) stated that the onset of rainfall of the current decade is dependent on the previous decade. Using the 0.05 alpha and 9 degrees of freedom, the critical value was 16.9190 and the calculated chi-square was 19.613. According to Toutenburg, (1992) if the calculated chi-square is greater than the critical value, we reject null hypothesis. The calculated chi-square was greater than the critical value, therefore we reject the null hypothesis. It can thus be concluded that the onset of rainfall of the current decade is dependent on the previous decade.

#### **3.7.4.7 Testing whether each decade is dependent on the other decade in Hoopstad**

In Hoopstad using the 0.05 alpha and 9 degrees of freedom, the critical value was 16.9190 and the calculated chi-square was 27.70435. It is stated that if the calculated chi-square is greater than the critical value, we reject null hypothesis. The calculated chi-square was greater than the critical value, therefore we reject the null hypothesis. Therefore, we conclude that the onset of rainfall of the current decade is dependent on the previous decade.

#### **3.7.4.8 Testing whether each decade is dependent on the other decade in Wesselsbron**

Moreover, using the 0.05 alpha and 9 degrees of freedom, the critical value was 16.9190 and the calculated chi-square was 9.583 in Wesselsbron. If the calculated chi-square is greater than the critical value, we reject null hypothesis. The calculated chi-square was less than the critical value, therefore we do not reject the null hypothesis. Therefore, in conclusion the onset of rainfall of the current decade is independent on the previous decade.

#### **3.7.4.9 Testing whether each decade is dependent on the other decade in Wolmaranstad**

In Wolmaranstad using the 0.05 alpha and 9 degrees of freedom, the critical value was 16.9190 and the calculated chi-square was 12.884. If the calculated chi-square is greater than the critical value, we reject null hypothesis. The calculated chi-square was less than the critical value, therefore we do not reject the null hypothesis. Thus, conclusion states that the onset of rainfall of the current decade is independent on the previous decade.

In comparison of the four CHIRPS point data, it is evident that there is a seasonality shift in Free State rainfall; it is getting drier over the years. Rainfall is appearing to occur mid-late summer season and the frequency of events is decreasing. Since 1981-2019 onset of rainfall has shifted approximately by 100 days in the entire Free State, which contributes meaningfully on the change in planting dates. Furthermore, whether the onset of rainfall on a current decade is dependent on the previous decade was tested and findings indicated that in Bultfontein and Hoopstad the onset of rainfall on the current decade is dependent on the previous decade. However, Wesselsbron and Wolmaranstad showed that onset of rainfall in the current decade is independent on the previous decade. These findings may be influenced by topography and cloud cover of each area. Bultfontein is much closer to Hoopstad (~ 58 km) than other areas, Wesselsbron and Wolmaranstad are closer to each other (~92.8 km) which may justify why the results of these areas agrees to each other.

#### **3.7.5 Temperature variation**

Figure 3.16 represent daily average temperature in a series of weather stations in Free State. It is observed that the fluctuations in average daily temperatures are similar in all stations. Temperatures are found to be increasing by ~ 1- 2°C in the entire Free State. For instance, in Bultfontein the monthly average in January 2005 was 23°C and in January 2016 was 25°C. There is evidence from the graphs that some days are warmer than the others within the same month and some are cooler than the other. The 6<sup>th</sup> of January 2016 had the highest temperature among all the stations (~32 °C) and the temperatures are shown to have increased in 2016 compared to the previous years (Figure 3.16). Warm temperatures are observed in summer season towards the end of November until February the following year and low temperature

are observed at the beginning of winter season from May until July. From March and April when temperatures start decreasing that is when frost occurs. The temperatures then start to increase again during spring season. Temperature is one of the climate indicators for agricultural production (Zuma-Netshiukhwi, Stigter, & Walker, 2013). Farmers use temperature and other climate conditions when deciding on the planting time and crop type. Therefore, it is important to understand temperature patterns to have a successful crop production.

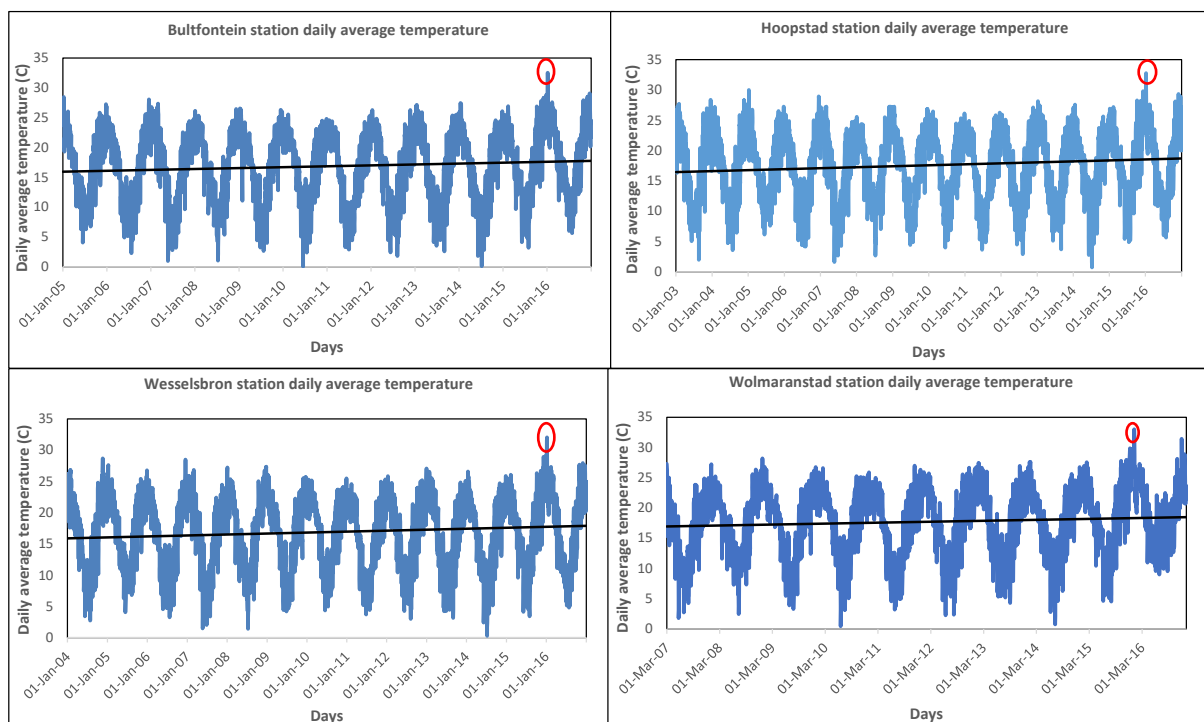


Figure 3.16: Daily average temperature from a series of weather stations in Free State, South Africa. Red circle shows the day that had the maximum temperature throughout the studied period. Data extracted from ARC database.

Figure 3.17 indicates average monthly temperature in Free State from a series of four weather stations. It is apparent that the average maximum temperature per month in Free State does not go above 26°C, while the minimum temperature drops to as low as 6°C in winter months. When temperatures drop to 0 degrees Celsius or lower frost occurs. Frost can negatively affect crops thus it is important to understand when it will occur to carefully plan for crop production. Prolonged cold temperatures can result in the shifting of crop production. To accommodate

frost crop development might end up being squeezed, so that when the frost strikes crops are already harvested. Temperature follows a similar pattern from all stations; where monthly average temperature peaks from September- March, then drops from April- August.

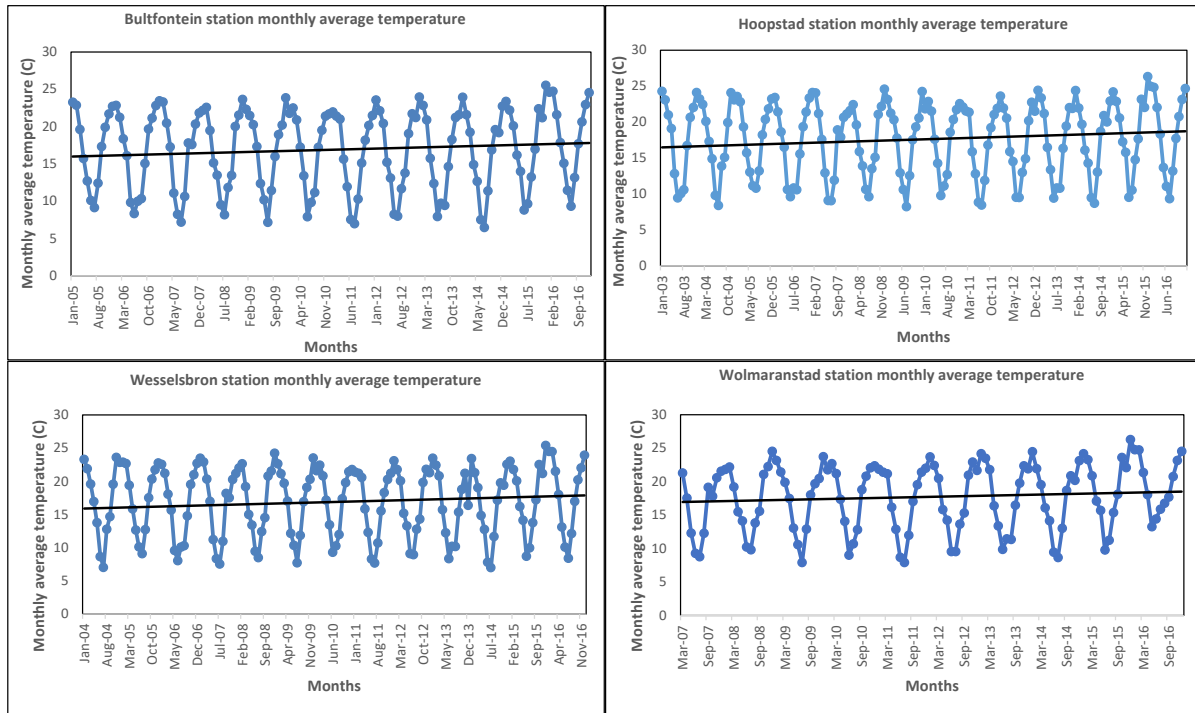


Figure 3.17: Monthly average temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database.

Figure 3.18 illustrates monthly maximum temperature in Free State from a series of four weather stations. Maximum temperatures are increasing in Free State over the years. All the years follow a similar seasonal trend whereby maximum temperature peaks in September (ranging from 30°C – 34°C) to March (ranging from 30°C – 36°C). Maximum temperatures then drop in April (ranging from 27°C – 31°C) to August (ranging from 25-31°C). The linear trendline provides clear indication that temperatures are increasing in Free State by approximately 1-2°C from one year to the next.

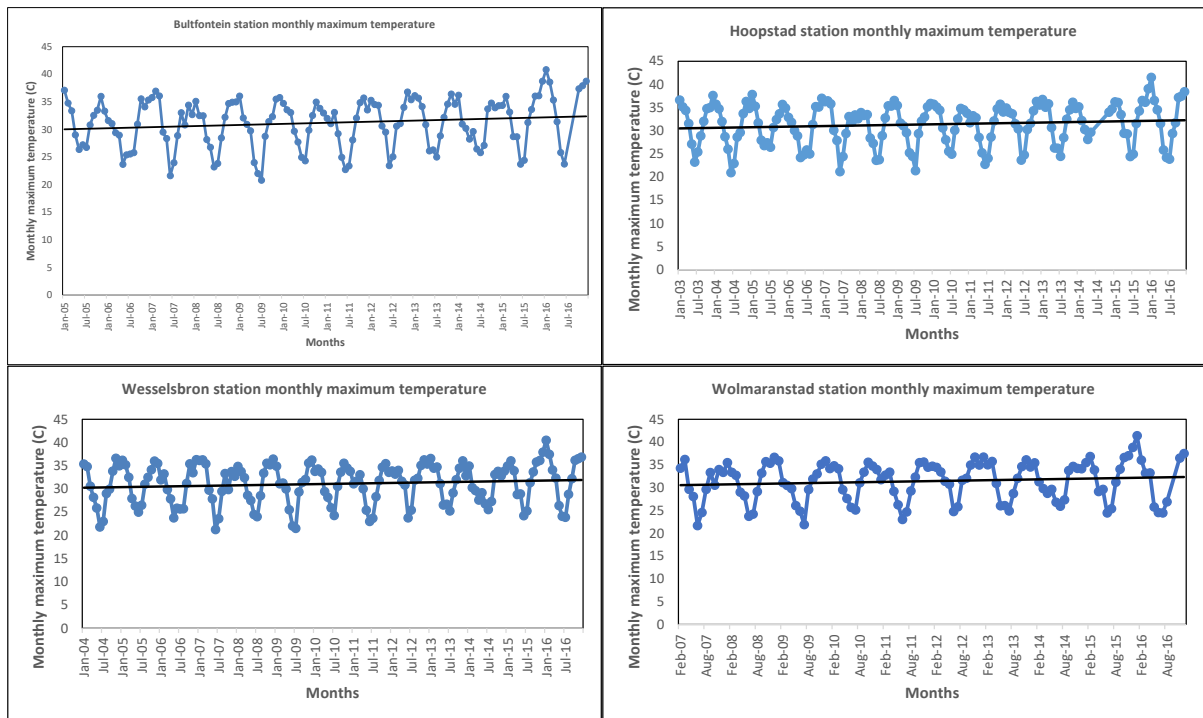


Figure 3.18: Monthly maximum temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database.

Figure 3.19 illustrates monthly minimum temperature in Free State from a series of four weather stations. Minimum temperatures are generally increasing in Free State over the years. All the years follow a similar seasonal trend whereby minus degrees temperatures are mostly experienced in winter months (April- August) and slightly warm temperatures are experienced in summer months (Sep- March). Minimum temperatures are observed to drop as low as -10 °C. Minimum temperature in Bultfontein station range between -9°C to 16°C, -6°C to 16°C in Hoopstad station, -10°C to 16°C in Wesselsbron station and -10°C to 20°C in Wolmaranstad station.

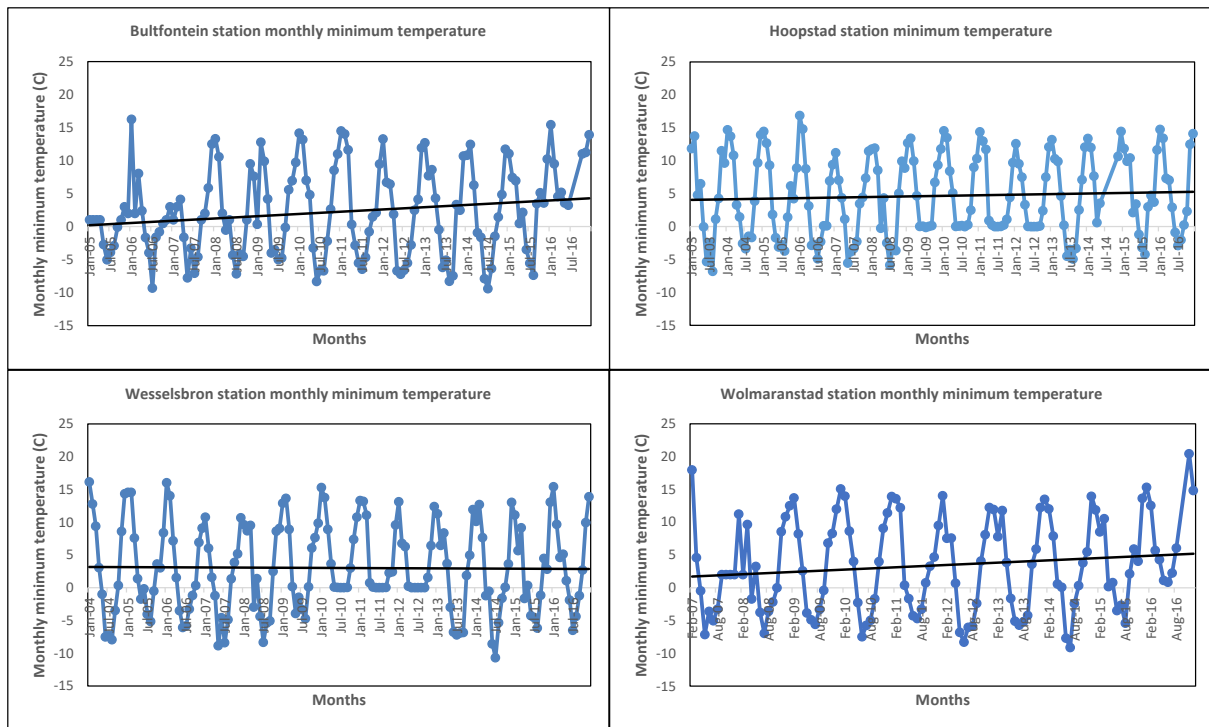


Figure 3.19: Monthly minimum temperature from a series of weather stations in Free State, South Africa. Data extracted from ARC database.

### 3.7.6 Frost variation

Figure 3.20 shows the total number of frost hours per month in a series of four weather stations. It is observed that frost occurs generally between April and September. However, frost varies in different years; some years had less frost hours (2009-2012), whereas others had several frost hours (2014). When frost hours are decreasing (2009-2012) it means the daily temperatures are increasing as observed in Figure 3.18. Less frost hours are noted around January and during this period the temperatures are mostly high because it is summer. Moreover, when frost hours are decreasing (2014) that means the daily temperatures are decreasing and it is usually around winter months (mostly June-July). It is notable from Figure 3.20 that frost mainly starts occurring in May in many years, which is an indication that the years are getting hotter thus frost period is decreasing. Data from the four weather stations does not start in the same year (i.e. Bultfontein starts in 2005, Hoopstad in 2003, Wesselsbron in 2004 and Wolmaranstad in 2007) because the weather stations were installed in different years. This makes the comparison challenging, however according to the presented data in Figure 3.20, 2014 was the coldest; number of frost hours were high across the four weather stations;

Bultfontein station had 191 hours in July 2014, Hoopstad had 120 hours, Wesselsbron 156 hours and Wolmaranstad station had 120 hours.

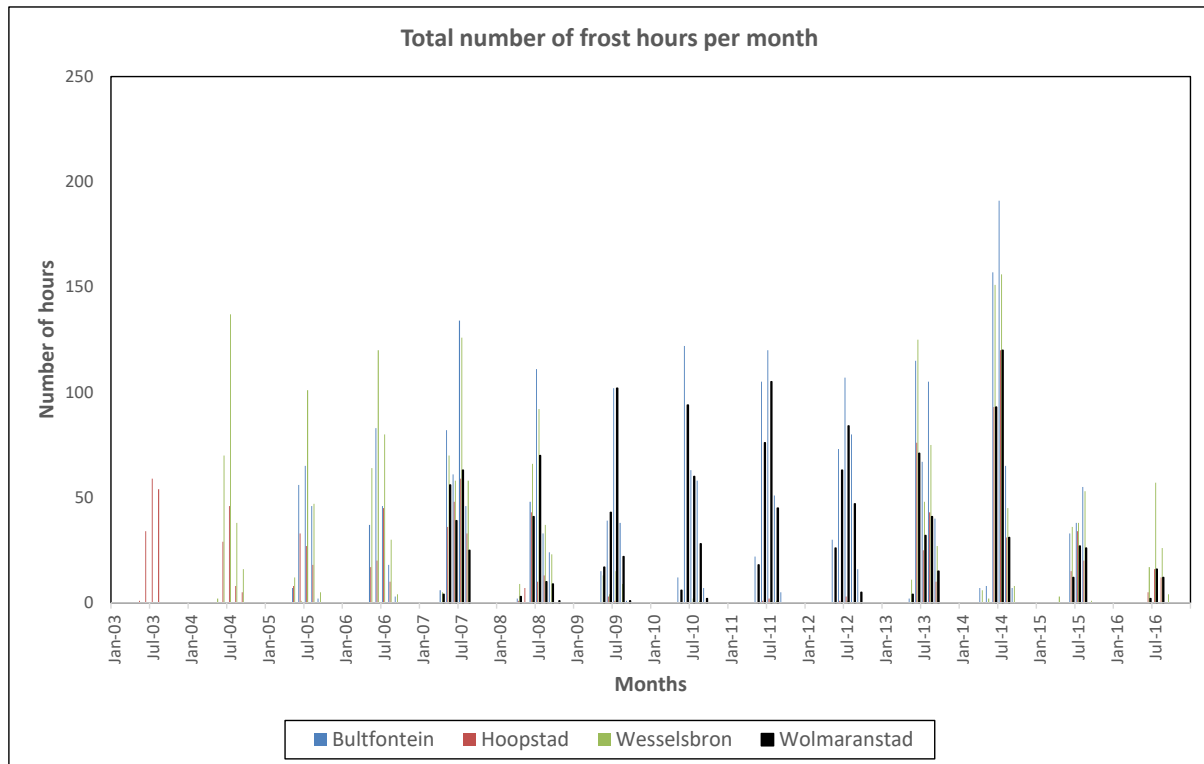


Figure 3.20: Total number of frost hours per month in a series of four ARC weather stations in Free State. Frost hours are observed from April- September. There are no frost hours observed from October- March. Data extracted in ARC database.

Figure 3.21 illustrates the overall frost hours per year in each station. There is a similar trend in all stations which first shows an increase in total number of frost hours between 2005 and 2008, the second cycle shows a decrease in total number of frost hours between 2009 and 2012, the frost hours further increase again from 2013-2015 and decrease in 2016. This means certain years were frostier and others were less frosty, but generally the years are getting hotter as frost hours are observed to decrease in 2016 from all stations.



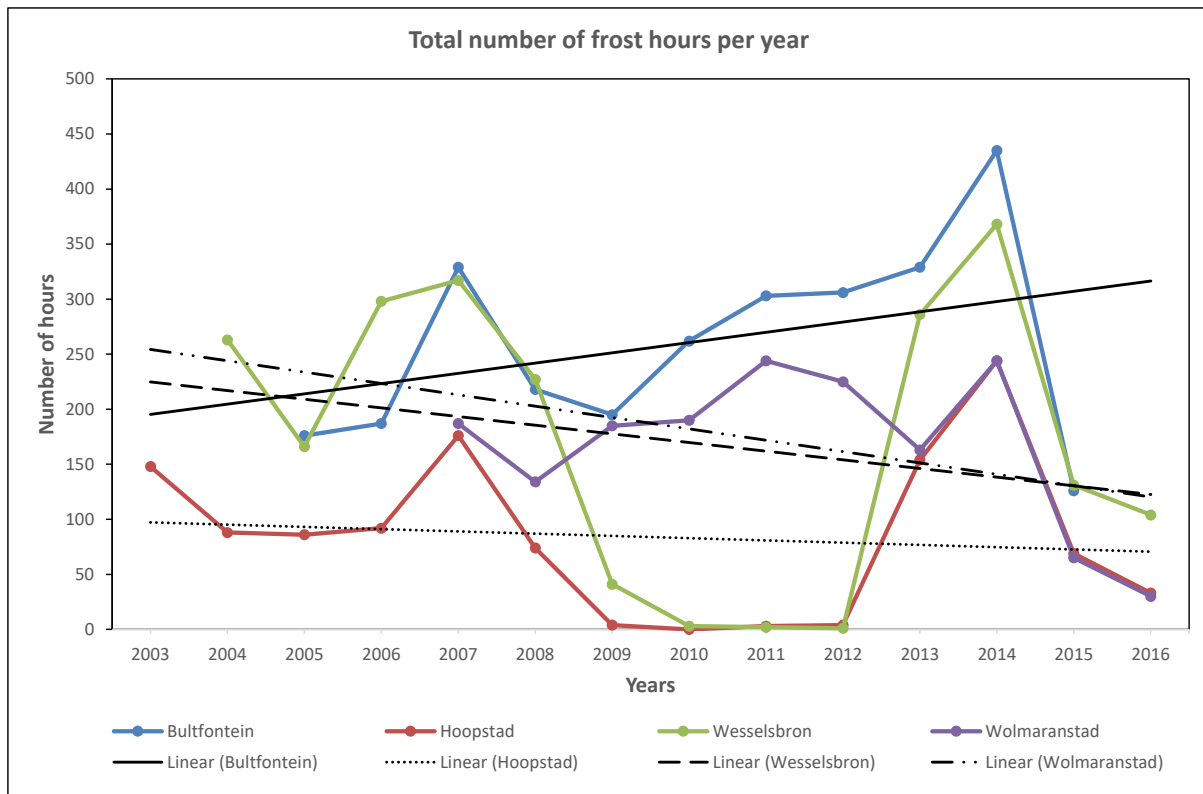


Figure 3.21: Total number of frost hours per year in a series of four weather stations in Free State. Graphs showing the variation on the number of frost hours over the years. Trendlines illustrate that number of frost hours are decreasing.

Figure 3.22 and 3.23 illustrates the total number of frost hours per year focusing on April and May months. These months are examined because maize crop has a potential of being damaged if frost occurs in these months. Therefore, Figure 3.22 and 3.23 indicates which years had high risk of crops being damaged by frost. According to results presented in Figure 3.22 only four years had frost in April (2007, 2008, 2014 and 2015) and the highest number of frost hours was 9. Several years experienced frost in May (Figure 3.23) and the highest number of frost hours was observed in 2007 from all the stations.

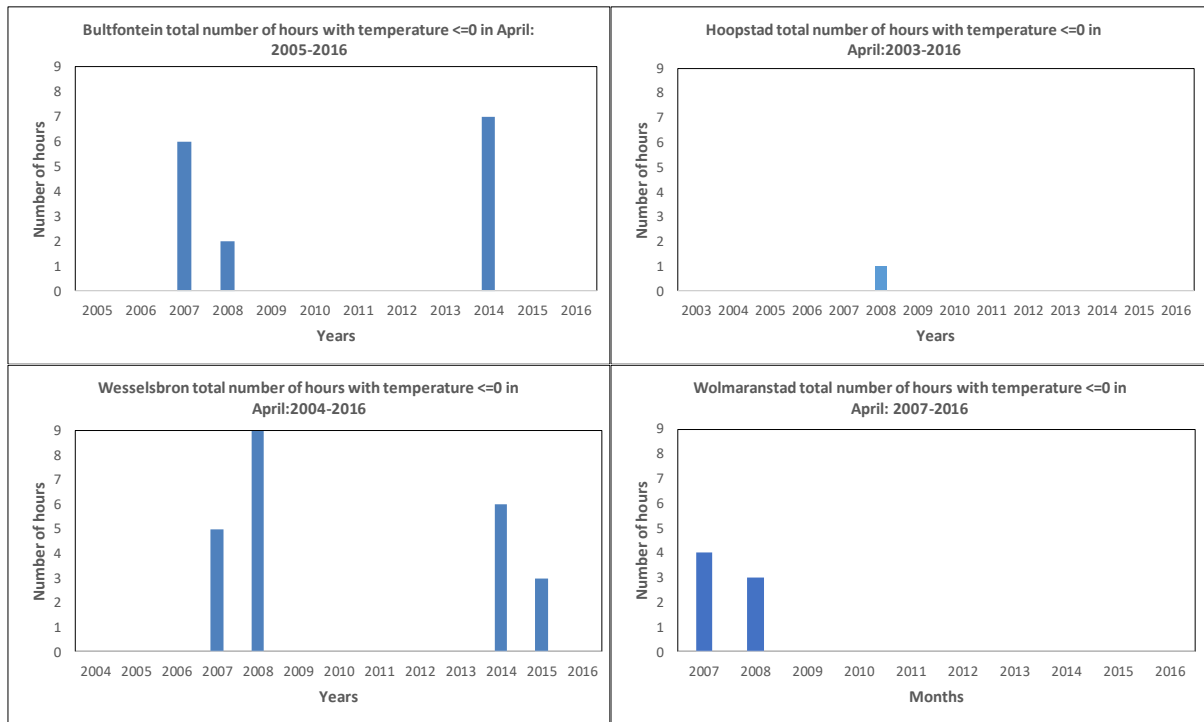


Figure 3.22: Total number of frost hours per year in April Bultfontein (top left), Hoopstad (top rights), Wesselsbron (bottom left) and Wolmaranstad (bottom right). In Bultfontein only 3 years had frost in April, 1 in Hoopstad, 4 in Wesselsbron and 2 in Wolmaranstad.

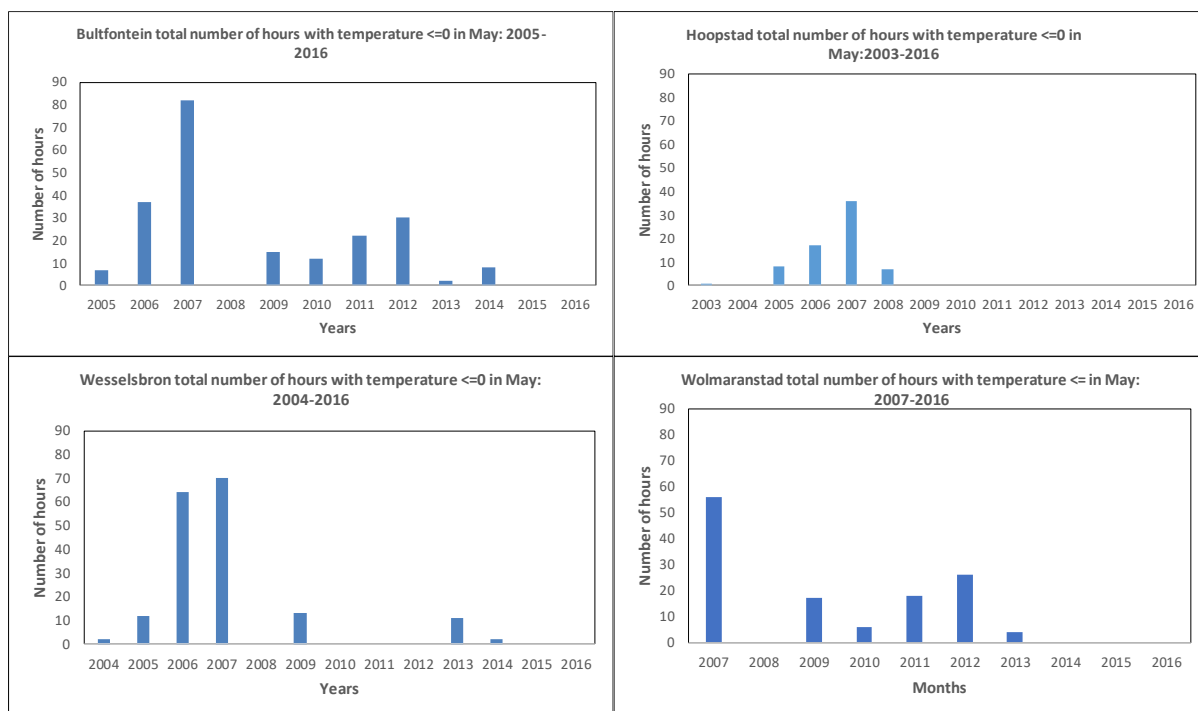


Figure 3.23: Total number of frost hours per year in May Bultfontein (top left), Hoopstad (top rights), Wesselsbron (bottom left) and Wolmaranstad (bottom right). In Bultfontein 9 years had frost in May, 4 in Hoopstad, 7 in Wesselsbron and 6 in Wolmaranstad.

The onset of frost is illustrated in Figure 3.24. It is evident from the results that there is a shift on the onset of frost in Free State. The onset of frost is shifting to May and resulting to frost period decreased over the years. From Bultfontein station the initial onset of frost in 2005 was in DOY 144 and later in 2016 there was no frost at all. In Hoopstad station the initial onset in 2003 was in DOY 148 and 14 years later frost started on DOY 180. In Wesselsbron station the initial onset was in DOY 128 and started in DOY 172 in 2016. Wolmaranstad station indicates that the initial onset was in day 118 in 2007 and later in 2016 it started in DOY 178. Generally, frost is observed to be shifting and becoming late over the years. The onset of frost has shifted by approximately 11 days in Bultfontein, 32 days in Hoopstad, 44 days in Wesselsbron and 60 days in Wolmaranstad in the studied period respectively. This is an advantage for summer crops because the crops are less likely to be damaged by frost, as by the time frost starts the crops would be already at the maturity stage. However, even though frost period is decreasing that means temperatures are increasing which in turn is also a potential threat to crops.

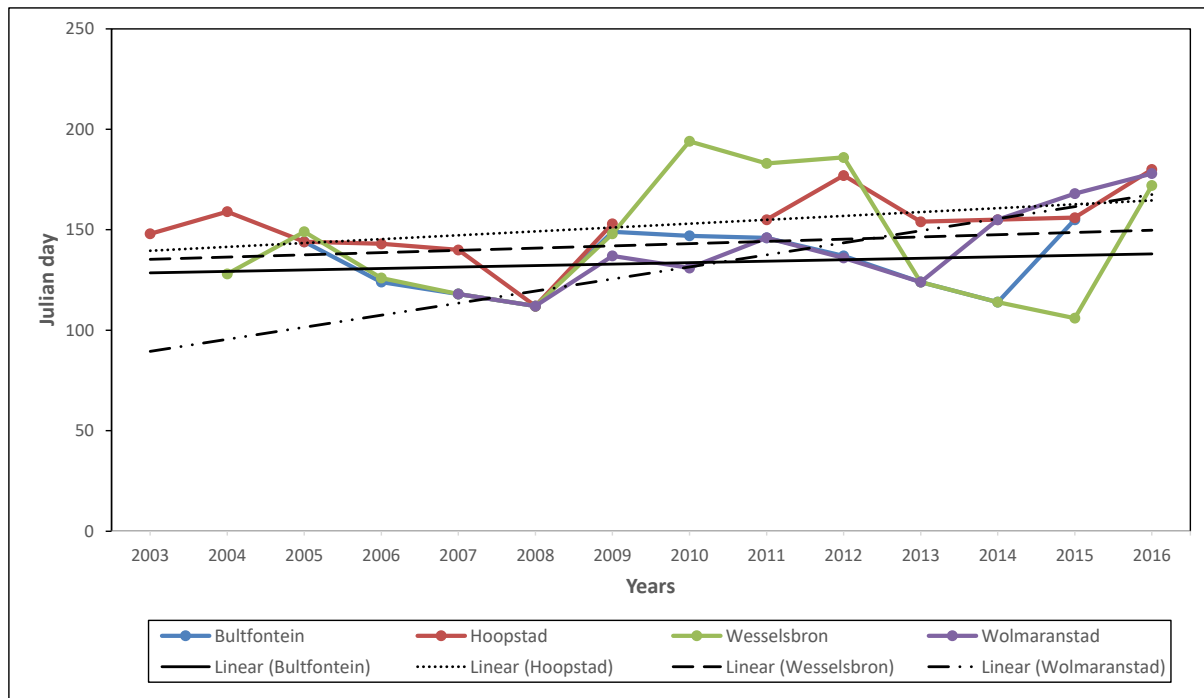


Figure 3.24: Onset of frost in a series of four weather station in Free State. Data starts from 2005 in Bultfontein, 2003 in Hoopstad, 2004 in Wesselsbron and 2007 in Wolmaranstad. Graphs showing the onset of frost is becoming late.

### 3.7.7 Wind speed data

#### 3.7.7.1 Daily average wind speed variation

Daily average wind speed from ERA5 data and ARC weather station in Bultfontein, Free State is presented in Figure 3.25. It is apparent that maximum daily wind speed averages do not exceed 8 m/s (Appendix 3.31). However, 8 m/s is high enough to make particles move thus causing dust storms. Both ERA5 and ARC data follow a similar trend, even though ARC data has lots of gaps which makes it less reliable.

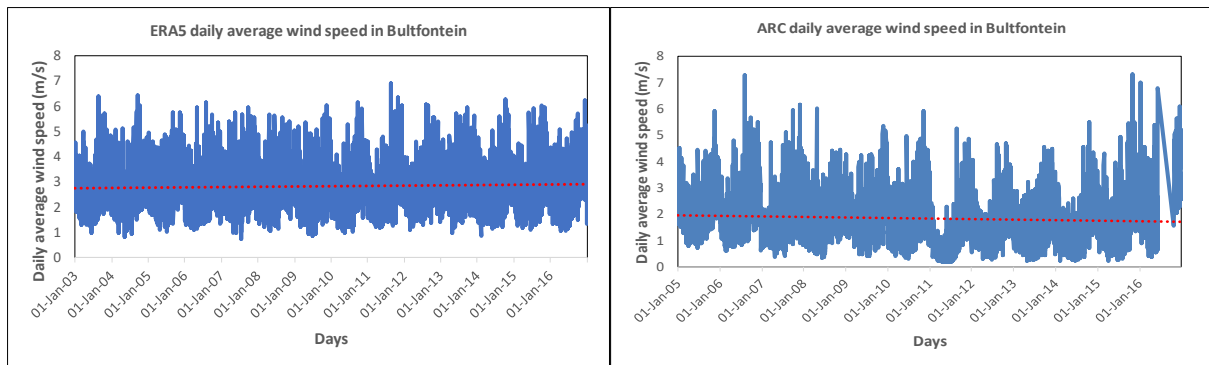


Figure 3.25: Daily average wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa

### 3.7.7.2 Monthly average wind speed variation

Figure 3.26 and Appendix 3.32 indicates monthly average wind speed from ERA5 and ARC weather station in Bultfontein, Free State. Monthly average wind speed ranges from 2.03 m/s – 3.80 m/s across the Free State Province. Both data sources have a similar trend.

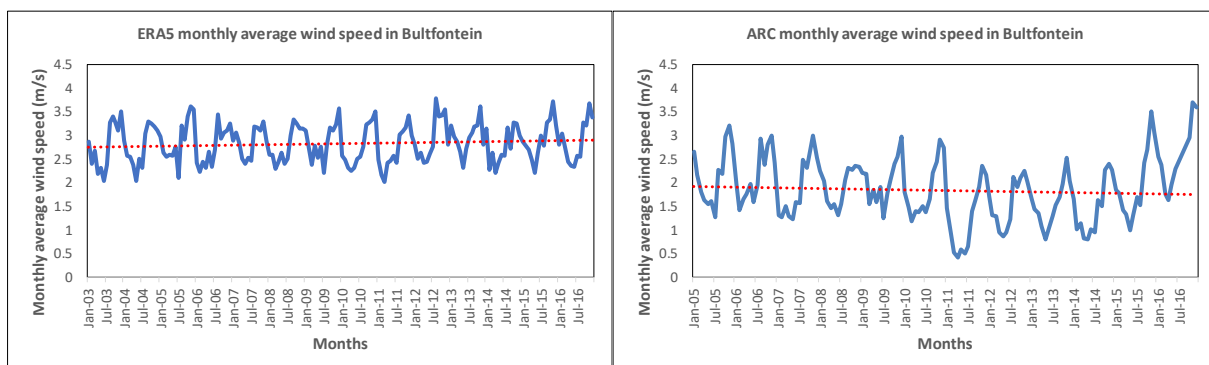


Figure 3.26: Monthly average wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa

### 3.7.7.3 Daily maximum wind speed variation

Figure 3.27 indicates daily maximum wind speed from ERA5 and ARC weather station in Bultfontein, Free State. According to (Fig 3.27 and Appendix 3.29) both datasets showed that there is no constant trend; in some years wind increases and some decreases. ARC maximum wind speed ranged between 10-15 m/s and ERA5 maximum wind speed was 10 m/s. High wind is observed from August to November and low wind is observed from February to July. There is a similar trend in all stations (Appendix 3.29), which shows that wind speed is general the same in the entire Free State with average maximum wind speed slightly above 4 m/s. The trend is similar from both data sources; however, ARC data is in a point data format and has many gaps which makes the data less reliable. High wind is observed in months (August and September) where the land is normally fallow (crops harvested and early stages of plantation), which makes the land prone to dust.

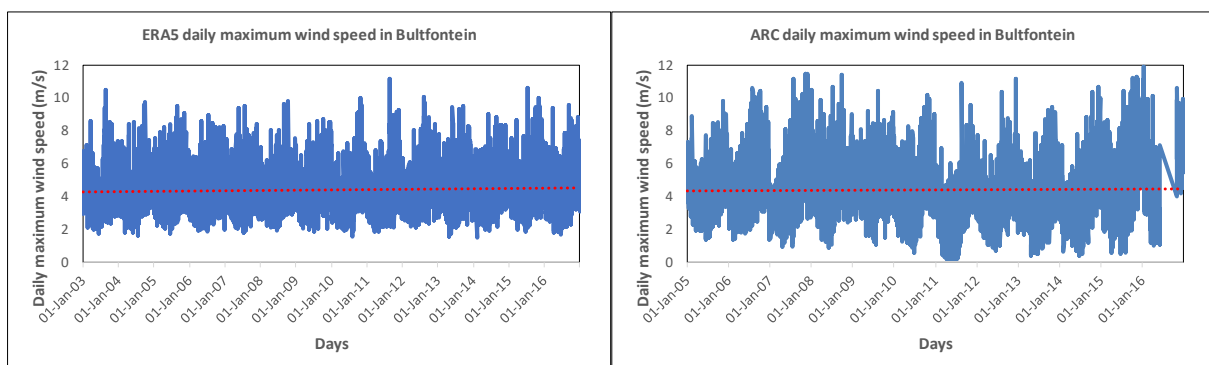


Figure 3.27: Daily maximum wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa

### 3.7.7.4 Monthly maximum wind speed variation

Monthly maximum wind speed from ERA5 data and ARC weather station in Bultfontein, Free State is presented in Figure 3.28 and Appendix 3.30. It is apparent that monthly maximum wind speed ranges from 4.81 m/s- 11.17 m/s in ERA5 and from 4.35 m/s – 11.9 in ARC data. Low wind speed is observed from February to July and high wind speed is observed from August to November. Surface roughness plays a substantial role in wind; when surface roughness is

reduced wind tends to increase and when surface roughness is increased wind tend to decrease. Therefore, in Free State the time of low winds corresponds with the period whereby land is usually covered with crops and the period of high winds corresponds with fallow lands, which makes the land susceptible to dust storms. Monthly average wind speed is generally between 7 and 8 m/s.

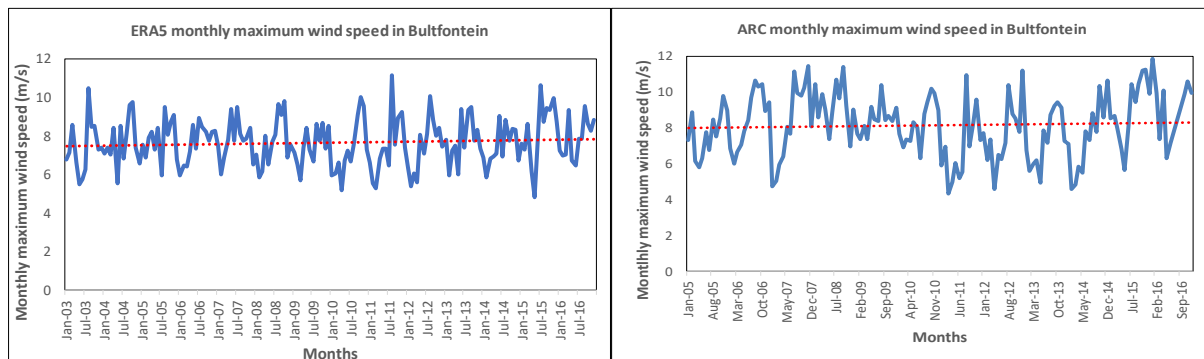


Figure 3.28: Monthly maximum wind speed from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa

### 3.7.7.5 Total monthly wind run variation

There are fluctuations in the monthly wind run (Fig 3.29 and Appendix 3.33). Wind run is observed to increase between August – December and to decrease between February-July. From ERA5 data in Appendix 3.33 Bultfontein weather station highest wind run was observed in August 2012 (10174 km). In Hoopstad weather station highest wind run was observed in August 2012 (10659 km). In Wesselsbron weather station highest wind run was observed in December 2005 (9799 km) and August 2012 (9659 km). In Wolmaranstad weather station highest wind run was observed in August 2012 (10491 km). It is apparent that 2012 was the windiest year. A similar trend is observed in ERA5 data and ARC data, however wind run values are slightly low in ARC data.

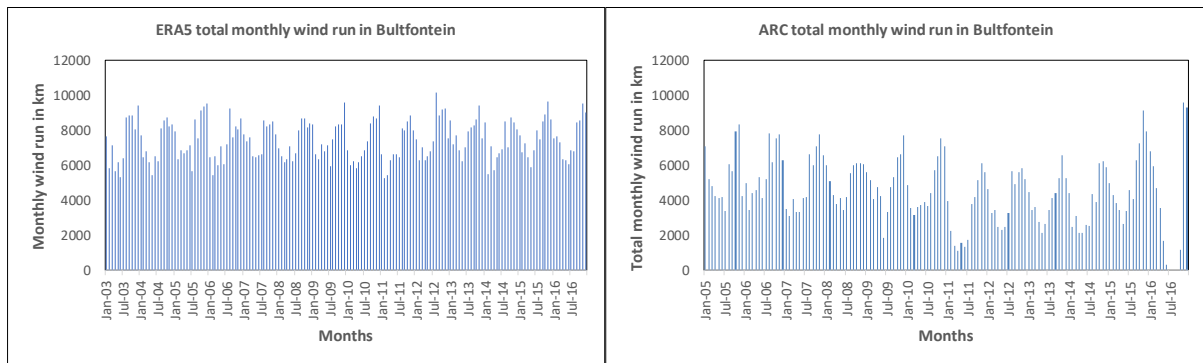


Figure 3.29: Total monthly wind run from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa

### 3.7.7.6 Total number of hours with wind greater than 6 m/s per month

The study was interested in wind greater than or equal to 6 m/s because at these speed particles starts moving. The number of hours with wind greater than 6 m/s are increasing over the years, which shows that it is becoming windier over the years. There is an interesting trend for the number of hours with wind speed greater than 6 m/s within a year and over the years. Most hours with wind speed greater than 6 m/s are observed from August-November (Fig 3.30 and Appendix 3.34) and fewer number of hours are observed between Feb and July. According to ERA5 data August 2012 had the highest number of hours (92 hours/month) than all the other years. According to ARC data November 2015 had the highest number of hours (131 hours/month) than all the other years.

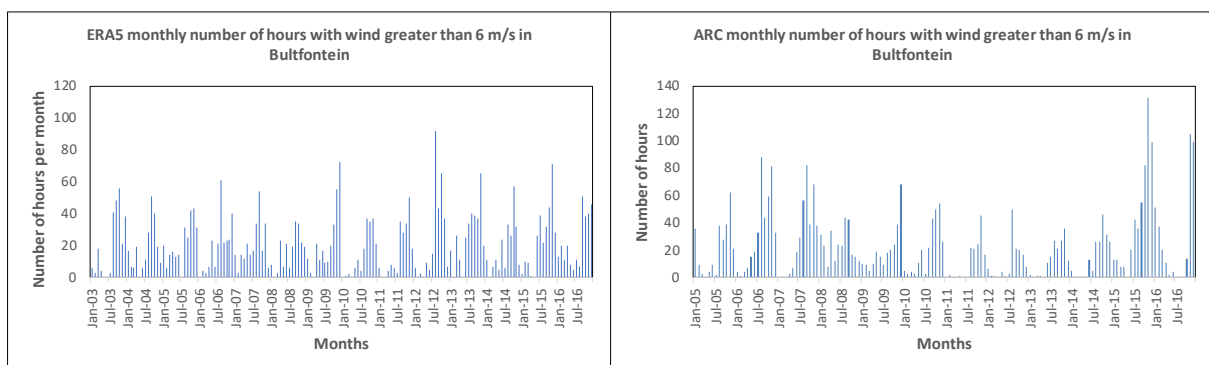


Figure 3.30: Monthly number of hours with wind greater than 6 m/s from ERA5 (left) and ARC (right) in Bultfontein station in Free State, South Africa



### 3.7.8 Evapotranspiration (ET<sub>0</sub>) data

Reference evapotranspiration was analysed with the purpose of comparing it with wind speed. Figure 3.31 represent (a) daily, (b) monthly and (c) annual reference evapotranspiration in Bultfontein station. Both wind speed and reference evapotranspiration have a similar trend; they are increasing over the years. An interesting trend is observed whereby during crop season (Feb-Apr) wind speed decreases and evapotranspiration also decreases. Moreover, during dry season (Aug- Oct) wind speed increases and evapotranspiration increases. It is known that surface roughness contributes significantly both in wind speed and rate of evapotranspiration, thus during dry season when land is bare wind speed is observed to increase. When surface roughness increases, low wind is expected and moderate to high evapotranspiration is expected if other factors that contributes to ET are present. Wind speed is one of the meteorological factors that determines evapotranspiration (Anderson & French, 2019), however when vegetation cover is sparse evapotranspiration becomes low.



Figure 3.31: Total evapotranspiration (ET<sub>0</sub>) in Bultfontein station daily (top left), monthly (top right) and annually (bottom left)

### 3.7.8.1 Relationship between wind speed and evapotranspiration (ET<sub>0</sub>)

ERA5 wind speed and ARC wind speed was compared with ARC evapotranspiration (Fig. 3.32). The results indicated that there is a poor relationship between ERA5 wind speed and ARC ET<sub>0</sub> ( $R^2 = 0.37$ ). There is also a poor relationship between ARC wind speed and ARC ET<sub>0</sub> ( $R^2 = 0.32$ ). The relationship is however positive meaning when wind speed increases evapotranspiration also increases. A moderate to strong positive relationship between wind speed and ET<sub>0</sub> is expected because wind speed is one of the weather factors that influences evapotranspiration (Anderson & French, 2019).

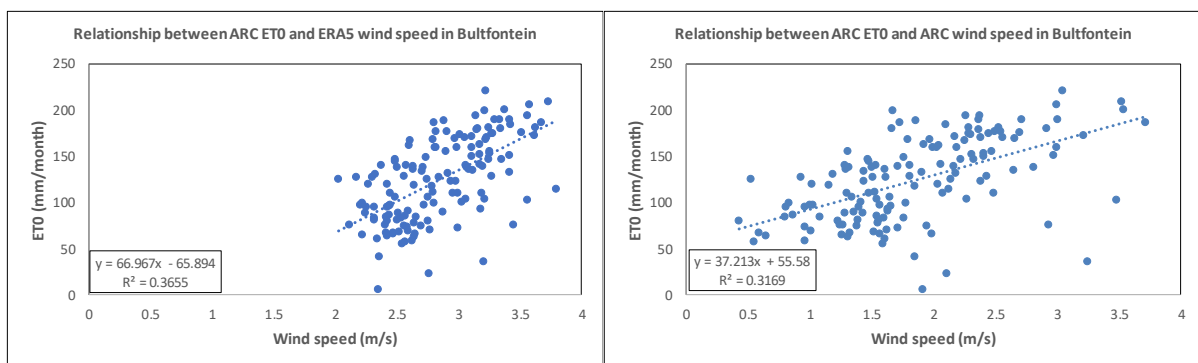


Figure 3.32: Relationship between monthly ARC ET<sub>0</sub> and monthly ERA5 wind speed (left) and relationship between monthly ARC ET<sub>0</sub> and monthly ARC wind speed (right) in Bultfontein. ET is increasing with increasing wind speed.

Wind speed and evapotranspiration were further analysed in crop (Feb-Apr) and dry seasons (Aug-Oct). From Figure 3.33 (left) wind speed follow a certain pattern whereby at the beginning of crop season (Feb-Apr) the wind speed is high and gradually decreases in the middle of the season and increase again at the end of the season. Additionally, at the beginning of dry season (Aug-Oct) wind speed is observed to be low and then gradually increases towards the end of dry season. There is a meaningful wind speed fluctuation in both seasons. For instance, some years the crop season begins with low winds and gradually increase, whereas other years the crop season begins with high winds and gradually decrease. The dry season also begins with low winds in some years and others begin with high winds. Evapotranspiration (Figure 3.33 right) also shows a certain trend; at the beginning of crop season (Feb-Apr) ET

rates are high and then gradually decreases towards the end of the season. Moreover, at the beginning of dry season (Aug-Oct) ET rates are low and gradually increases towards the end of the season. In comparison, during crop season when wind speed is low (average monthly wind speed 2.53 m/s) evapotranspiration is low (average total monthly ET 119.49 mm/month) and during dry season when wind speed increases (average wind speed 3.17 m/s) evapotranspiration also increases (average total monthly ET 135.10 mm/month).

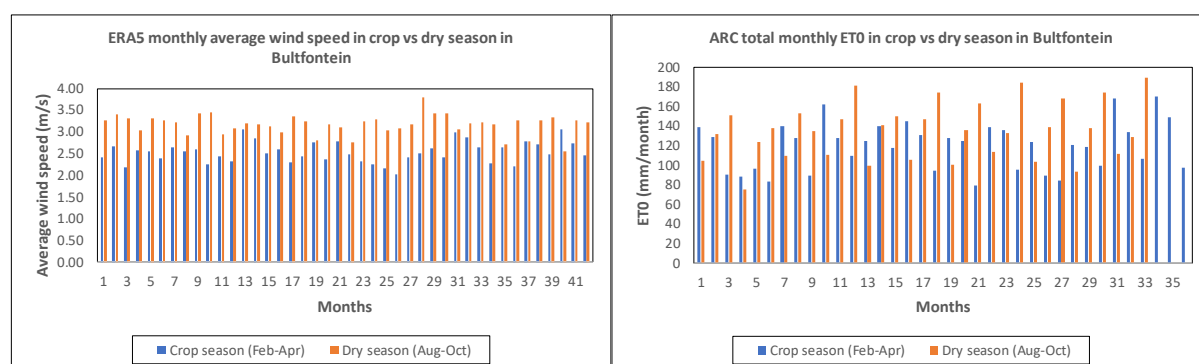


Figure 3.33: ERA5 monthly average wind speed (left) and ARC total monthly ET<sub>0</sub> (right) in crop and dry season in Bultfontein.

Relationship between wind speed and evapotranspiration in crop and dry seasons was further assessed. Figure 3.34 illustrates that there is a poor but positive relationship between wind speed and evapotranspiration in both seasons. The relationship between ARC wind speed and ARC ET<sub>0</sub> is poor ( $R^2 = 0.20$ ) but better than ERA5 wind speed and ARC ET<sub>0</sub> ( $R^2 = 0.14$ ) in crop season. Furthermore, there is no difference in the relationship between ARC wind speed and ARC ET<sub>0</sub> ( $R^2 = 0.07$ ), and ERA5 wind speed and ARC ET<sub>0</sub> ( $R^2 = 0.07$ ) in dry season. When wind speed increases evapotranspiration also increases at a very low rate and when wind speed decreases evapotranspiration decreases. Wind speed is one of the four weather factors that drives evapotranspiration; however, it is not the only factor that affects ET; high rates of evapotranspiration are also expected when the surface is well covered with vegetation thus during a dry season when the land is bare evapotranspiration slightly decreases and vice versa.

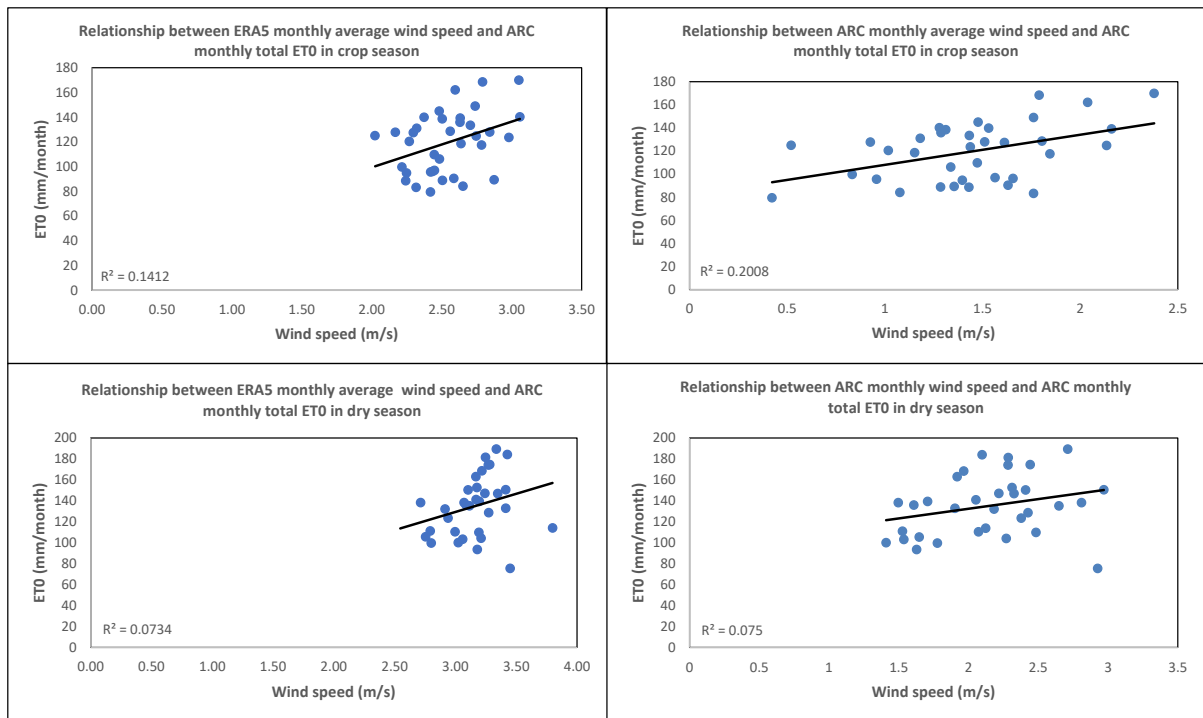


Figure 3.34: Relationship between ERA5 wind speed and ARC ET0 in a crop season (top left), relationship between ARC wind speed and ARC ET0 in crop season (top right), relationship between ERA5 wind speed and ARC ET0 in a dry season (bottom left), relationship between ARC wind speed and ARC ET0 in a dry season (bottom right) in Bultfontein.

Relationship between ERA5 and ARC monthly average wind speed was examined (Fig. 3.35). Even though these are two completely different datasets, there is a moderate relationship between them ( $R^2 = 0.57$ ). This means when ERA5 wind speed increases ARC wind speed also increases, and when one decreases the other one also decreases. This means both these methods produce almost the same estimates; even though ARC data is in a point format and had many gaps which might have affected the relationship between these datasets.

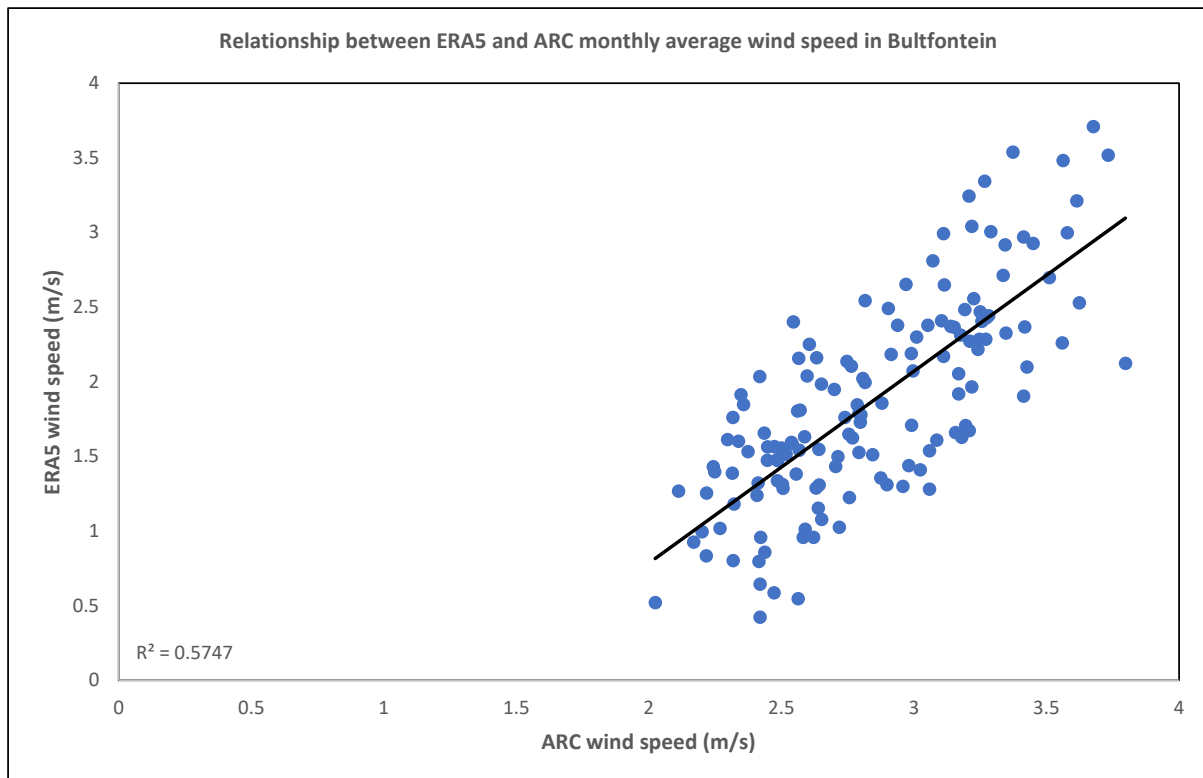


Figure 3.35: Relationship between ERA5 and ARC monthly wind speed in Bultfontein. There is a positive linear relationship between ERA5 and ARC monthly average wind speed.

### 3.8 Discussion

#### 3.8.1 Determining climate constraints to crop production

Weather station rainfall, CHIRPS and SPEI data were used to examine the climatic constraints on agricultural activities in Free State. Free State rainfall was studied and analysed with the purpose of determining the seasonality and timing of rain. Rainfall is slightly decreasing in Free State, South Africa. According to the rainfall data analysed, the onset and amount of rainfall are changing over the years (Figure 3.6); with summer rain occurring late in the season (onset in mid-November) and in small quantity that is not adequate to grow crops. Our analysis is in agreement with Davis et al., (2016) who found that most recent studies in South Africa have observed decreases in rainfall and the number of rainfall days over parts of the country. Shifting of rainfall poses challenges to farmers: (i) shifting of planting dates and or (ii) leaving the land fallow for that specific year. When farmers decide to shift the planting dates

to accommodate the late rainfalls, high risk of crop failure is expected due to frost and other weather uncertainties. On the other hand, if farmers decide to leave the land bare as the result of delayed onset of rain and inadequate soil moisture, fallow land becomes the major source of dust which is the main problem in Free State agricultural lands.

It is notable that rainfall, and agricultural drought plays a substantial role in crop production. Below average rainfall and above average hot temperatures; which leads to agricultural drought if continued for 3-6 months Rouault & Richard, (2003), leaves farmers with no choice but to shift the crop planting dates to avoid crop failure (Masupha & Moeletsi, 2017). Shifting the crop planting dates is relatively not an expensive strategy to cope with drought for rain-fed maize as argued by (Masupha & Moeletsi, 2017). However, that might result in negative consequences such as decrease in harvested grain yields, poor quality of crops, which in turn can affect the economy and in worse cases the farmers might have to leave the land fallow in that particular year.

Rainfall and temperature are the most critical environmental factors Zuma-Netshiukhwi et al., (2013), which helps farmers to make decisions regarding type of crops and planting time. Farmers mostly incorporate rainfall and temperature to decide about planting. These two factors when combined can determine the potential of having exceptional circumstances in a specific year. When rainfall is below average and temperature rising at a rapid rate, exceptional circumstances are subjected to occur. Based on the results of this study drought is a frequent event that affects the national economy and farmers in all levels. Drought result into farmers losing tons of yields due to crop failure. When farmers are affected by drought, they opt for bare fields to avoid losing tons of crops. However, bare fields are observed to be the major dust sources in Free State during the period of high winds. Generally, an increase in rainfall results to more land being cultivated, however a decrease in rainfall amount leads to substantial land being left fallow.

It is observed from this study's SPEI results that there is meaningful variation of wet and dry cycles over the years. According to Du Pisani et al., (1998) and Masupha & Moeletsi, (2017), Southern Africa has a high variable climate, with recurrent droughts which are a predominant feature in agriculture. Rainfall deficit is the most important climate variable indicating the presence and severity of drought (Du Pisani et al., 1998). The present study rather agrees with this statement, as years with inadequate rainfall were observed to have moderate to severe droughts. Baudoin et al., (2017); Masupha & Moeletsi, (2017) further argue that it is not only

below average rainfall that results to drought but also high temperatures, high winds and low relative humidity. This is also apparent from the current study; years with low rainfall had temperatures relatively above average. These findings rather match with climate predictions made by (Engelbrecht et al., 2015). The rainfall and temperature data are showing the climate variability in a small scale and SPEI is showing it in a broader scale. The rainfall data illustrate which years were dry or wet and temperature data indicates whether the temperatures are increasing or decreasing over the years. The SPEI then indicates whether the year with high temperatures or low rainfall was hit by drought and how severe.

According to the present study and other studies, drought have shown an increasing trend with prolonged periods of extensive drought affecting South Africa from 1960's up to present. Our analysis is in agreement with Harmse et al., (2020) who also reported in their study in the Upper Karoo that droughts have not ended but their intensity has decreased. Several studies Bahta et al., (2016); Baudoin et al., (2017); Du Pisani et al., (1998); Masupha & Moeletsi, (2017); Rouault & Richard, (2003), have observed that South Africa is naturally susceptible to drought and the drought affect the national economy, local communities and farmers in all levels. Farmers tend to loose tons of yields due to crop failure as the results of unfavourable weather conditions or squeezed crop development. Bahta et al., (2016); Rouault & Richard, (2003) and others have noted that communal farmers are the one's mostly affected by prolonged droughts. (Bahta et al., 2016) Bahta, Jordaan and Muyambo, (2016) reported that communal farmers receive insufficient support from government for drought risk reduction, thus they are always vulnerable to drought. Since it is evident that drought is a natural hazard that will always affect farmers, it is therefore necessary to bring proper mitigation measures to cope with it.

### **3.8.2 Temperature variation and impact of frost in Free State crop production**

Free State temperature is observed to be increasing over the years. These findings are supported by Engelbrecht et al., (2015); Hoffman et al., (2011) who projected a future increase in semi-arid and arid temperatures. Rising temperatures have both positive and negative impacts in crop production. When temperature rise at a rate greater than rainfall, it results in evaporative demand being greater than water supply, and thus soil become dry and plants experience stress resulting in crop failure. However, the positive aspect about increase in temperature is that it shortens the frost days. This is evident on the results of this study; temperatures are increasing,

and frost days are becoming short. Frost is observed to be occurring late (May) over the years which cause less risk to plants as they already have fully matured and possibly ready to be harvested. Frost days are becoming less over the years which is evidence that it is becoming hot over the year. Increase in temperature has resulted into less frost days which is an advantage for crops. The present study has reported that frost is decreasing and occurring mostly mid-May due to increased temperatures. Hoffman et al., (2011) in their investigation found that temperatures are projected to increase by  $\sim 1.5^{\circ}\text{C}$  on the coast and  $2.3^{\circ}\text{C}$  inland of the coastal mountains by 2025 thus frost is expected to continuously decrease as well. Additionally, it is evident that Free State is becoming windier over the years.

### **3.8.3 Impact of wind to the occurrence of dust in western Free State**

High winds during dry season are reported in Free State. Eckardt et al., (2020); Vos et al., (2020) observed high winds between August and November which is a major contributor to dust production, matching with the findings of the present study. According to this study's results some years are windier than others in Free State. Dust sources are increasing with increasing abandoned lands. Vegetation cover plays a significant role in wind erosion. When surface has sparse vegetation, high wind is expected as there is nothing to block the wind and vice versa. Interestingly the windier years had many dust sources (for example 2011 and 2015) and had low rainfall which means the land was possibly left bare due to delayed or insufficient rain to grow crops. Furthermore, wind speed is a factor that affects ET rates. Findings indicated that at the beginning of crop season both wind speed and ET tend to be high and then decrease gradually. During dry season both wind and ET are low then gradually increase. During dry season when ET and wind speed are high, rainfall is usually low. During the period of low rainfall, vegetation cover is usually low and thus the area becomes susceptible to dust occurrence. These findings are in agreement with Rezaei et al., (2016) who noted that low rainfall and high ET results to low vegetation and thus the area becomes prone to wind erosion. It is apparent that variation in rainfall onset and cessation, and rising temperatures leads to shifting of plant dates and possible leaving the land fallow. The fallow land then in turn becomes major dust sources due to increased wind in these areas. Therefore, proper mitigation measures to minimise the consequences are needed. Such mitigations include leaving crop residues after harvesting. The crop residues will block wind and thus results to low winds and reduced dust sources. Government can invest in irrigation equipment to assist the rainfed crops



when rainfall is not enough. When farmers are equipped with resources to mitigate the effects of drought, loss of yields due to crop failure would be reduced and thus avoiding negative effect on the economy.

### **3.9 Conclusion**

This chapter aimed to investigate the climate constraints to Free State crop production. To achieve this aim three objectives were formulated with the first one determining the variation of rainfall in Free State. To answer this objective CHIRPS, ARC and SPEI data were used. SPEI data showed that drought is becoming prominent and severe over the years. Based on the investigated years; some years had moderate, and some had severe drought and others were normal years. Drought has been observed to be the consequences of low rainfall, high temperatures, high wind, and low relative humidity. Both CHIRPS and ARC data showed that there is a seasonal shift on the onset of rainfall; rainfall has shifted to late summer by approximately 62 days on average from 1981-2019 in Free State. Furthermore, ARC showed a slight increase (357-408 mm/year) in rainfall from 2005- 2016 and CHIRPS showed a slight decrease (458-404 mm/year). Other studies have observed that there is a slight decrease in SA rainfall and number of rainfall days. These results correspond with the results of the present study even though ARC results are showing a slight increase. The slight difference from the results is expected since the compared two datasets are completely different from each other; CHIRPS data has a spatial resolution of 0.05 and ARC data is in a point data format and has missing values. Missing values in a dataset are recognised as a limitation because they might result to unrealistic or biased findings. However, based on the findings it was concluded that rainfall is slightly decreasing in semi-arid and arid regions with droughts reoccurring and thus negatively affecting crop production. The farmers depend on these factors to decide on planting times and crop types. Extreme weather conditions further results in a decrease of crop yields as some crops cannot stand undesirable weather conditions.

The second objective was to determine temperature and frost variation and how they affect crop production in Free State. To achieve this objective ARC temperature data was used. The results showed that temperatures have increased by  $\sim 1-2^{\circ}\text{C}$  in Free State and frost has decreased, and its onset has shifted by  $\sim 11$  days. Frost normally starts occurring in April but

according to the results it has shifted to May and low in extent, some years had not received frost at all (i.e., 2016 in Bultfontein station). This is evidence that temperatures are increasing. These results are supported by other studies who projected a future increase in semi-arid and arid temperatures. Decrease in frost is an advantage to plants especially if they are planted late. With the observed decrease in frost variation farmers can still plant maize as late as January and get to harvest time without crops being killed by frost. However, an increase in temperatures might result to plants losing massive amount of water especially if evaporative demand is greater than water supply and thus resulting to crop failure. Increase in temperatures require farmers to continuously irrigate their crops if they want them to retain enough moisture. Irrigation is not certainly feasible in FS as crops usually gets planted over thousands of hectares making it difficult to continuously irrigate them, hence farmers use the rainfed technique. The ARC data had missing data which made it less reliable, however the results still agreed with other people's results, and it was then concluded that temperatures are increasing leading to decrease in frost.

The third objective was to determine how wind speed affects the occurrence of dust. To achieve this objective ARC and ERA5 data were used. Both datasets showed that there is no constant trend; in some years wind increases and some decreases. The ARC maximum wind speed was 10 – 15 m/s and ERA5 maximum wind speed was 10 m/s. Both datasets showed that high wind speed occurs from August- November. Other studies done in FS have also observed high winds between August and November which is a major contributor to dust production, matching with the findings of the current study. The limitation of the two datasets is that ARC is in a point data format and ERA5 has a spatial resolution of 30 km, which makes these datasets completely different and not easy to compare. However, based on the results it was concluded that high wind corresponds with dry months and thus stimulates the production of dust in FS drylands. To mitigate the occurrence of dust during dry months farmers can make sure they don't leave the fields completely bare; they can either leave crop residues, stubbles, or plant winter crops to avoid bare fields. It has been evident from the present study that surface roughness plays a vital role in dust production, therefore crop residues, stubbles and winter crops can act as wind breaker and prevent soil particles from moving.

### ***Study Limitations***

The main limitation to the study was the quality of weather data. The weather data was obtained from ARC and there were missing values. However, to reduce the risk of being imprecise, gap filling was done using data from adjacent stations that had full data for that period. Furthermore, where both stations had missing data for the specific period CHIRPS data was used for rainfall and regression method for temperature data. Additionally, the weather data starts in different years (i.e., Bultfontein 2005, Hoopstad 2003, Wesselsbron 2004 and Wolmaranstad 2007) because weather stations were installed in different years. However, this makes it difficult to do the comparison. To try and overcome this issue, comparison was done over long periods instead of doing it year by year.

## **Chapter 4: Soil Organic Carbon storage**

### **4.1 Significance of the study**

It is crucial to understand the value of ecosystem services to properly manage them. Storage of soil carbon in grassland is one of the ecosystem services that have been neglected. Soil carbon storage is a significant ecosystem service, resulting from interactions of ecological processes. The ecological processes are affected by human activities, and these activities can lead to carbon loss or improved storage. Soil organic carbon (SOC) is therefore a vital factor of soil with significant effects on the functioning of terrestrial ecosystem. When carbon is released to the atmosphere it causes negative effects as it is one of the greenhouse gasses that leads to global warming. However, carbon sequestration is critical for plants as they use carbon during photosynthesis. Studies have shown that grassland can store more carbon than cultivated land. Therefore, appropriate land management is vital so that more carbon can be stored rather than being lost. Hence, the purpose of this chapter is to determine the land management options suitable for improving soil ecosystem services. Furthermore, this study wished to contribute to the knowledge of land management strategies suitable for enhancing the storage of soil organic carbon in Free State. Currently, there are no land management strategies designed and implemented to improve the storage of soil organic carbon in Free State. This chapter will first look at the amount of carbon and nitrogen that is currently present in the FS soils. Second section of the chapter will then focus on the role of soil texture and grain size distribution in storing nutrients. Finally, the chapter will investigate land management strategies that are suitable for storage of carbon.

### **4.2 Aim**

To determine which land management option is suitable for improving soil ecosystem services.

### 4.3 Objectives

- To determine the amount of soil organic carbon and nitrogen in grassland and cultivated land.
- To determine the role of soil texture and grain size distribution in storing nutrients.
- To establish which land management option is suitable for storing more carbon.

### 4.4 Background to the study

This chapter explore the value of ecosystem services that are being lost in the Free State in association with land cover/use change, climate change and farming practices. Ecosystem services (ES) are the direct and indirect benefits that people obtain from ecosystems, as well as products and services (Costanza et al., 1997). There are several ecosystem services, but the present study focuses on the support service as soil organic carbon forms part of it. Soil organic carbon (SOC) results from interaction of ecological processes, and is regarded as an important ecosystem service (Blanco-Canqui et al., 2013). It is the interaction between the dynamic ecological processes of photosynthesis, decomposition and soil respiration that results in the storage of soil carbon. Storage of atmospheric CO<sub>2</sub> to the soils as SOC can potentially reduce climate change, therefore it is vital that the rate of carbon sequestration becomes higher than the rate of carbon loss from the soils to the atmosphere.

Grant et al., (2015) argue that loss of SOC affects the environment negatively as it releases CO<sub>2</sub> to the atmosphere. More CO<sub>2</sub> in the atmosphere can possibly enhance climate change by increasing temperatures. Soils with improved SOC are always preferable as they have several advantages. Those advantages include providing the soil with a good quality, soil tends to have high water infiltration and holding capacity, and high in nutrient content. Moreover, improved SOC storage in the soil does not only sequesters atmospheric C but often improves soil physical, chemical, and biological processes and properties (Blanco-Canqui et al., 2013). It is therefore important to proper manage the soil to retain the SOC. For soils not to lose high amount of SOC appropriate management strategies should be implemented. These strategies may include practicing minimal or no till and controlling erosion by leaving crop residues after harvesting.

West and Post, (2002) argue that in agricultural soils, the fertility of the soil, soil tilth, soil sustainability and crop production are positively affected by organic carbon. Therefore, changes in agricultural management can increase or decrease SOC. For instance, rangelands with minimal livestock grazing can increase SOC, whereas continuous disturbance of the land by cultivating can decrease SOC. Sequestration of atmospheric CO<sub>2</sub> can result from improved agriculture management for accumulation of SOC, thereby moderately mitigating the existing rise in atmospheric CO<sub>2</sub>. Furthermore, thought has been given to the implementation of C credit trading in addition to the environmental benefits to soil C sequestration (West & Post, 2002). An economic incentive for C sequestration initiatives may be provided through the C credit trading system. To increase SOC, changes in agricultural practices are essential to either upsurge organic matter inputs to the soil, reduce decomposition of SOM and oxidation of SOC or a combination. These processes include but not limited to the following practices; minimizing tillage, intensity, reducing or stopping the fallow period, planting winter cover crop, shifting from monoculture to rotation cropping or altering soil inputs to intensify primary production (West & Post, 2002). The loss of SOC can thus be inverted by applying practices that sequester C, accumulating SOC to reach a certain equilibrium, which West & Post, (2002) state it might be reached in 40 to 60 years.

Additionally, loss of SOC can be reversed by minimizing or completely ending cultivation and returning to the original land cover or other perennial vegetation. Trees, plants, and crops absorb carbon dioxide through the process of photosynthesis. The carbon then becomes stored as biomass in tree trunks, branches, foliage and roots and soils (Smith et al., 2012). Plants then convert this carbon dioxide into energy via the process of photosynthesis. Huston and Wolverton, (2009) define net primary production (NPP) as the rate at which carbon dioxide and water are converted by plants into energy-rich carbon compounds. Boyd, (2011) and Yu et al., (2020) add that NPP is the organic mass gathered by green plants in unit time and area and also the remaining part of the total organic matter produced by plants after photosynthesis minus autotrophic respiration. The Earth's NPP appropriate management is crucial for balancing and decreasing the atmospheric concentration of carbon dioxide (Huston & Wolverton, 2009).

Del Grosso et al., (2002) suggest that greenhouse gas emission can be remunerated by the carbon sequestration in soil organic matter (SOM). According to (Del Grosso et al., 2002) it has been observed that some land management practices (such as conventional tillage, summer fallow) can reduce carbon from the soil and that carbon exhausted soils can sequester C when

land management has been changed. Additionally, the advantage of soils as they act as a sink for atmospheric CO<sub>2</sub> is that soil fertility and water retention are observed to increase when C increases in soil. The net fluxes of nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) tends to increase in the atmosphere due to agricultural activities, thus the greenhouse gas benefits of increasing soil C are at least moderately balance. Del Grosso et al., (2002) state that the atmospheric CO<sub>2</sub> concentrations are higher than those of N<sub>2</sub>O and CH<sub>4</sub>, however N<sub>2</sub>O and CH<sub>4</sub> are important greenhouse gases (GHG) as they contribute largely to the greenhouse gas effect than CO<sub>2</sub>.

According to Jian et al., (2020) changes of many woodlands and grasslands to cropland are results of an increase in the world population and food production necessities. Jian et al., (2020) further state that between 1850 and 1980, approximately 900 million hectares of naturally vegetated lands were transformed to cropland and pastures across the globe, with the conversion process continuing up until today in many parts of the world. It is therefore evident that SOC losses result from converting natural vegetation lands to croplands. However, more atmospheric carbon can be sequestered by withdrawing carbon losses in cropland soils. Higher SOC is linked with better soil health and fertility, hence increasing SOC may help to improve agricultural productivity. Shift in land management practices, including the use of cover crops within rotations has been proposed as a way to increase SOC stocks (Jian et al., 2020).

On the Intergovernmental Panel on Climate Change (IPCC) report of 2019, it is stated that in the climate system land ecosystems play a significant role, due to their large carbon pools and carbon exchange fluxes with the atmosphere. Land serve as a large CO<sub>2</sub> sink and this sink has been accredited to growing atmospheric CO<sub>2</sub> concentration, an extended growing season in cool environments, or forest regrowth. However, whether this sink will continue is one of the major doubts in carbon cycle and climate modelling. Moreover, land use causes changes in vegetation cover and those changes may result in regional cooling or warming through transformed energy and momentum transfer between ecosystems and the atmosphere. There is great assurance that greenhouse gas decrease measures in agriculture, livestock management and forestry would have considerable climate change mitigation potential, with co-benefits for biodiversity and ecosystem services. This would be as the result of current magnitude of greenhouse gas emissions and CO<sub>2</sub> removal in land ecosystems. Future climate change and increasing atmospheric CO<sub>2</sub> concentration are anticipated to emphasize present challenges by changing biomes or affecting crop yields, as well as over land-based climate change mitigation.

Land degradation is a serious issue for ecosystems around the world due to the loss of concrete or possible productivity or utility. Unsustainable agriculture, forestry, socio-economic pressure are drivers of land degradation. Soil degradation is of a concern, due to the long period essential to reinstate soils as well as the hasty degradation of primary forests through fragmentation. High-carbon-stock wetlands are the most susceptible ecosystems to degradation. High CO<sub>2</sub> emissions and degradation are also the consequences of draining the natural wetlands for use in agriculture. Land degradation is a significant aspect that contributes to doubts in the mitigation possibilities of land-based ecosystems. Furthermore, degradation that decreases forest biomass and SOC results to higher rates of runoff and hence to increasing flood risk.

#### **4.5 Literature review**

Agricultural management plays a substantial role in increasing or decreasing SOC. One of the advantages of increased SOC is that it increases water and nutrient holding capacity, soil structure creation and firmness and energy source for microbial community (Loke, Kotzé, Preez, & Twigge, 2019). Soil C is thus often used as an indicator of soil degradation. Therefore, replacement of cultivation with secondary grassland management can reverse degradation process, including a deterioration in soil C, which is the most basic and serious risk to environmental and agricultural sustainability across the globe (Loke et al., 2019). Furthermore, studies have shown that converting cultivated land to grassland is important as that will provide the ecosystem with more atmospheric carbon sink rather than a source. It is therefore vital to understand the carbon cycle both in grassland and cultivated land to recognize the role of carbon in the ecosystem. DAYCENT carbon model was used to determine the amount of SOC that is being lost to continuous cultivation and to determine how long will it take for SOC to reach an equilibrium if land cover were to be changed from cultivation to grassland.

##### **4.5.1 Carbon cycle in grassland and cultivated land**

Carbon cycle is a movement of carbon between the atmosphere and the land. Scoltock, (2013) state that carbon is found in four natural sources: atmosphere, lithosphere, biosphere, and hydrosphere. In the atmosphere carbon is mainly found as carbon dioxide that has been respired by plants and animals. In the lithosphere it is found in a form of carbonate rocks,



fossil fuels (petroleum, coal and natural gas), dead and decaying animals and animal waste (Scoltock, 2013). Moreover, in biosphere carbon is found stored in plants and trees as carbon dioxide and they use it during photosynthesis to make the building blocks of food. Lastly, in hydrosphere carbon is found dissolved in ocean water and lakes.

Carbon gets released into the atmosphere from the sources and form carbon dioxide (Figure 4.1). Carbon dioxide gets removed from the atmosphere and become stored in C pools of varying lifetime and this process is called carbon sequestration (Abdalla et al., 2010). Carbon sequestration is the capturing and securely storing of carbon by biotic (photosynthesis) and abiotic (injection and geological strata or ocean) processes (Lal, 2004). Biotic processes of carbon sequestration are based on photosynthesis and conversation of atmospheric carbon into the terrestrial pool comprising biomass (above and below-ground), soil humus and biogenic carbonates (Lal, 2004).

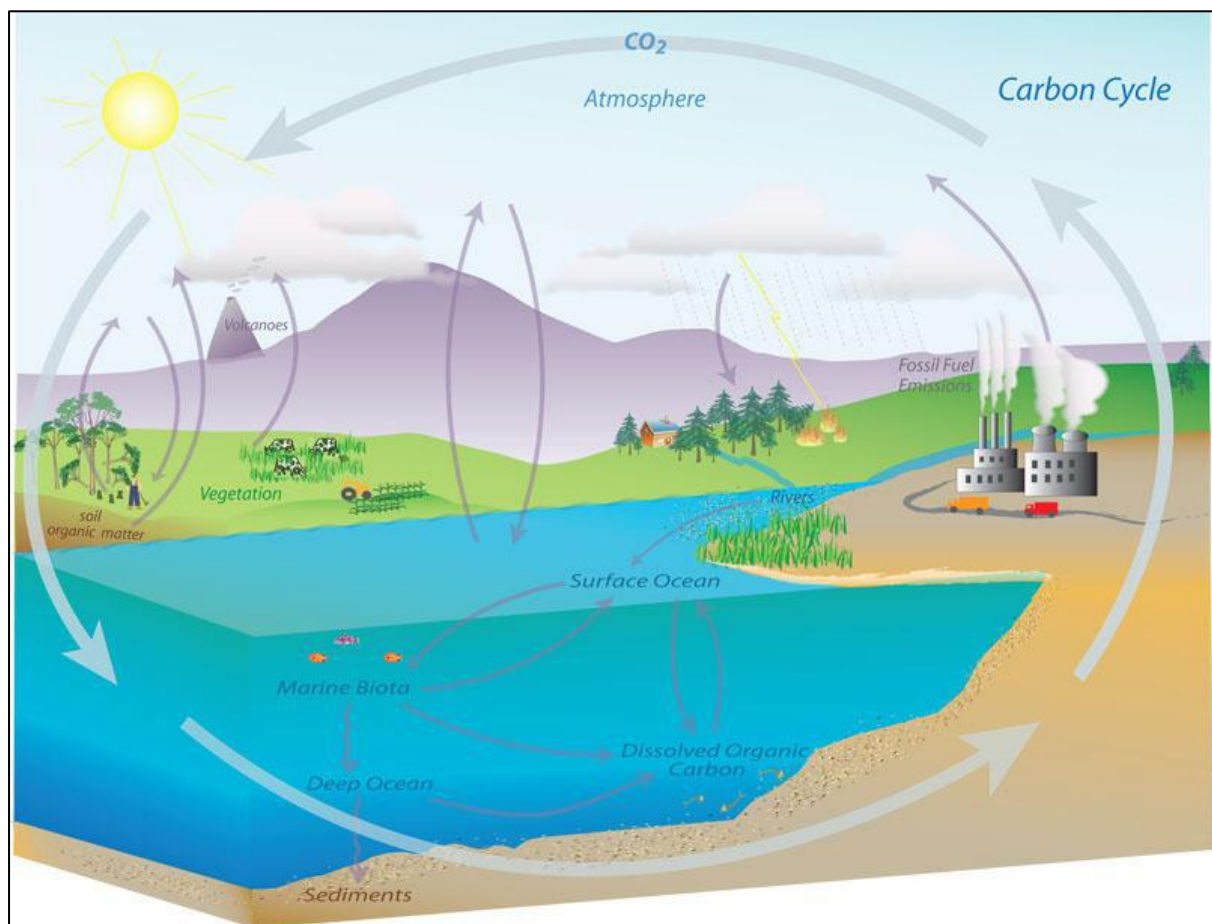


Figure 4.1: Carbon cycle (Scoltock, 2013). Diagram showing the movement of carbon in the ecosystem

## **Carbon cycle in grassland vs in dryland or cultivated land**

According to Scurlock & Hall, (1998) natural grasslands both tropical and temperate play a substantial but poorly recognized role in the global carbon cycle. The process of carbon cycle in grassland involves photosynthesis and respiration (Van Den Pol Van Dasselaar & Lantinga, 1995). Through photosynthesis vegetation converts atmospheric carbon dioxide into organic matter, while the vegetation and soil releases carbon dioxide into the atmosphere (Zhou et al., 2020). Photosynthesis is a vital part of carbon input from the atmosphere to the grassland ecosystem. Moreover, the carbon cycle is characterized by photosynthesis in the form of material and energy basis and include both above-ground and underground parts (Zhou et al., 2020). Factors such as temperature, precipitation, atmospheric carbon dioxide, growth season length and soil texture indirectly affect grassland ecosystem carbon. Zhou, Li and Yue, (2020) states that these factors affect the grassland ecosystem carbon by affecting plant community composition, plant physiological characteristics and hydrothermal conditions. Furthermore, grassland coverage and vegetation growth conditions are affected by grazing and reclamation and thus affect the formation and distribution of grassland NPP.

In cultivated land there is high rates of soil respiration, while the input of fresh plant debris to soils are lower (Schlesinger & Andrews, 2000). Crops use substantial amount of carbon during plant growth; however, the carbon does not get to be stored in deep soil pools as crops become harvested at a certain time. Moreover, the content of organic matter is observed to decline because of the conditions for decomposition, soil aeration and moisture content which are often improved when soils are disturbed. Land management plays a significant role in the cycling of carbon in dry cultivated land. Schlesinger and Andrews, (2000) argue that loss of SOC is lower when no-till agriculture is practiced. There are thus several biogeochemical models used to predict carbon in both grassland and cultivated land. Some of those models are described below.

### **4.5.2 Biogeochemical models**

Climate change is affected by carbon and nitrogen in the terrestrial ecosystem, therefore it is important to simulate these fluxes and their allocation in order to identify their impact in the ecosystem (Myoung, Choi, & Park, 2011). Biogeochemical models are thus used to predict carbon and nitrogen. These models simulate the growth and death of plants and carbon and

nitrogen cycles under certain conditions. The variations in atmospheric CO<sub>2</sub> concentration, soil water, temperature, and irradiance lead to biogeochemical models investigating the influence on the fluxes and allocations of carbon and nitrogen. Moreover, Grant et al., (2015) state that these models are used on crop productivity and changes to soil quality factors to estimate the impact of changes to climate and carefully contemplate the suitable agricultural management practices. One of the disadvantages of biogeochemical models is that they have a local spatial scale as they lack the ability to regulate the type of vegetation that may possibly live in a certain location and estimate changes in the species or community composition (Myoung et al., 2011). The mostly used biogeochemical models include BIOME-BGC, PnET and DAYCENT models.

#### **4.5.2.1 BIOME-BGC model**

BIOME-BGC as an eco-physiological model captures plant physiological processes (Myoung et al., 2011). The model has a daily temporal and global spatial resolutions. BIOME-BGC model basically simulates daily photosynthesis, respiration, carbon allocation, litterfall and decomposition of plants. The model incorporates dynamic vegetation processes such as the establishment, growth, competition, and mortality of plants Myoung et al., (2011) and these processes depend on daily weather conditions.

The daily carbon gain and losses by plants are accumulated during a year (Myoung et al., 2011). To get the total amount of carbon produced throughout the year, respiring carbon is subtracted from carbon fixation. Canopy radiation absorption, water interception, photosynthesis and litter inputs are controlled by leaf area index (LAI). The main advantages of BIOME-BGC are the management and land use consideration and the impacts on the biogeochemistry of a specific land. Furthermore, the model parameters are flexible; they change subjected to natural disturbances or changes in environmental conditions and management interventions.

#### **4.5.2.2 PnET model**

PnET is a forest physiology model that describes the relationship of vegetation processes (Aber & Federer, 1992). These processes include photosynthesis, respiration, transpiration, litter production and decomposition. PnET model in its original version has a monthly time-scale and originally had no specified spatial resolution Aber & Federer, (1992), but currently stand to regional spatial resolution (Myoung et al., 2011). The model estimates the carbon, water fluxes, and nitrogen in forest ecosystems. It estimates all the fluxes monthly except the carbon in wood and fine roots which is estimated yearly. PnET model is unique from other models based on the three following features: a) to capture the important features of forest ecosystem processes, few input parameters are required; b) input parameters are derived directly from field measurements, and they describe physical, chemical or biological processes (e.g., foliar N concentration and fraction of precipitation intercepted); and c) lastly the model besides capturing the fluxes and cycles of nitrogen and carbon, it also incorporates the fluxes and cycles of additional elements such as calcium, magnesium, potassium, sodium, sulphur and phosphorus (Aber & Federer, 1992). Moreover, the LAI is not explicitly calculated in this model because the main purpose of the model is to estimate the net primary production (NPP) and the rate of photosynthesis.

#### **4.5.2.3 DAYCENT carbon model**

DAYCENT carbon model is the daily time step version of the Century biogeochemical (W. J. Parton, 1996). It stimulates fluxes of carbon I and Nitrogen (N) between the atmosphere, vegetation, and soil. Nutrient availability, water, and temperature controls the plant growth. The function of external nutrient additions and soil organic matter (SOM) decomposition is nutrient supply (W. J. Parton, 1996). The model inputs are daily maximum and minimum temperatures, and precipitation, timing, and description of management events (e.g. fertilization, tillage, harvest) and soil texture data. Parton, (1996) elaborate that the key sub models include plant production, SOM decomposition, soil water and temperature by layer, nitrification, and denitrification and CH<sub>4</sub> oxidation. Del Grosso *et al.*, (2005) illustrate that the recent improvements in DAYCENT include the effect of solar radiation on plant growth rates, increased precision in the scheduling of management events and the option of simulating seed germination as a function of soil temperature and harvest as a function of growing degree days

accumulated since germination. The model consistently simulates SOM levels, crop yield, and trace gas flux for several native and managed systems. The model has been effectively used by several studies (Abdalla et al., 2010; Del Grosso et al., 2005, 2009; Li et al., 2006; Smith et al., 2012; Stehfest et al., 2007) and some of the studies are summarized below. DAYCENT carbon model is suitable to answer the research objective which is to determine the amount of SOC that selected management options can accumulate. The model requires daily weather data (precipitation, maximum temperature, and minimum temperature) and soil data (percentage of clay, sand, and silt content), bulk density, soil carbon and nitrogen. Soil samples, crop yield data and above ground standing biomass of grasslands were collected to establish the initial and possible final states of the model.

Table 4.1: Summary of biogeochemical models

|                     | BIOME-BGC                                                                                                                                                       | PnET                                                                                                                                                                                            | DAYCENT                                                                                                                                                              |
|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Temporal resolution | Daily                                                                                                                                                           | Monthly                                                                                                                                                                                         | Daily                                                                                                                                                                |
| Spatial resolution  | Global scale                                                                                                                                                    | Regional scale                                                                                                                                                                                  | Global scale                                                                                                                                                         |
| Input parameters    | Daily temperature, precipitation, humidity, solar radiation, and day length. Description of site vegetation such as leaf C:N ratio, maximum stomata conductance | Monthly average radiation, average minimum and maximum temperature, total precipitation, average insolation, and site variables such as: latitude, water holding capacity, leaf specific weight | daily maximum and minimum temperatures, and precipitation, timing, and description of management events (e.g. fertilization, tillage, harvest) and soil texture data |

The above-described models are some but not all biogeochemical models that can be used to simulate the fluxes of water, carbon, and nitrogen in ecosystems. BIOME-BGC, and PnET are described briefly and only went in detail to DAYCENT carbon model which is the model suitable to answer research question for the present study. DAYCENT carbon model was therefore chosen because it allows the simulation of carbon and nitrogen specifically in grassland and cultivated land. DAYCENT carbon model allows flexibility and control to input parameters starting from weather parameter, crop parameters and land management options. The weather file is not fixed, it can start and end to the year of your choice. Additionally, DAYCENT carbon model allows parameter files such as crop.100, cult.100, grazing and harvest to be edited and improved according to the site preference conditions. Crop.100 file gives options to choose the crop of your choice and change sensitivity of the crops to soil moisture by adjusting the WSCOEFF accordingly. Cult.100 file allows to choose the type of cultivator that is suitable for the area. Grazing file has grazing types such as low grazing with no effect on production, low grazing with moderate impact on production and grazing with high impact on production and allows you to choose the grazing type suitable for the simulation. Harvest file has different harvest methods and allows you to choose the one suitable for the study site and lastly DAYCENT allows you to choose the land management option (herbivory, fire, herbivory and fire, no herbivory and no fire) that best describe the area. Furthermore, to stabilize the nitrogen pools DAYCENT normally performs 100 years of spin up simulation.

The wide variety and flexibility to input parameters made it easy to choose and adjust accordingly the parameters suitable for the Free State soils, which made DAYCENT carbon model the most suitable model for the present study. PnET model is not suitable for Free State, Bultfontein soils because it simulates carbon in forest ecosystems. PnET is designed to predict LAI, foliage production, transpiration and water yield, total net photosynthesis and net primary production of forest ecosystem (Aber & Federer, 1992). The selected study site in Bultfontein, Free State is therefore characterised by cultivated lands and grasslands with no forest plantations, which makes the PnET model not applicable for the present study.

#### 4.5.2 Summarized studies about SOC and DAYCENT Carbon model

In drought-prone environments continued soil cultivation has been identified as a major cause of land degradation and a danger to soil quality. Loke et al., (2019) evaluated land use effects on soil C, fractions, and SOC quality across three semi-arid agro-ecosystems (Harrismith, Tweespruit and Kroonstad) in central South Africa. Soil samples were collected from croplands, primary and secondary grasslands at 0-200 mm layer and analysed for various soil C fractions in each agro-ecosystem. All analyses were done on bulk soil samples and the SOC structure was characterized with  $^{13}\text{C}$  nuclear magnetic resonance (NMR) spectroscopy. The results indicated that change of primary grassland into croplands reduced C fractions by 27 to 90 % across the three agro-ecosystems. On the other hand, reversing cultivated soil into perennial grassland re-established and improved soil C fractions by (3 to 129 %) to characterize primary grasslands. Furthermore, results showed that organic C decomposition was lesser in the cultivated soils comparative to natural and restored soils. In summary, this study demonstrated the potential of secondary grassland management to rehabilitate degraded cultivated soils with implications for restoration of agro-ecosystem functions and services. The current study will also adopt the same approach to determine how much SOC can be stored if cultivated lands are converted back to grassland in Free State, South Africa.

It is important to be familiar with the kinetics of organic matter transformations in arable soils to manage them sustainably. A study by Lobe et al., (2001), investigated the effects of cropping period on pools of C and N in coarse-textured savanna soils of the South African Highveld. Three different agro-ecosystems in Free State, South Africa were sampled. Composite samples were taken from the top 20 cm of soils that have been cropped for lengths of time varying from 0 to 98 years. Subsequently, SOC and N concentrations were assessed in bulk soil (<2 mm), as well as in clay (<2  $\mu\text{m}$ ), silt (2-20  $\mu\text{m}$ ), fine sand (20-250  $\mu\text{m}$ ) and coarse sand (250-2000  $\mu\text{m}$ ) separates. The results presented that continuing cultivation of native grassland decreased soil C and N concentrations by 65 and 55 %, respectively. Losses of SOM happened from all particle-size separates, even though the amount of loss constants increased as particle size increased (Lobe *et al.*, 2001). It was observed that concentrations of organic C reached equilibrium after 34 years for the bulk soil and after 55 years for clay-size separates. However, organic matter attached to silt sustained to be lost as the cropping continued, possibly owed to

wind erosion. Findings proved that changes in soil properties continued even after almost 100 years of cultivation.

An increase in GHG emissions (mainly  $\text{N}_2\text{O}$  and  $\text{CH}_4$ ) and more  $\text{NO}_3$  leached below the root zone and into waterways results from strengthening of agriculture and change of native vegetation to cropland (Del Grosso et al., 2009). Agricultural soils are frequently a cause but may also be a sink of  $\text{CO}_2$ . IPCC emission factor methodology is usually used to obtain the regional and larger scale estimates of GHG emissions. DAYCENT biogeochemical model was used to realistically represent GHG emissions for non-rice major crop types (corn, wheat, soybean). N losses from croplands were estimated using IPCC methodology based exclusively on N inputs. In contrast, DAYCENT accounts for soil class, daily weather, historical vegetation cover and land management practices such as crop type, fertilizer additions and cultivation events. Global dataset of weather, soils, native vegetation and cropping fractions were mapped to a  $1.9^\circ \times 1.9^\circ$  resolution. Non-spatial data were anticipated to be comparable within crop types across regions. Model produced baseline GHG emissions and N losses for irrigated and rainfed cropping were compared with land management alternatives proposed to mitigate GHG emissions. Lower N losses resulted from reduced fertilizer, but crop yields were reduced by a similar proportion. DAYCENT model results suggested that there is a substantial probability to decrease GHG emissions from cropped soils and to increase yields. It was observed that exactness application of fertilizer and nitrification inhibitors allow for more than N uptake by plants and decrease gaseous N losses and  $\text{NO}_3$  leaching. Furthermore, non-till cultivation which enables C sequestration in soils, together with nitrification inhibitors provided the maximum decrease in GHG fluxes among the scenarios considered.

Del Grosso et al., (2002) presented evidence to show that DAYCENT can reliably simulate soil C levels, crop yields and annual trace gas fluxes for various soils. DAYCENT was used to compare the net GHG fluxes for soil under different land uses. Changes in SOC, the C equivalents of  $\text{N}_2\text{O}$  emissions and  $\text{CH}_4$  uptake and the  $\text{CO}_2$ , costs of N fertilizer production were all accounted for to calculate net GHG flux. The model results and data presented that dryland soils that are exhausted of C due to conventional till winter wheat or fallow cropping can store C upon changing to no till, by decreasing the fallow period or by returning to native vegetation. Moreover, the model recommended that dryland agricultural soils will be net sources of GHG even though the magnitude of the source can be meaningfully decreased, and yields can be improved upon shifting to no till annual cropping.



Crop residue can be a feasible source for biofuel production and other industrial products; however their elimination from agricultural land might negatively impact productivity and environmental quality (Smith et al., 2012). A study by Smith et al., (2012) used three process-based models (CENTURY, DAYCENT and DNDC) and the CAMPBELL empirical model to simulate SOC variation and were compared to observations from 14 residue removal experiments with the temperature climate areas of Canada and the Midwestern USA. The experimental results shown that residue elimination effects on SOC were more expected to be observed with greater rates of residue removal, after longer periods and with greater rates of N fertilizer. The average measured SOC variation for residue elimination across all experimental sites and periods was  $-235 \text{ gm}^{-2}$  (i.e., 33 % of SOC in top 20 cm) while the SOC change as predicated by the models were -423, -417, -201, and  $218 \text{ gm}^{-2}$  for the CENTURY, DAYCENT, DNDC and CAMPBELL models, respectively. All model estimates were near or within the range of uncertainty of estimates derived from measurements. The above reviewed literature has motivated the use of suitable method for this chapter. These methods and type of data that will be used in this chapter are widely used to answer similar research questions to the present study.

## **4.6 Methodology**

This chapter mainly focus on the amount of carbon stored in grassland and cultivated land which is a value of ecosystem. The aim of the chapter was to determine which land management option is suitable for improving soil ecosystem services, however in the process of achieving the aim the amount of soil organic carbon (SOC) and nitrogen stored in both grassland and cultivated land were determined. Furthermore, the role of soil texture and grain size distribution in the sampled soil types were determined.

### **4.6.1 Selection of sampling points**

The entire study area has been stratified into four main soil types based on the EU Soil Classification System. The four most important regional soil types for both cultivation and grazing are Arenosols, Luvisols, Calcisol and Lixisol. These soil types contain differing proportions of sand and clay and vary in depth and suitability for cultivation and susceptibility

to wind erosion. Each site was selected based on two main reasons: type of soil and land cover or land use. A total of six sites were sampled, four of them were in native, undisturbed grassland in different soil types and two were cultivated lands in different soil types.

#### **4.6.2 Data collection**

##### **4.6.2.1 Materials**

The following equipment's were used to collect the soil samples:

- GPS to mark point for each sample
- Auger
- Hand spade and hammer
- Bucket
- Depth meter (Leica Laser DISTO™ X 310)
- Plastic sample bags and permanent marker
- Eijkelkamp Bulk Density Soil Sampler

##### **4.6.2.2 Methods**

###### **Procedure for collecting soil samples**

DAYCENT carbon model requires site specific information as one of the input parameters. Therefore, following the DAYCENT carbon model manual prepared by Parton et al., (2020) soil samples were successfully collected in Bultfontein, Free State, South Africa. For each site the coordinates of a sampling point were first taken. An auger was used to dig a range of soil layers (0-2 cm to 75-90 cm range), where 75-90 cm was the deepest range that a hand operated auger can achieve without an extension (Figure 4.2). A pooled mixture of 4 auger cores for each depth was mixed in a bucket and a sub-sample approximately 1 kg was taken. The depth of a hole was continuously measured using the Leica Disto meter before and after taking a sample for each range before proceeding with the next sample. Samples obtained varied in different soil types as an impermeable layer was reached at different depths (i.e., 35 cm, 45 cm, and 60 cm) and was not reached in deeper soil types (e.g., Arenosols). The samples were pre-dried in the sun for 5-10 minutes and returned to zip sample bags as shown in (Figure 4.3).



Figure 4.2: Digging soil at different range of layers using an auger. Picture taken in September 2019



Figure 4.3: Air drying collected soil samples for ~ 10 minutes. Picture taken in September 2019



## Bulk density

Bulk density is required by DAYCENT carbon model as an input parameter (William J Parton et al., 2020). Bulk density for each soil type and land use was measured using an Eijkelkamp Bulk Density Soil Sampler following the standard procedures detailed in the manual prepared by (Gill, Clayton, & Richardson, n.d.). A hand spade was used to dig a hole of approximately 13 cm depth. A cylinder of a known volume ( $100 \text{ m}^3$ ) was knocked into the soil layer down using a hammer until the cylinder was judged to be full of the soil (Figure 4.4). A hand spade was then used to carefully extract the cylinder, avoiding loss of any particles, and the soil was levelled off in the cylinder using a sharp knife and was then properly closed. The soil sample in a cylinder was then transferred to a small sample bag and allowed to air dry by leaving the sample bag open for 5-10 minutes.



Figure 4.4: Measuring bulk density. Both pictures showing the procedure to get the bulk density soil sample. Picture taken in September 2019

## Grassland biomass

Bransby and Tainton, (1977) outlined the standard recommendations for the use of disk pasture meter (DPM) to estimate the standing biomass. Following those recommendations, DPM was used to get grassland biomass, 10 points were measured in a 10-meter square (Figure 4.5). As several regression equations Trollope & Potgieter (1986); Gwate, (2017) have already been developed for the relationship between disk height and above ground biomass (AGB) in native grasslands, these published equations were used for all future predictions of AGB ( $\text{gDM m}^{-2}/\text{yr}^{-1}$ ). A simple linear regression ( $y = 2.8x - 1.9$ ) adopted from Gwate, (2017) which is suitable for commercial land was used to calibrate the DPM. Based on the calibration, AGB ( $\text{gDMm}^{-2}/\text{yr}^{-1}$ ) was estimated using the mean DPM settling height for each site point respectively. The purpose of getting AGB was to validate the DAYCENT carbon model outputs in grassland areas. In cultivated land, harvest yield data obtained from the farmers was used to validate the model results.



Figure 4.5: Measuring grassland biomass using disk pasture meter. Picture taken in September 2019

### 4.6.3 Soil analysis

#### 4.6.3.1 Total soil organic carbon (SOC) and nitrogen

To answer the first objective which is to determine the amount of SOC and nitrogen, all the soil samples were first weighed as they are and were then transferred into an aluminium foil and air dried for ~24 hours. The laboratory drying process was shorter since the samples had been pre-dried in the sun for 5-10 minutes immediately after sampling. Fine roots were separated from each sample from 0-2 cm to 30-45 cm depth. Roots were weighed separately to get the fine root biomass and returned to the actual soil sample and mixed back into the sample. Fine root biomass data was also used in the validation of the predictions from DAYCENT.

Soils were sieved through 1 mm sieve and approximately 3 g was taken for carbon and nitrogen analyses. The amount of sample needed for carbon analysis is 20 mg for agricultural soils, however ~ 3 g was taken to allow for repeats. The soils were also tested for calcium carbonates ( $\text{CaCO}_3$ ) by adding Hydrochloric acid (HCL) in each sample. The 3 g of soil sample was transferred into a known test tube size and about 10 ml of HCl was added in a sample and shaken to allow for reaction to happen. In samples where  $\text{CaCO}_3$  was present a fizz reaction was observed. The samples were shaken and left in an ultrasonic bath for 1 hour at 80 °C, allowing for a complete reaction to occur. After an hour, samples were taken out of the ultrasonic bath and filled with distilled water to 45 ml and left standing over night (Figure 4.6). Samples were then centrifuged for 5 minutes to allow the sediment to completely settle at the bottom of test tube. The water was decanted, test tubes refilled again with distilled water to rinse the sample again and centrifuged. This process was repeated 3 times until the water was clean without the yellow colour it had from the beginning. Samples that still had floating particles after centrifuging were sieved through 106  $\mu\text{m}$  sieve during decanting. Samples were then oven dried at 60 °C for 36 hours. Soils were weighed after cooling down and compared with the initial weight to determine the amount or percentage of inorganic matter in each sample. Samples were numbered accordingly and sent to Archaeology lab at the University of Cape Town for carbon and nitrogen analyses.





Figure 4.6: Process of removing carbonates in the soil samples using HCl. Pictures taken in October 2019.

#### 4.6.3.2 Texture analysis

To answer the second objective which is to determine the soil texture and grain size distribution for each soil type, actual soil samples from the field were weighed and then sieved through 2 mm, and 1 mm sieves. The particles above 2 mm were weighed and recorded and the particles above 1 mm but below 2 mm were weighed. The sample below 1 mm was also weighed, and this is the sample used for texture analysis in Malvern Mastersizer 2000 which was invented by Malvern Instruments in United Kingdoms. The sample below 1 mm was separated several

times using the riffle splitter until ~ 2 grams was obtained. The 2 grams sample was split into 3 samples of different masses (~0.3g, 0.5g, and 1g) to allow 3 trial runs in the Malvern Masterizer 2000. The three samples were transferred into test tubes and about 20 ml of tap water was added and allowed to stand overnight to allow particles to disaggregate.

#### 4.6.3.2.1 The Malvern Mastersizer 2000

A manual prepared by Malvern Instruments Ltd., (1997) was adopted as a guide to successfully use the Malvern Mastersize 2000 to analyse soil samples. Following the soil preparations; after allowing the samples to stand overnight, the suspension was stirred and pumped into the measuring zone and introduced to the laser diffractometer (Figure 4.7). The results of the three replicates were later averaged giving standard results for each sample. The results were then displayed as particle size distribution. The data was exported to an MS Excel worksheet for further analysis and calculations. The size classes recorded by the Malvern Masterizer 2000 were then summed into categories representing clay, silt, and sand.



Figure 4.7: Measuring the grain sizes distribution using Malvern Mastersizer 2000. Both pictures showing the process of measuring grain size. Pictures taken in November 2019.



#### **4.6.3.2 Gradistat Analysis**

Grain size is the most essential property of sediment particles, affecting their entrainment, transport and deposition (Blott & Pye, 2001). A computer software program GRADISTAT was developed for quick analysis of grain size statistics. This analysis can be done from any of the standard measuring techniques, such as sieving and laser granulometry. GRADISTAT is built and runs within Microsoft excel spreadsheet package. The program is flexible, as it accept standard and non-standard size data, and further produce a range of graphical outputs that comprise the frequency and triple plots (Blott & Pye, 2001). The grain size statistics and moments methods by Folk and Ward (1957) are also rapidly calculated by GRADISTAT. For the software to generate the output results, the percentage of sediment present in several size fractions must be recorded. This input data can be the weight taken on a series of sieves, or the percentage of sediment detected in size classes derived from a laser granulomter, x-ray sedigraph or coulter counter. In this study size classes were derived from a laser granulometer. The GRADISTAT software allows the variation of statistics such as mean, mode, sorting, skewness, kurtosis, and a range of cumulative percentile values to be calculated. Blott and Pye, (2001) note that the program also offers a physical description of the textural class such as ‘muddy sandy gravel’. Furthermore, Blott & Pye, (2001) state that the program provides graphs of the grain size distribution and cumulative distribution of the data in both micrometre and phi units and displays the sample grain size on gravel-sand-mud and sand-silt-clay triangular diagrams. GRADISTAT is therefore an appropriate grain size distribution analysis tool that was adopted by the current study.

#### **4.6.3.3 Land management options**

##### **4.6.3.3.1 Bulk density**

To answer the third objective which is to establish the land management option suitable for storing more carbon, bulk density and pH were determined and further used as inputs when setting up the DAYCENT model. Following the bulk density protocol from Outcomes, (2002), samples for bulk density were oven dried for ~ 24 hours at 105 °C. The dry samples were then weighed to get the mass of a dry soil. The mass of a dry soil was divided by the total volume

of the cylinder to get the bulk density (Equation 4.1). Bulk density data was used as one of the inputs for creating a soil.in file which is further an input for DAYCENT model.

$$\text{Bulk density (BD)} = \frac{\text{total dry mass (g)}}{\text{volume of copecky ring (cm}^3\text{)}} \quad (4.1)$$

#### 4.6.3.3.2 pH analysis

Following the standard operating procedures by Ashbrook, (2014) to determine soil pH, soil samples from each sampling site were sieved through 2 mm sieve. A 50 ml centrifuge bottle was placed on a scale. The weight of the bottle was set to tare and about 2 g of soil was weighed to the centrifuge bottle. About 20 ml of potassium chloride (KCl) was added to the soil sample. The sample was shaken and left for 3 hours before taking the measurement. The pH was then measured using the pH meter. Before taking the reading the pH meter was calibrated using pH 4 and pH 7 buffer solutions. pH data was used as one of the inputs for creating a soil.in file which is further an input for DAYCENT model

#### 4.6.3.3.3 DAYCENT Carbon model set up

DAYCENT carbon model was used to obtain the NPP of each site. Prior setting up the model certain primary study site data must be collected. The site data include the following parameters: latitude and longitude of site, texture data (sand, silt, and clay fractions), and bulk density. A site specific soils.in file for each site was created using latitude and longitude of the site, bulk density, soil pH and soil texture information. Bultfontein weather data was obtained from Agricultural Research Council for a period of 2005-2019. The ground measured weather data had some gaps in the years due to malfunction in the weather station. Therefore, Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data was used to gap fill the ground measured data. A schedule file (in Appendix 4.2) was created for each site using suitable land management option for different soil types. Table 4.2 summarises how the model was successfully set up for each land management option.

Table 4.2: Summary of how DAYCENT model was set up for each land management scenario in different soil types

| Type of soil | Cultivated land                                                                                                                                                                                                                                                                                                                                                                                                                           | Native grassland                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Arenosols    | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = C6</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = KNZ</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GM_K and GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> |
| Luvissols    | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = C6</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = KNZ</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GM_K and GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> |

|          |                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------|-------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Calcisol | No model set up for Cultivated land in Calcisol | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = KNZ</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GM_K and GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> |
| Lixisol  | No model set up for Cultivated land in Lixisol  | <ul style="list-style-type: none"> <li>• Weather data (2005-2019)</li> <li>• Soil.in file</li> <li>• Site.100 file that corresponds with weather file</li> <li>• Schedule file: <ul style="list-style-type: none"> <li>➤ Initial system = 1 for cropland &amp; grassland</li> <li>➤ Initial crop = KNZ</li> <li>➤ Weather choice = F</li> <li>➤ Grazing = GM_K and GL_K</li> <li>➤ Management options; no fire and herbivory</li> </ul> </li> </ul> |

#### **4.6.3.3.4 Schedule files description**

To successfully run DAYCENT model, ten scenarios were created. These scenarios were made based on what is happening in Free State agricultural land.

##### **1 Arenosols-Cultivated land Herbivory (AR-CULT-HERB)**

Scenario called ‘Arenosols – business as usual’, namely land preparation using industrial scale agricultural practices (minimum till, weed treatment with glyphosate); planting of cash crop with multi-row planter, with simultaneous addition of fertilizer i.e. typical precision agriculture practice; crops of choice is GMO maize (Roundup Ready), but it could also be sunflower or groundnuts; during growth there is weed control using glyphosate; pest control after planting as and when necessary; harvest of crop, followed by Herbivory of crop residues by cattle.

The model was simulated under Arenosols cultivated land. The cultivated land site is dominated by maize plantation or other cash crop. The planting time for maize is October, usually 2 or 3 weeks after the first rain in Spring but could be anytime up to the end of December. The date was determined from the farmers records as well as the growth signal assessed from the MODIS EVI product. The growing cycle for maize is normally 120 days, which means harvesting will take place in March before frost occurs in April. Local growth cycle was confirmed from MODIS EVI product. The simulation was done under the following conditions: initial system 1 which is the cropland, initial crop type C6 which is corn, CULT N which is no till, HARV G meaning the grain or yield was harvested, FERT N10.9 gN/m<sup>2</sup> fertilizer amount was applied as per Free State recommendations, weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the simulation under cultivated land was light post-harvest herbivory only which is GL\_K. GL\_K means there was low grazing intensity with no effect in production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **2 Arenosols-Grassland Herbivory (AR-GRASS-HERB)**

Scenario ‘Arenosols – restoring abandoned cultivated land to native grassland with the view to sequestering carbon in the soil, combined with herbivory by cattle’

The model was simulated in Arenosols soil type under grassland. The grassland site is dominated by native grass. The land is only used for grazing animals. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the first simulation under grassland in Arenosols was herbivory; which is GM\_K grazing option; meaning there was low grazing intensity with moderate effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **3 Arenosols-Grassland no herbivory (AR-GRASS-no HERB)**

Scenario ‘Arenosols – restoring abandoned cultivated land to native grassland with the view to sequestering carbon in the soil, combined with minimal herbivory (very low stocking rate well below that recommended by DAFF) by wildlife, especially bulk grazers such as zebra, wildebeest and buffalo’

The model was simulated in Arenosols under grassland. The grassland site is dominated by native grass. There is no animal grazing taking place on the land. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the second simulation under grassland in Arenosols was no herbivory; which is GL\_K grazing option; meaning there was low grazing intensity with no effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

#### **4 Luvisols-Cultivated land Herbivory (LU-CULT-HERB)**

Scenario called ‘Luvisols – business as usual’, namely land preparation using industrial scale agricultural practices (minimum till, weed treatment with glyphosate); planting of cash crop with multi-row planter, with simultaneous addition of fertilizer i.e. typical precision agriculture practice; crops of choice is GMO maize (Roundup Ready), but it could also be sunflower or groundnuts; during growth there is weed control using glyphosate; pest control after planting as and when necessary; harvest of crop, followed by Herbivory of crop residues by cattle)

The model was simulated in Luvisols under cultivated land. The cultivated land site is dominated by maize plantation or other cash crop. The planting time for maize is October, usually 2 or 3 weeks after the first rain in Spring but could be anytime up to the end of December. The date was determined from the farmers records as well as the growth signal assessed from the MODIS EVI product. The growing cycle for maize is normally 120 days, which means harvesting will take place in March before frost occurs in April. Local growth cycle was confirmed from MODIS EVI product. The simulation was done under the following conditions: initial system 1 which is the cropland, initial crop type C6 which is corn, CULT N which is no till, HARV G meaning the grain or yield was harvested, FERT N10.9 gN/m<sup>2</sup> fertilizer amount was applied as per Free State recommendations, weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the simulation under cultivated land was light post-harvest herbivory only which is GL\_K. GL\_K means there was low grazing intensity with no effect in production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

#### **5 Luvisols-Grassland Herbivory (LU-GRASS-HERB)**

Scenario ‘Luvisols – improving native grassland with the view to sequestering carbon in the soil, combined with herbivory by cattle’

The model was simulated in Luvisols under grassland. The grassland site is dominated by native grass. The land is only used for grazing animals. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather

data file. The management option for the first simulation under grassland in Luvisols was herbivory; which is GM\_K grazing option; meaning there was low grazing intensity with moderate effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **6 Luvisols-Grassland no Herbivory (LU-GRASS-no HERB)**

Scenario ‘Luvisols – improving native grassland with the view to sequestering carbon in the soil, combined with minimal herbivory (very low stocking rate well below that recommended by DAFF) by wildlife, especially bulk grazers such as zebra, wildebeest and buffalo’

The model was simulated in Luvisols under grassland. The grassland site is dominated by native grass. There is no animal grazing taking place on the land. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the second simulation under grassland in Luvisols was no herbivory; which is GL\_K grazing option; meaning there was low grazing intensity with no effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **7 Calcisol-Grassland Herbivory (CA-GRASS-HERB)**

Scenario ‘Calcisol – improving native grassland with the view to sequestering carbon in the soil, combined with herbivory by cattle’

The model was simulated in Calcisol under grassland. The grassland site is dominated by native grass. The land is only used for grazing animals. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the first simulation under grassland in Calcisol was herbivory; which is GM\_K grazing option; meaning there was low grazing intensity with moderate effect



on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **8 Calcisol-Grassland no Herbivory (CA-GRASS- no HERB)**

Scenario ‘Calcisol – improving native grassland with the view to sequestering carbon in the soil, combined with minimal herbivory (very low stocking rate well below that recommended by DAFF) by wildlife, especially bulk grazers such as zebra, wildebeest and buffalo’

The model was simulated in Calcisol under grassland. The grassland site is dominated by native grass. There is no animal grazing taking place on the land. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the second simulation under grassland in Luvisols was no herbivory; which is GL\_K grazing option; meaning there was low grazing intensity with no effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **9 Lixisol-Grassland Herbivory (LI-GRASS-HERB)**

Scenario ‘Lixisol – improving native grassland with the view to sequestering carbon in the soil, combined with herbivory by cattle’

The model was simulated in Lixisol under grassland. The grassland site is dominated by native grass. The land is only used for grazing animals. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the first simulation under grassland in Lixisol was herbivory; which is GM\_K grazing option; meaning there was low grazing intensity with moderate effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **10 Lixisol-Grassland no Herbivory (LI-GRASS-no HERB)**

Scenario ‘Lixisol – improving native grassland with the view to sequestering carbon in the soil, combined with minimal herbivory (very low stocking rate well below that recommended by DAFF) by wildlife, especially bulk grazers such as zebra, wildebeest and buffalo’

The model was simulated in Lixisol under grassland. The grassland site is dominated by native grass. There is no animal grazing taking place on the land. The simulation was done under the following conditions: initial system 1 which is the grassland, initial crop type KNZ (Konza tall grass), weather choice F; this weather choice reads the daily values for precipitation, minimum and maximum air temperature plus extra optional weather drivers from the start of a weather data file. The management option for the second simulation under grassland in Lixisol was no herbivory; which is GL\_K grazing option; meaning there was low grazing intensity with no effect on production. The starting year for simulation was 2005 and last year was 2019, corresponding with the weather data.

## **4.7 Results**

### **4.7.1 Introduction**

The main aim of this chapter is to determine which land management option is suitable for improving soil ecosystem services. The first set of results wishes to answer objective one, which is to determine the amount soil organic carbon and nitrogen in grassland and cultivated land. The findings of SOC and nitrogen storage in different sites are presented. Secondly the grain size distribution and texture analysis for each soil type are presented to answer the second objective which is to determine the role of soil texture and grain size distribution in storing nutrients. Lastly the summary of each soil type condition during sampling period and DAYCENT carbon model outputs are presented to answer the third objective.

#### 4.7.2 SOC and nitrogen

SOC and nitrogen were analysed from Archaeology lab at the University of Cape Town. From the results it is apparent that grassland can store more carbon than cultivated land. Soil type also play a substantial role in storing carbon from grassland and cultivated land. According to Figure 4.8 and appendix 4.1, a Lixisol soil type in grassland 4 stored substantial carbon than the rest of other soil types with an average carbon of 1.23 g and maximum of 1.86 g stored from 0-2 cm to 20-30 cm depths. Luvisols in grassland 3 stored a significant amount following Lixisols, then Calcisol in grassland 2 and Arenosols stored the least carbon with an average of 0.18 g and maximum of 0.22 g from 0-2 cm to 30-45 cm depths. It is evident from the results that more carbon is stored from the topsoil layers (0-2 cm and 2-5 cm) (Appendix 4.1). Nitrogen also follows the same trend as carbon; high nitrogen is found in grassland and least nitrogen is found in cultivated land. Lixisol grassland stored more nitrogen with average nitrogen of 0.09 g stored from 0-2 cm to 20-30 cm and maximum of 0.12 g. Arenosols and Luvisols in cultivated land stored average of 0.02 and maximum of 0.03 g respectively. More nitrogen is stored in the top layer of grassland Lixisol (0.12 g). Arenosols cultivated land stored more nitrogen in the top layer 0-2 cm (0.03 g) and last layer 30-45 cm (0.03 g). These results provided evidence that soil type also plays a significant role in nitrogen storage, with Lixisol storing considerable nitrogen and Arenosols storing less nitrogen. SOM data is used as a baseline data for achieving the aim and is also one of the inputs for DAYCENT carbon model.

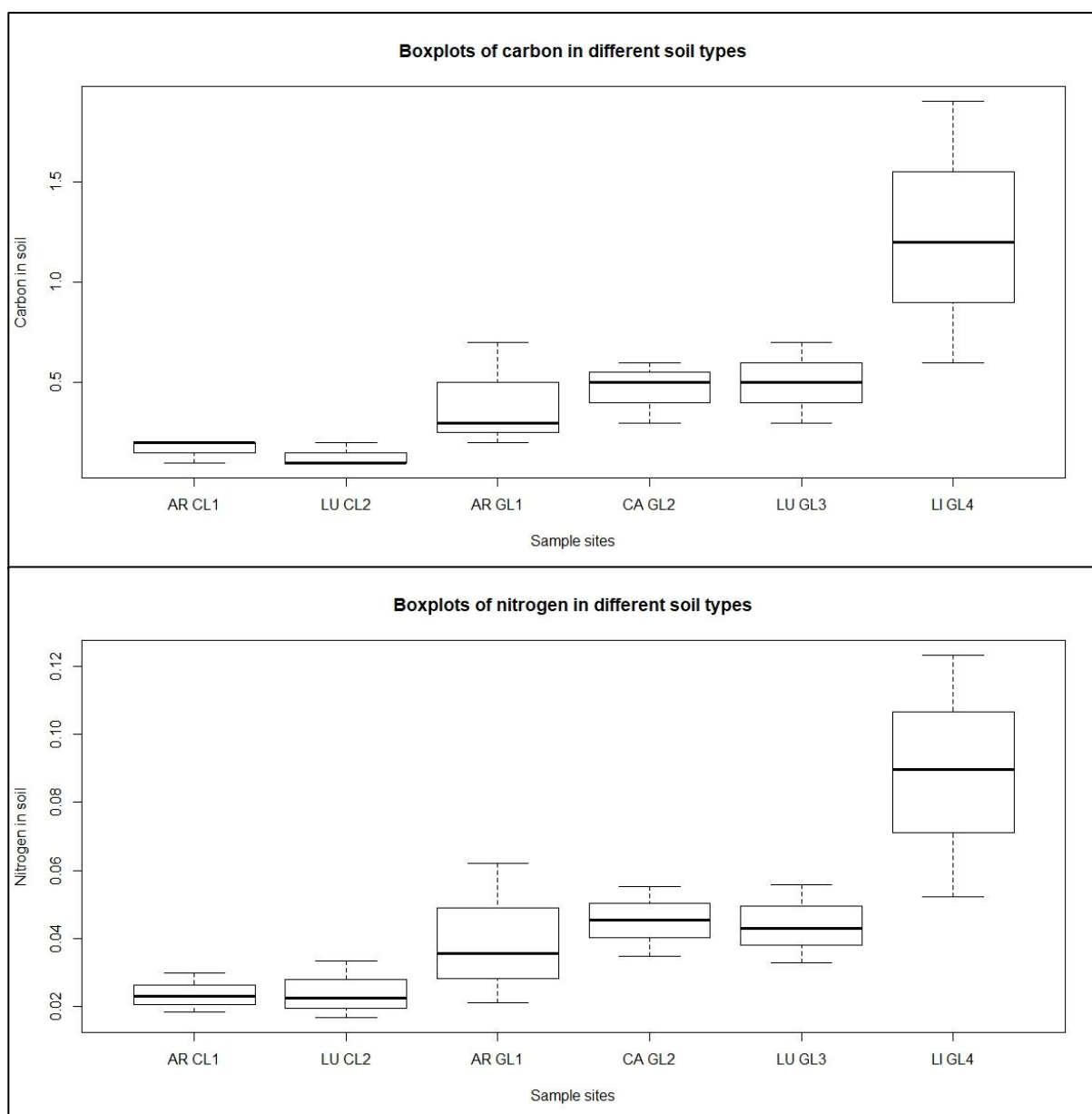


Figure 4.8: Amount of Carbon and nitrogen stored in cultivated land and grassland sites with different soil types Arenosols cultivated land 1 (AR CL1), Luvisols cultivated land 2 (LU CL2), Arenosols grassland 1 (AR GL1), Calcisol grassland 2 (CA GL2), Luvisols grassland 3 (LU GL3), and Lixisol grassland 4 (LI GL4). Top graph showing carbon and bottom showing nitrogen

Furthermore, relationship between Carbon and nitrogen in cultivated land and grassland sites was assessed (Figure 4.9). The results indicate that there is a strong relationship between carbon and nitrogen content ( $R^2 = 0.98$ ), an increase in carbon content also result in an increase in

nitrogen. However, there is general low carbon and nitrogen content in cultivated land as compared to grassland. This is because of the high soil disturbance in cultivated land as the land is constantly used for agricultural activities, whereas the grasslands are not frequently disturbed giving them the chance to accumulate more nutrients. These results rather agree with the results of Jones and Donnelly, (2004) which suggest that land management practices that remove the disturbance to soil C have the utmost impact on C sequestration.

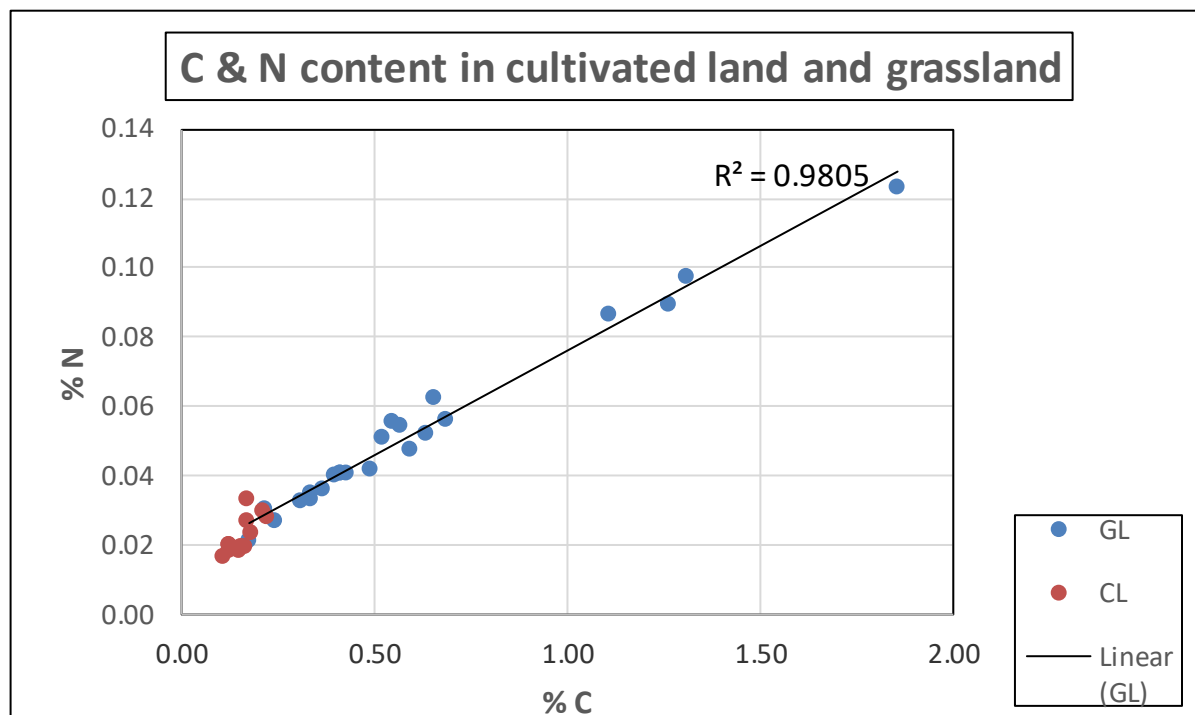


Figure 4.9: Amount of carbon and nitrogen content in cultivated and grassland sites

Figure 4.10 further presents which soil type can accumulate more carbon and nitrogen in sampled soils of Free State. Lixisol has indicated to accumulate more nutrients than the rest of the soil types average carbon of 1.23 and 0.09 of nitrogen, Arenosols average carbon of 0.18 and 0.02 of nitrogen and Luvisols in cultivated land have shown to accumulate the least nutrients, mainly due to continuous disturbance of the soil which leads to lot of nutrients being lost.

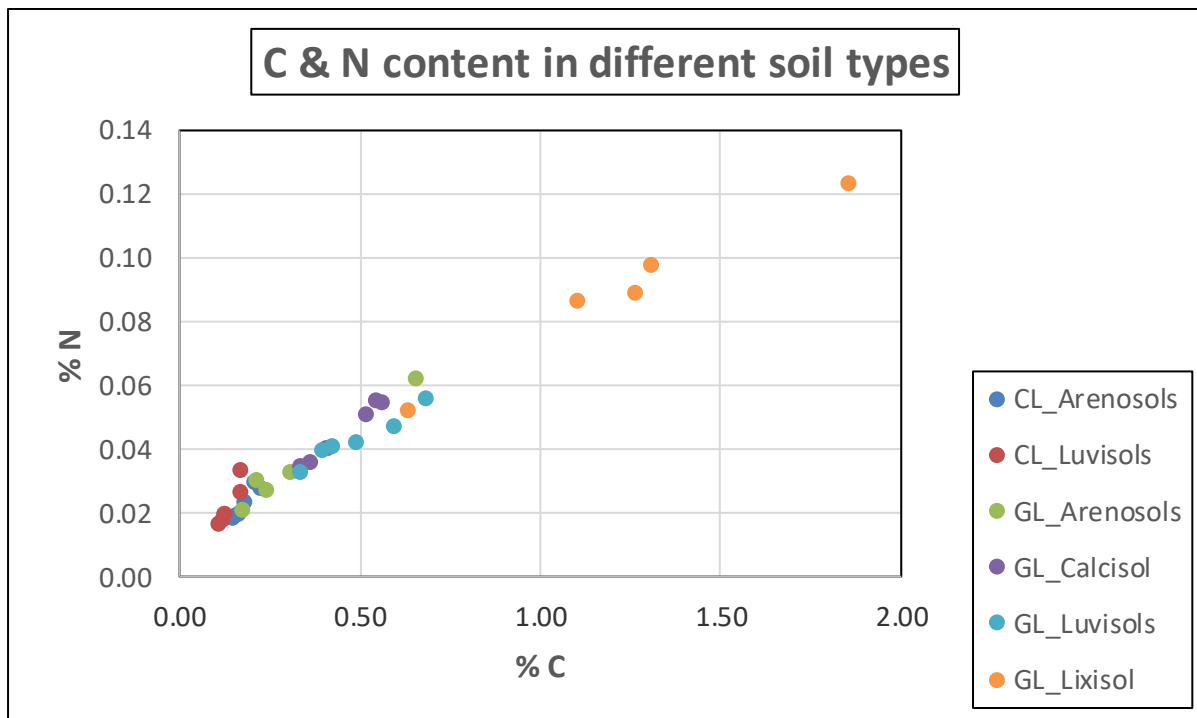


Figure 4.10: Amount of carbon and nitrogen in different soil types under cultivated and native grasslands

#### 4.7.2.1 Soil organic carbon isotopes

Figure 4.11 shows the standard corrected delta carbon 13 ( $^{13}\text{C}$ ) and carbon 12 ( $^{12}\text{C}$ ) differences in different soil sites with varying depths. Both  $^{13}\text{C}$  and  $^{12}\text{C}$  are stable isotopes, with  $^{13}\text{C}$  occurring naturally and  $^{12}\text{C}$  forming from the old degrading  $^{13}\text{C}$ . From Figure 4.11 it is apparent that there is a decrease in the ratio with increasing depth in all soil types. This shows that the deeper in the soil, the older the SOC. The smaller the ratio, the older the C at that depth. The ratio gets smaller as the  $^{13}\text{C}$  degrades. It is observed that in almost all cases, the deeper samples had older carbon (30-45 cm). This is where carbon would consequently be stored for longer, however generally there is relatively little carbon at that depth.

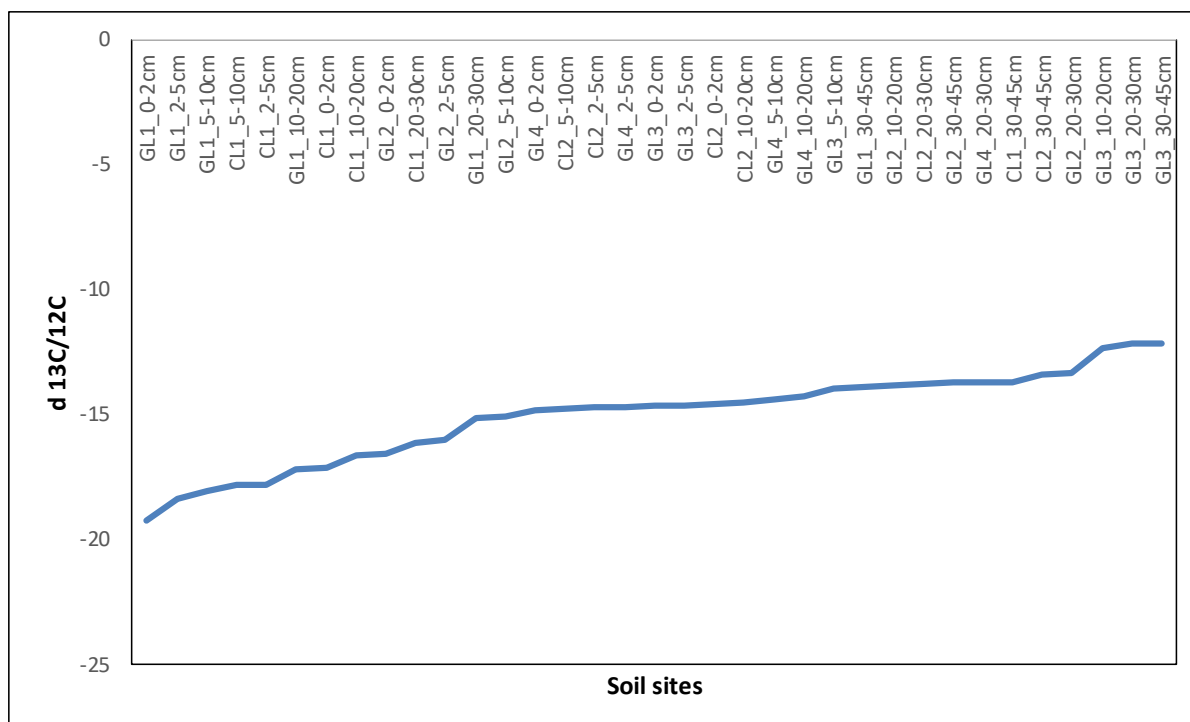


Figure 4.11: Standard corrected delta carbon 13 (<sup>13</sup>C) and carbon 12 (<sup>12</sup>C) in different soil sites

Figure 4.12 indicates the standard corrected delta <sup>13</sup>C /<sup>12</sup>C versus C:N ratio. Arenosols grassland is more clustered between (-16 and -20) with the C:N ratio between (8 and 11) and cultivated land between (-15 and -18) with the C:N ratio between (7.5 and 8.5). This means as <sup>13</sup>C /<sup>12</sup>C ratio increases the new the SOC and decrease in <sup>13</sup>C /<sup>12</sup>C the old the SOC. It is evident that Arenosols is dominated by new SOC stored in shallow depths. This is due to the continues use of the land for agricultural activities. Regular tilling of the surface by ploughing disturbs the microbes and uses up the older carbon, so it does not get stored effectively. However, minimum till or no-till can reduce this effect. Carbon isotopes in Luvisols cultivated land are clustered between (-13 to -15) and the C:N ratio is between (4 and 8), whereas in Luvisols grassland carbon isotopes are clustered between (-11 and -15) <sup>13</sup>C /<sup>12</sup>C with C:N ratio between (9 and 13). This again indicates that cultivated land in Luvisols has newer SOC stored in shallow depths as compared to grassland. Luvisols grassland has an older SOC stored deeper in the soil. These results indicate that carbon stored in Calcisol is older than carbon stored in Arenosols, but smaller than the one in Luvisols and Lixisol grasslands. Lixisol grassland has relatively the oldest carbon stored in the deeper soils as compared to the rest of the soil types.

This is mainly because the Lixisol are not likely to be used for agricultural activities, thus they always in their natural state. Generally, these results give confidence that carbon can substantial be stored effectively in grassland especial in the deeper soil depths.

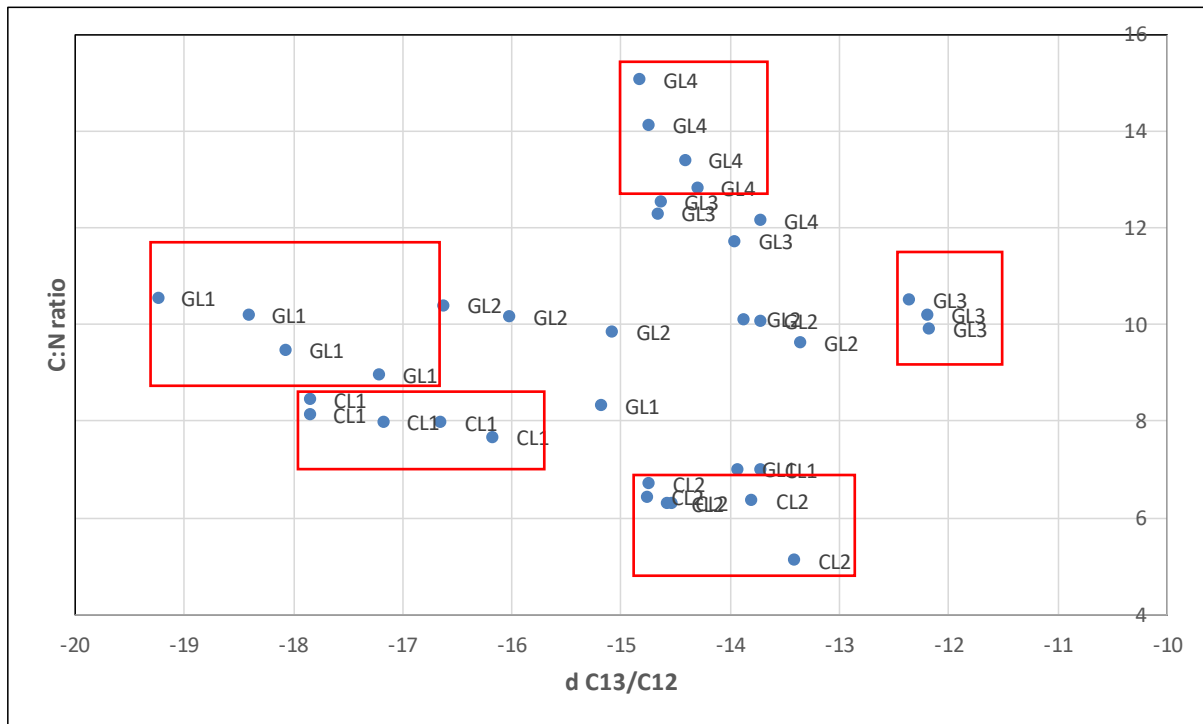


Figure 4.12: Relationship between the standard corrected delta  $^{13}\text{C} / ^{12}\text{C}$  and C:N ratio in soil samples with different soil types, Bultfontein, Free State

#### 4.7.3 Soil texture and grain size distribution

Malvern Mastersize 2000 was used to analyse the soil particle distribution of different soil types at different depths. Figure 4.13 illustrates the particle size distribution of each soil type at different sites. All the graphs follow a similar trend with a sharp peak in particle diameter at 70-90  $\mu\text{m}$  range. Approximately 60% of the soil particles from each soil type and site have a diameter that range between 70-90  $\mu\text{m}$ . This means the soils are sandier, as the bigger the particle diameter is the coarser the soil becomes. It is evident from the graphs that the deeper the soil the finer the soil particles (e.g., CL1 30-45 cm and CL2 30-45 cm). The graphs are a unimodal, bimodal, trimodal and polymodal. This is an indication that particle sizes are



unevenly distributed from each depth; in a certain soil range a unimodal distribution is observed and in another soil range of the same site a bimodal distribution is observed.

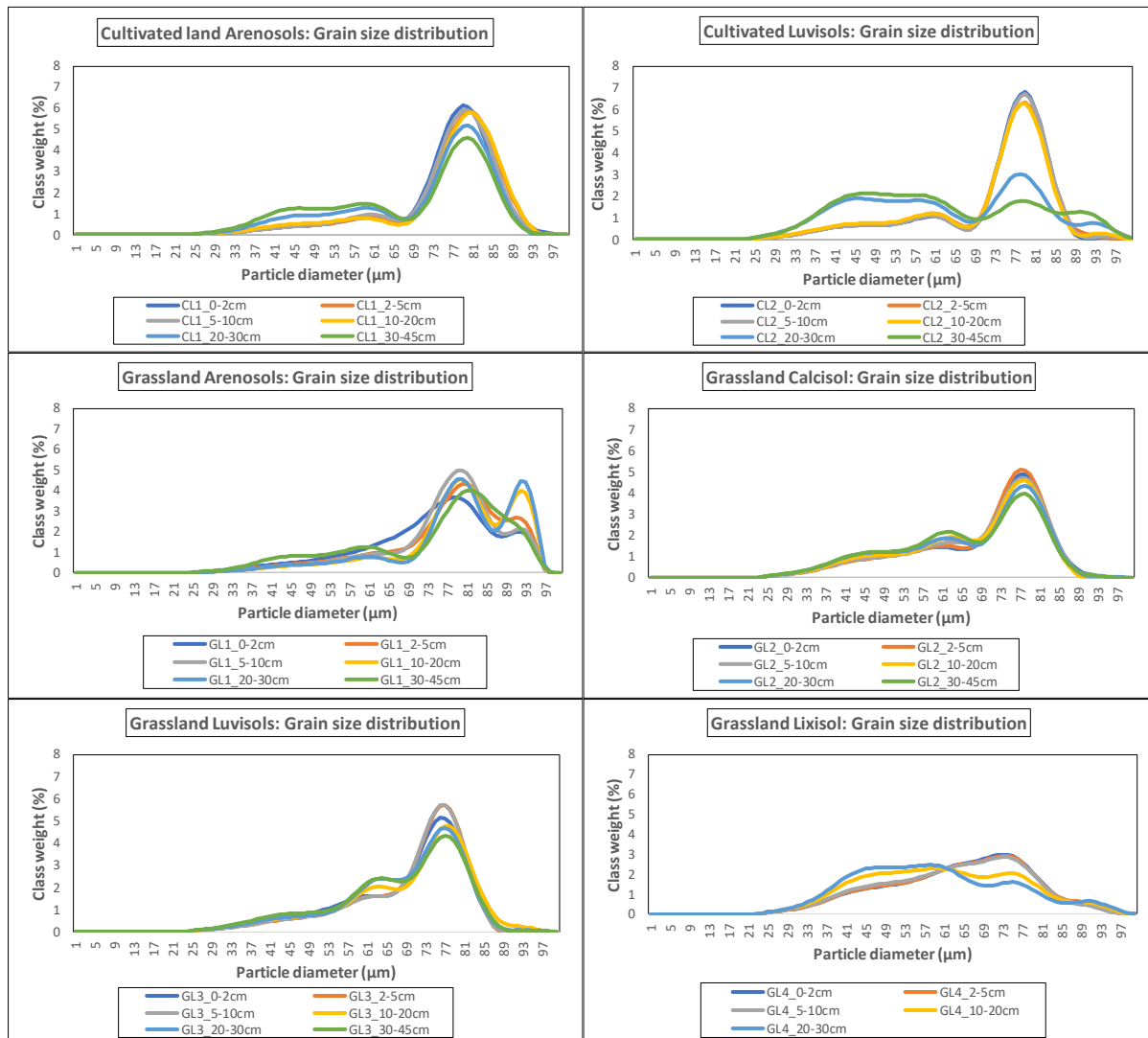


Figure 4.13: Grain size distribution in cultivated and grassland sites with different soil types.

Each soil sample was further analysed for texture using GRADISTAT and the triangular diagram for sand-silt-clay is presented in Figure 4.14. The triangular diagram indicates that soil samples fall under two categories: the silty sand and sandy silt (Figure 4.14). The Arenosols in cultivated land consists of 80% sand, 18% silt and 2% clay. Luvisols in cultivated land consists of 75% sand, 22% silt and 3% clay. Arenosols in grassland has 68% sand, 29% silt and 2%

clay. Calcisol in grassland consist of 60% sand, 36% silt and 4% clay. Luvisols grassland has 60% sand, 36% silt and 4% clay and Lixisol in grassland has 40% sand, 54% silt and 6% clay. More carbon was observed to be stored in soils with moderate sand content (Lixisols = 40 % of sand) and high silt content (Lixisols = 54 % of silt) and less carbon was stored in soils with high sand content (Arenosols = 80 % of sand) and moderate silt content (18 %). Generally, the soils in Free State are observed to be sandier and less clay. The texture data was also required as input for the DAYCENT carbon model.

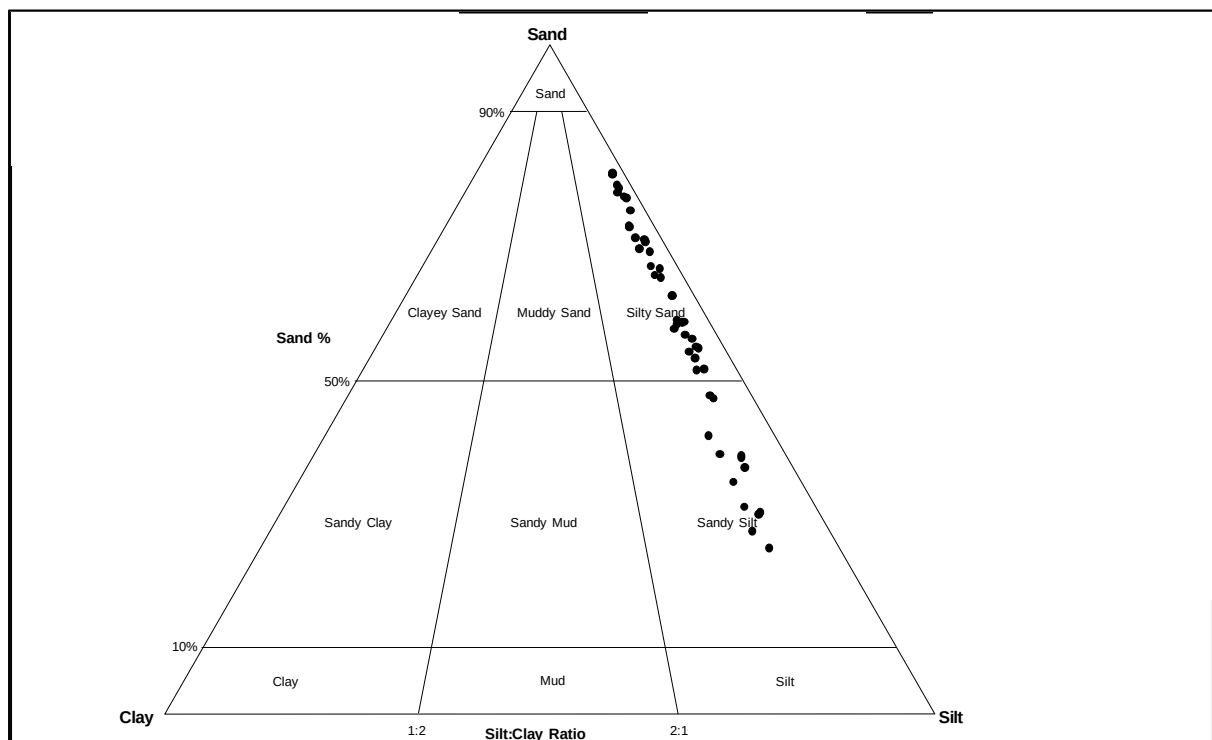


Figure 4.14: Sand silt clay diagram for different soil types at different sampling sites in Free State

Figure 4.15 indicates the ratio of sand, silt, and clay in different soil types. It is apparent that Arenosols both in cultivated and grassland has high sand content compared to the other soil types, followed by Luvisols, Calcisol and Lixisol respectively. Lixisol has high content of silt, followed by Calcisol, Luvisols and Arenosols respectively. Moreover, Lixisol is characterised by high clay content than the other soil types, followed by Calcisol. This brings to attention why these soil types are not mostly used for agricultural activities, as soils with high clay

content are generally not suitable for ploughing, however they tend to retain a lot of nutrients since they are always in their native state. These soil types are less prone to soil erosion since there is minimal disturbance in them.

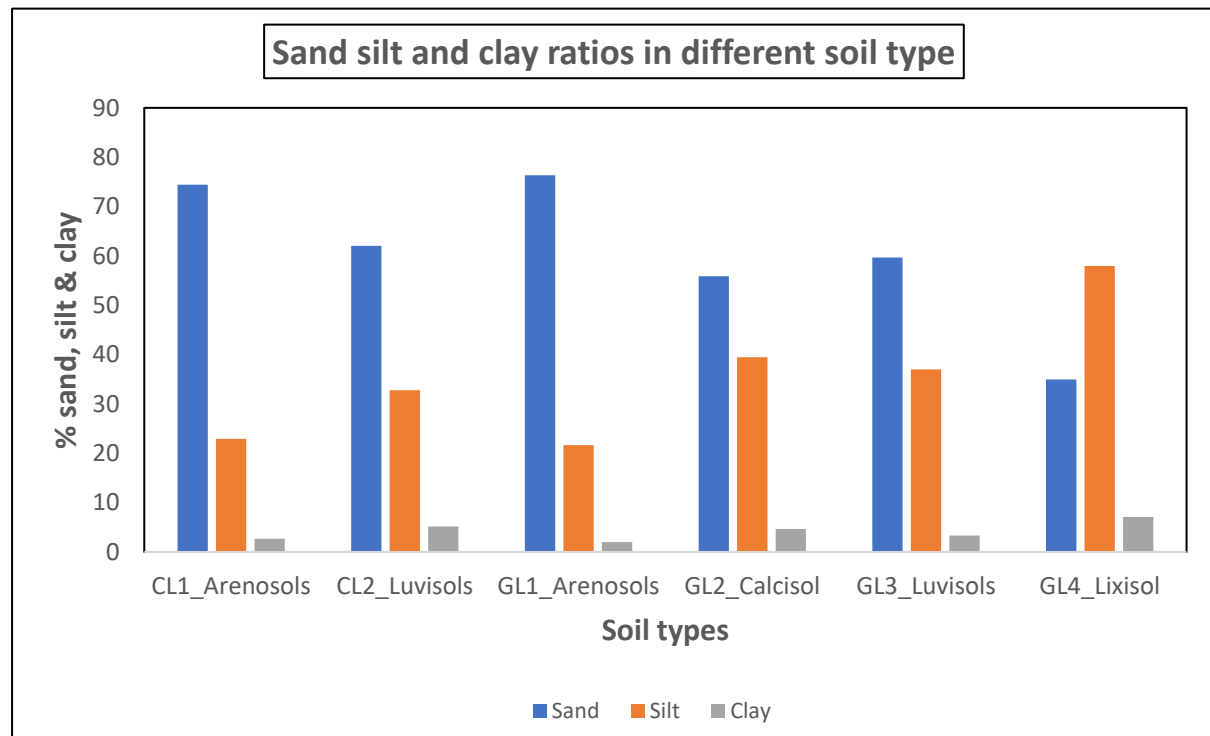


Figure 4.15: Sand, silt, and clay ratios in different soil types of Bultfontein

#### 4.7.4 Land management options

Four different soil types in Bultfontein were sampled: Arenosols, Luvisols, Calcisol and Lixisol. Arenosols and Luvisols have two sampling sites (i.e., Cultivated land and native grassland), which makes the sampling sites six. The table below summarize each soil type under the different land management options.

Table 4.3: Summary of soil types under two management options

| Type of soil | Cultivated land                                                                                                                                                                                  | Native grassland                                                                                                                       |
|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Arenosols    | <ul style="list-style-type: none"> <li>• Soil is relatively loose (sandier)</li> <li>• Bare cultivated land</li> <li>• During sampling time (03 Sep 2019), there were crop residue</li> </ul>    | <ul style="list-style-type: none"> <li>• Soil is intact</li> <li>• Native grassland</li> <li>• The grass was minimal grazed</li> </ul> |
| Luvisols     | <ul style="list-style-type: none"> <li>• Soil is relatively loose (sandier)</li> <li>• Bare cultivated land</li> <li>• During sampling time (03 Sep 2019), there were no crop residue</li> </ul> | <ul style="list-style-type: none"> <li>• Soil is intact</li> <li>• Native grassland</li> <li>• The grass was minimal grazed</li> </ul> |
| Calcisol     | <ul style="list-style-type: none"> <li>• No cultivated site</li> </ul>                                                                                                                           | <ul style="list-style-type: none"> <li>• Soil is intact</li> <li>• Native grassland</li> <li>• The grass was minimal grazed</li> </ul> |
| Lixisol      | <ul style="list-style-type: none"> <li>• No cultivated site</li> </ul>                                                                                                                           | <ul style="list-style-type: none"> <li>• Soil is intact</li> <li>• Native grassland</li> <li>• The grass was minimal grazed</li> </ul> |

#### 4.7.4.1 DAYCENT and MODIS PsnNet

Figure 4.16 shows the net primary production (NPP) of grassland with and without herbivory in four different soil types. From the four soil types it is apparent that if a constant herbivory is applied the NPP from DAYCENT would initial increase approaching the MODIS PsnNet levels, and then starts decreasing until it is below MODIS PsnNet. The decrease in NPP is likely to occur if regular herbivory is applied in a grass. These results indicate what the possible carbon paths will be given these land use scenarios. The system will reach an equilibrium in storing carbon beyond which these land use scenarios will keep both soil organic carbon and above-ground carbon stock at a constant level. These results match with the results from other studies. Lobe et al., (2001), observed that soils do reach equilibrium in storing carbon with concentrations of organic C reach equilibrium after 34 years for the bulk soil and after 55 years for clay-size separates.

The no herbivory scenarios show a DAYCENT NPP initial increase that is close to MODIS levels in the first few years, however the DAYCENT NPP decreases over the years. This trend is possible because when the system become moribund, the grass does not grow infinitely but rather dies, therefore when the grass stops growing organic matters are not stored. Above ground biomass (AGB) was used to validate the accuracy of DAYCENT and MODIS outputs. The results indicate that DAYCENT and MODIS outputs underestimate the NPP as compared to AGB. However, the AGB results are likely to be biased due to study limitations which include not being able to clip the grass at the beginning of the growth cycle.

CHIRPS was also plotted on the MODIS and DAYCENT outputs (Figure 4.16). From these land management scenarios CHIRPS showed to be initially higher than MODIS and DAYCENT, however from 2012 CHIRPS started decreasing until it was below MODIS levels. MODIS and DAYCENT outputs also showed a decline during the years in which CHIRPS was low. This indicates that precipitation is one of the factors that are crucial for plant growth. In a study by (Xiaojia Li et al., 2011) it was observed that precipitation and soil organic matter are vital for plant growth, this is evident in this study as well.

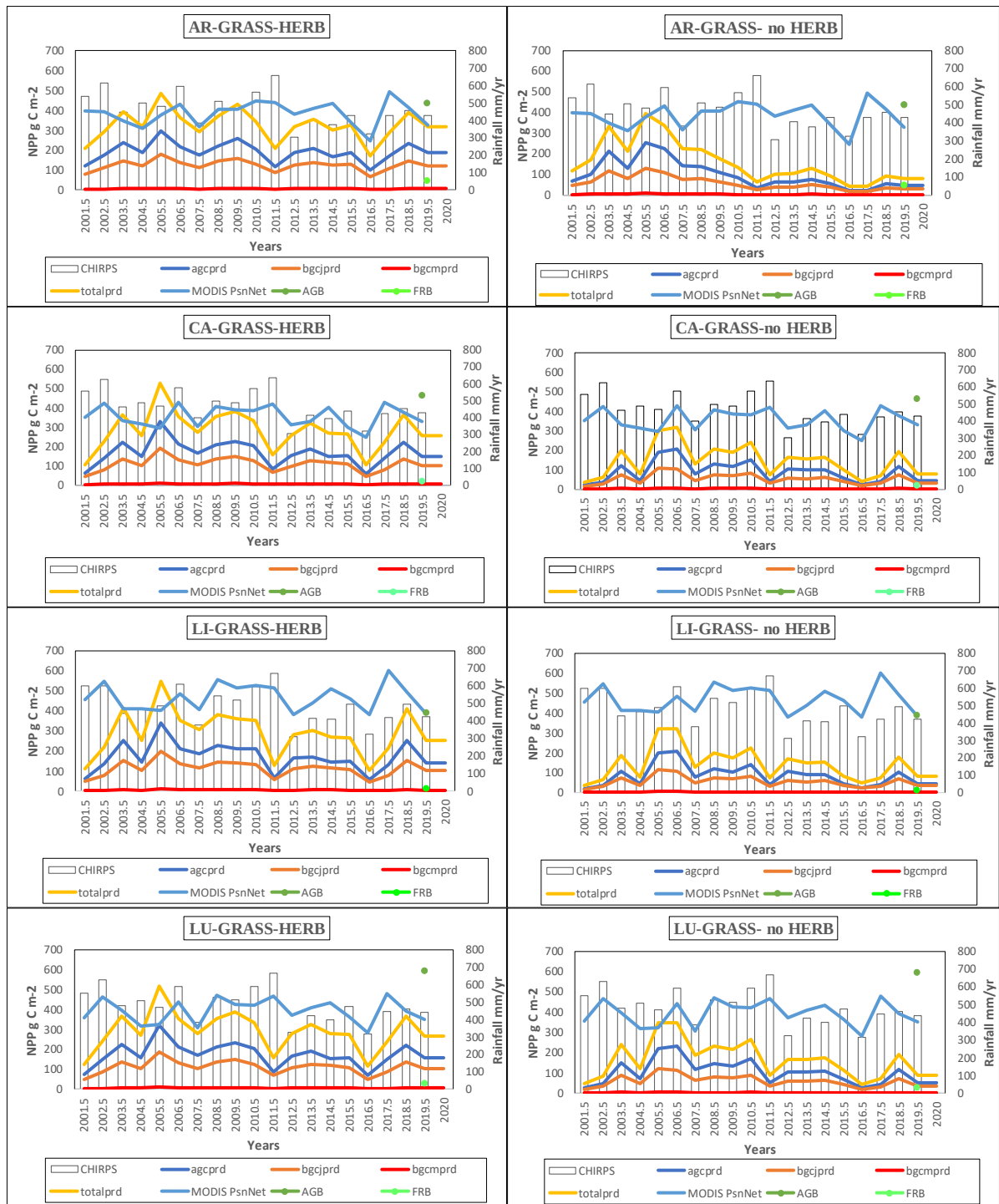


Figure 4.16: Net primary production of grassland with and without herbivory in four different soil types and CHIRPS data from 2001-2020 in Free State, South Africa

Figure 4.17 shows the net primary production (NPP) of cultivated land with herbivory in two different soil types. From the Arenosols cultivated land it is apparent that if cultivation continues and a constant herbivory is applied the NPP from DAYCENT would initial increase approaching the MODIS PsnNet levels, and then the DAYCENT NPP would reach an equilibrium and become constant around 350 g C m<sup>-2</sup>/year. From the Luvisols cultivated land it is apparent that if cultivation continues and a constant herbivory is applied the NPP from DAYCENT would initial increase approaching the MODIS PsnNet levels and remain above MODIS PsNet and become constant around 350 g C m<sup>-2</sup>/year. Generally, there is no significant variation between the NPP of DAYCENT and MODIS PsnNet. The maize yields in Arenosols also match with MODIS PsnNet and DAYCENT outputs. An increase in NPP is expected during the first few years as the soil is still rich in nutrient content, however the continuous use of soil for agricultural purposes results in nutrient deficiency. SOC decreases if cultivation continues. Lobe et al., (2001) illustrates that the SOC attached to soil becomes lost when cultivation continues. Conventional till and fallow lands are the major causes of carbon decrease. West and Post, (2002) argue that more carbon can be stored if farmers can move to no till, reduce fallow lands, or fallow periods and convert cultivated land to grassland. These results therefore indicate what the possible carbon paths will be given these land use scenarios; the soils will lose more carbon and store less due to being continuously disturbed. The cultivated land will become a source of atmospheric carbon rather than being a sink.

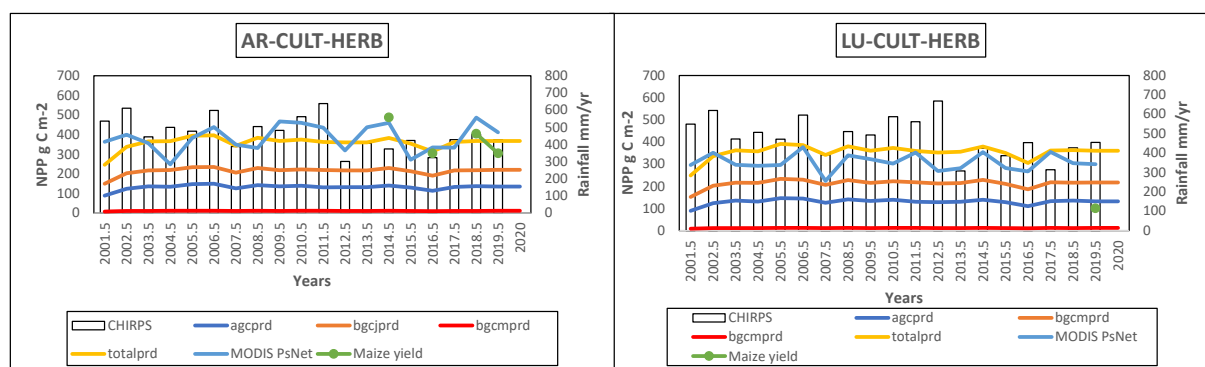


Figure 4.17: Net primary production of cultivated land with herbivory in two different soil types and CHIRPS data from 2001-2020 in Free State, South Africa

Aboveground primary net productivity of the grassland sites in Free State has been compared with the results of the other studies (Table 4.4). The AR-GRASS AGB (433 g DM m<sup>-2</sup>/year) and CA-GRASS AGB (462 g DM m<sup>-2</sup>/year) were not significantly different from the AGB predicted by (Everson & Everson, 2016) (471 g DM m<sup>-2</sup>/year) even though they were slightly lower. The LI-GRASS AGB (388 g DM m<sup>-2</sup>/year) was not significantly different from AGB obtained by (Gwate, 2017) in three sites ( 324 g DM m<sup>-2</sup>/year, 348 g DM m<sup>-2</sup>/year and 314 g DM m<sup>-2</sup>/year). LU-GRASS had the highest AGB (593 g DM m<sup>-2</sup>/year) than all the other sites from the present study and other studies compared with. Generally Free State, Bultfontein had high AGB predictions in the four sites as compared to other studies. However, these results are likely to be biased because the grass was not clipped at the beginning of the growth cycle, therefore the AGB was probably the accumulation of more than one year.

Table 4.4: Predicted annual dry matter production (g DM m<sup>-2</sup>/year) using canopy cover and DPM method.

| Site                            | Location                 | *MAR<br>(mm) | **DPM<br>method              | Line intercept<br>(Flombaum &<br>Sala 2006) |
|---------------------------------|--------------------------|--------------|------------------------------|---------------------------------------------|
|                                 |                          |              | ++ANPP g<br>+DM m-2/<br>year | ++ANPP g +DM<br>m-2/ year                   |
| Quaternary S50E (Gwate<br>2017) | 31°40'41 S<br>27°35'12 E | 772          | 324                          | 314                                         |
| Quaternary T12A (Gwate<br>2017) | 31°31'25S<br>27°45'27E   | 655          | 270                          | 283                                         |
| Quaternary T35B (Gwate<br>2017) | 31°04'05 S<br>28°17'34E  | 786          | 348                          | 288                                         |
| Combined (S50E, T12A &<br>T35B) | (see above)              |              | 314                          | 290                                         |



|                                                            |                         |            |     |     |
|------------------------------------------------------------|-------------------------|------------|-----|-----|
| Danckwerts & Trollope (1980, grazed trial)                 | 32°42'05 S<br>26°27'18E | 409        | 252 | N/A |
| O'Connor (2008, grazed commercial and communal rangelands) | 29°45'01 S<br>29°33'07E | 893        | 292 | N/A |
|                                                            | 29°49'01 S<br>29°37'57E | 862        | 244 | N/A |
| Everson & Everson (2016, biennial burnt)                   | 28°56'17 S<br>29°15'41E | 880        | 471 | N/A |
| Ndovela (2014, un-grazed burning trial)                    | 32°32'28 S<br>27°27'47E | 680        | 254 | N/A |
| AR-GRASS                                                   | 28°15'87S<br>26°06'62E  | ***45<br>9 | 433 | N/A |
| CA-GRASS                                                   | 28°20'36S<br>25°90'78E  | 459        | 462 | N/A |
| LI-GRASS                                                   | 28°34'03S<br>26°73'53E  | 459        | 388 | N/A |
| LU-GRASS                                                   | 28°28'97S<br>26°02'47E  | 459        | 593 | N/A |

\*Mean annual rainfall, \*\*Disk pasture meter, <sup>+</sup>Dry matter, <sup>++</sup>Aboveground primary net productivity, \*\*\*FS MAR (Lynch, 2004)

Additionally, the NPP of grassland with and without herbivory for 2019 only is presented in Figure 4.18, showing the total amount of carbon stored in that year. The soil samples and grassland biomass validation data were collected in 2019 for the study. Above ground biomass (AGB) for both grassland herbivory and no herbivory scenarios are higher than DAYCENT NPP and MODIS PsnNet outputs for 2019. The AGB results are likely to be biased because the accumulation of carbon is not for one year, since the grass was not clipped at the beginning

of the growth cycle, meaning the accumulation was possible over one year hence the AGB is high. Predicted AGBs in some South African grassland studies Everson & Everson, (2016); Gwate, (2017); O'Connor, (2005) were slightly lower than the predicted AGB in Free State grasslands.

The fine root biomass results indicated that AR-GRASS can accumulate more carbon than all the other soil types (44.93 g DM m<sup>-2</sup>/year) followed by LU-GRASS (24.37 g DM m<sup>-2</sup>/year), CA-GRASS (17.74 g DM m<sup>-2</sup>/year) and LI-GRASS (8.36 g DM m<sup>-2</sup>/year) respectively. However, these levels are generally very low as compared to the levels of fine root biomass storage from other studies. According to Li et al., (2011) root biomass was estimated to be 1381.41 ± 245.29 g m<sup>-2</sup> in the top 20 cm soil, accounting for 85 % of the total root biomass. Jackson et al., (1996) and Macinnis-Ng et al., (2010) studies presented that the total fine root biomass contributed about 1 kg m<sup>-2</sup>. Based on these studies it is thus evident how low the fine root biomass is in the grasslands of the Free State. The Free State soils are very much disturbed due to agricultural activities taking place in the area. The continuous disturbance in the soil can consequently lead to low carbon storage by the soil. Lobe et al., (2001) argued that continuing cultivation or disturbance of natural grassland reduce soil C and N concentrations by 65 and 55 %, respectively. These findings agree with the findings of the present study.

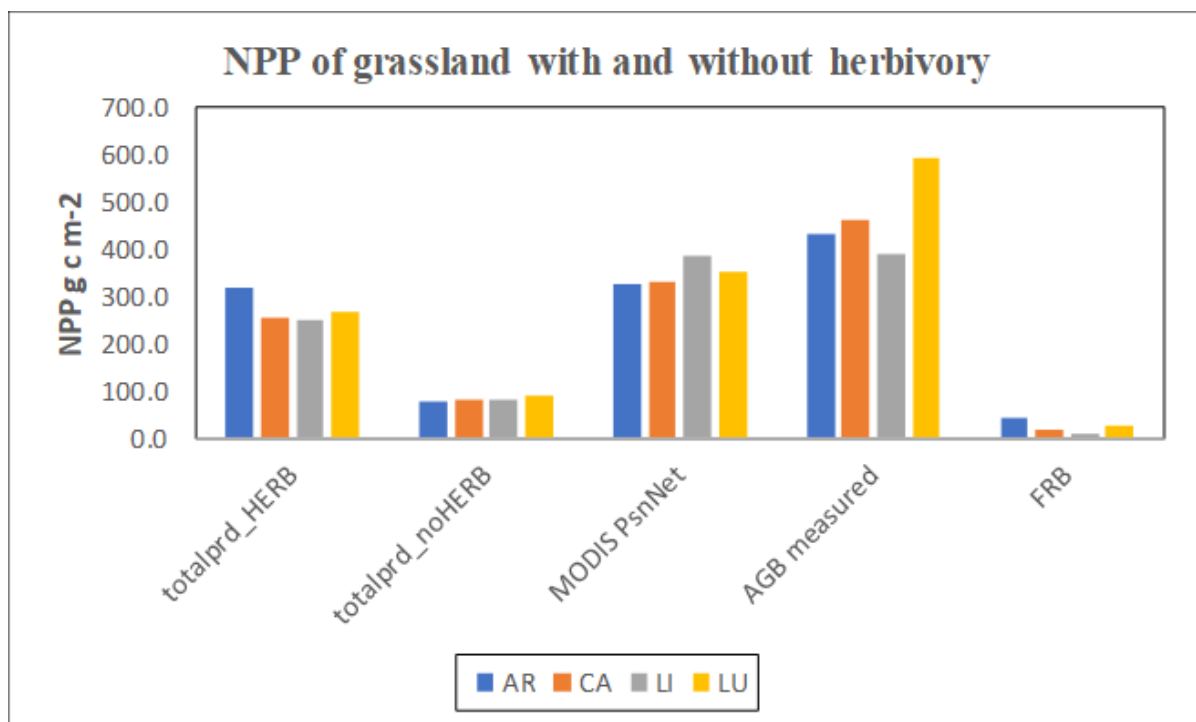


Figure 4.18: Net primary production of grassland with and without herbivory in four different soil types; Arenosols (AR), Calcisol (CA), Lixisol (LI) and Luvisols (LU) in 2019

The NPP of cultivated land with herbivory for 2019 only is illustrated in Figure 4.19, showing the total amount of carbon stored in that year. The NPP is compared with maize yields to validate the accuracy of DAYCENT and MODIS PsNet models. AR-Cult accumulated 246 g c m-2 of carbon in 2001 and increased to 396 g c m-2 maximum in 2006 and never went below 300 g c m-2 again. LU-Cult accumulated 248 g c m-2 of carbon in 2001 and increased to 391 g c m-2 maximum in 2005 and never went below 300 g c m-2 again. In comparison, NPP for cultivated land with herbivory in 2019 is slightly higher than the NPP for grassland with herbivory in both Arenosols and Luvisols, however the difference is not significant. The grassland is used to graze livestock; therefore, overgrazing might be the reason the grassland NPP is slightly lower than cultivated land NPP in 2019. Overgrazed land is characterized by patches of grass which will absorb less carbon than if the land was covered with good vegetation.

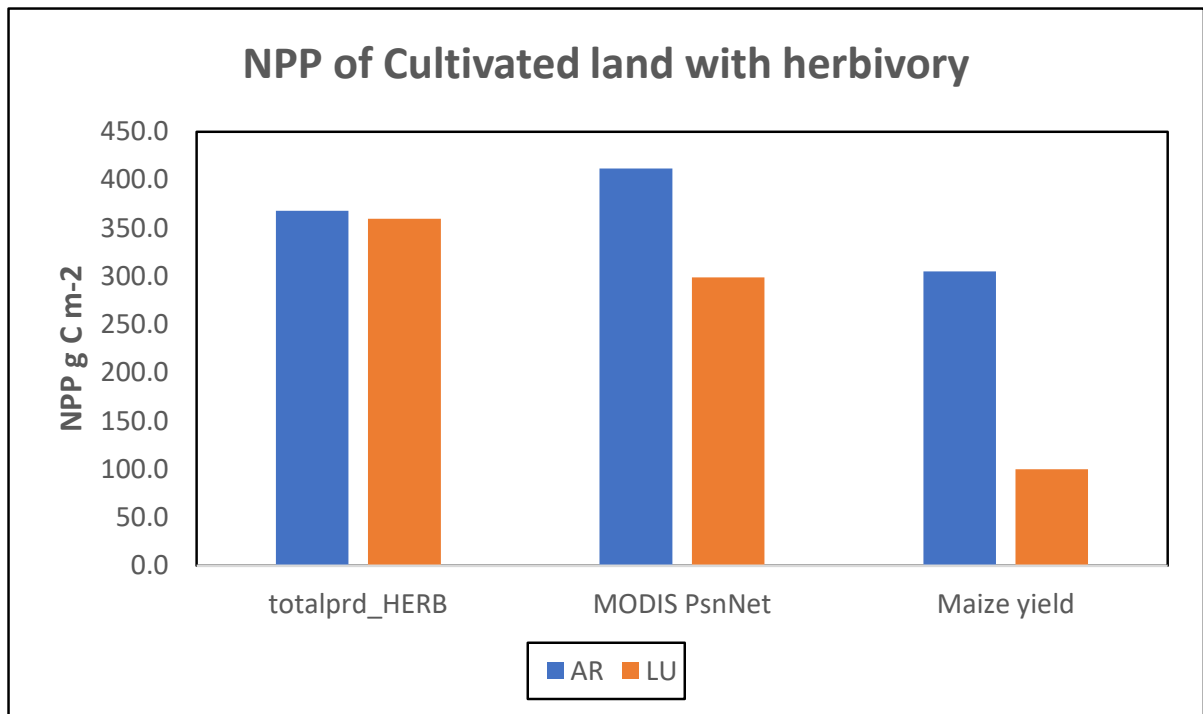


Figure 4.19: Net primary production of cultivated land with herbivory in two different soil types; Arenosols (AR) and Luvisols (LU) in 2019.

Figure 4.20 shows the distribution of fine root biomass across the different soil depths in four soil types. The AR-GRASS accumulated more carbon than any other soil types, followed by LU-GRASS, CA-GRASS, and LI-GRASS respectively. The results indicate that high fine root biomass was stored from 2-20 cm depths. The fine root biomass decreased with an increase in soil depth. These findings comparatively match the findings from other studies (Jackson et al., 1996; Xiaojia Li et al., 2011).

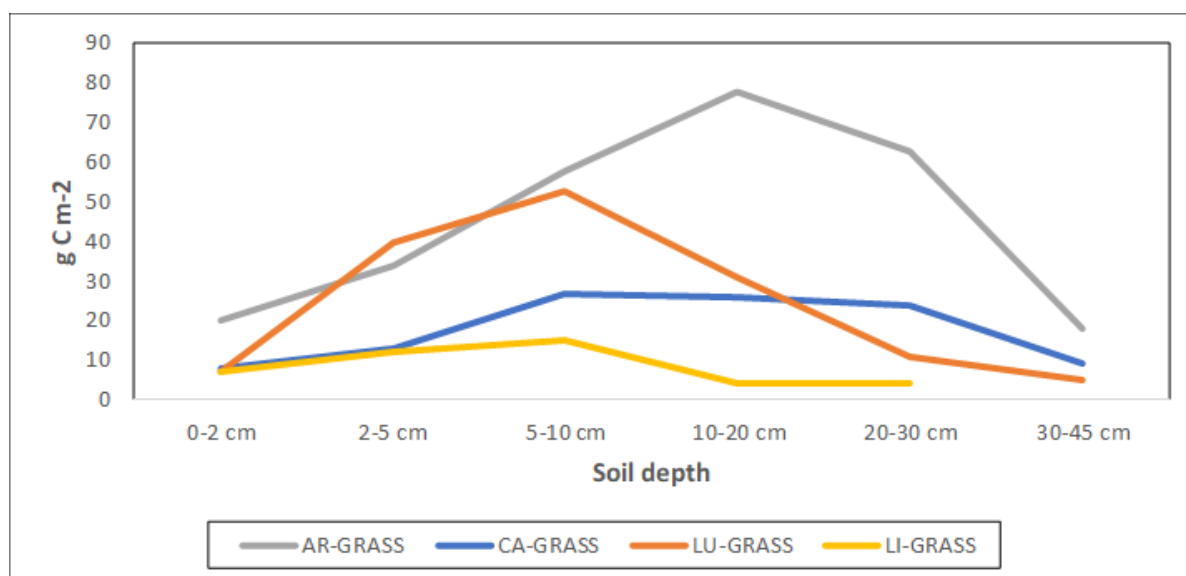


Figure 4.20: Distribution of fine root biomass across the different soil depths in different soil types; Arenosols grassland (AR-GRASS), Calcisol grassland (CA-GRASS), Luvisols (LU-GRASS) and Lixisol (LI-GRASS).

## 4.8 Discussion

### 4.8.1 Factors contributing to the storage and distribution of SOC

Findings illustrated that Free State grassland can store more carbon than cultivated land. These results are rather in agreement with Jones et al., (2005) who found that land management practices that leads to excessive disturbance of C sequestration have less carbon stored. There is reduced disturbance in Free State grassland, whereas cultivated lands are frequently disturbed hence they store less carbon. There are several other factors that contribute to accumulation of SOC besides the land cover or land use and those include: soil type, soil texture, aboveground biomass, and fine root biomass. These factors were critical analysed and seemingly they play a meaningfully role in accumulation of SOC. It is apparent from soil samples collected in 2019 that Lixisol which are high in silt content can store more carbon than the other soil types and Arenosols which are high in sand content can store the least carbon (Figure 4.8). A study done by Hartemink & Huting, (2008) noted that organic carbon is consistently low in Arenosols of Southern Africa and hardly exceeds  $10 \text{ gKg}^{-1}$ . This is mostly

because Arenosols are widely used for agricultural activities which then take up the carbon in the soil.

High carbon contents are found in soils with slightly higher clay content, and also high levels of carbon are associated with higher cation exchange capacities (Hartemink & Huting, 2008). Webb et al., (2013) observed that sandy soils and finer particulate quarte-rich soils are more efficient at SOC losses. The observation from these studies matches the findings of the present study. Above ground biomass (AGB) and fine root biomass are evident to also contribute significantly to the accumulation of SOC. DuPont et al., (2010) detected that under annual crops root biomass was less than half that of perennial grasslands, suggesting that large root-derived energy sources may contribute to composition of soil biota and accumulation of soil carbon. The distribution of root biomass further contributes to accumulation of carbon. An investigation on root biomass distribution done by Li et al., (2011) indicated that roots are mainly concentrated in the 0-20 cm layer and the root biomass decrease exponentially with increase in soil depth. The current study also observed the similar trend (Figure 4.18) where more roots are concentrated in 0-20 cm depth and in return more carbon was stored in these depths.

#### **4.8.2 Establishing suitable land management options for storing more carbon**

DAYCENT was used to simulate soil C in cultivated land with herbivory, grassland with herbivory and no herbivory. It is evident that native grassland can substantially store carbon, however moderate grazing should be applied. According to the results when herbivory is not applied the system eventually dies and therefore nutrients do not get stored. This explains the decrease of NPP in Figure 4.16. Even though grassland can store relative huge amount of carbon, there is evidence that they do not infinitely store carbon but rather reaches an equilibrium. When the land is being converted from conventional tillage to no tillage, a peak in carbon sequestration rates can be expected in 5 to 10 years with SOC reaching a new equilibrium in 15 to 20 years (West & Post, 2002). Lobe et al., (2001) also observed that soils do reach equilibrium in storing carbon with concentrations of organic C reach equilibrium after 34 years for the bulk soil and after 55 years for clay-size separates. NPP accumulated in cultivated land is slightly lower than NPP accumulated in grassland. These results match with other studies; Jiao et al., (2009) noted that converting grassland to cropland has made SOC to

decrease in the 0-30 cm soil depths and this is evident in the present study. Del Grosso et al., (2002) successfully used DAYCENT and found that dry soils that are depleted of carbon due to conventional till can store carbon when converted to no till by of course decreasing the fallow period or reversing to natural grassland. These findings were also observed in several other studies which provides evidence that restoring land to native grassland should be a priority in order to sequester more carbon (DuPont et al., 2010; Jian et al., 2020; Loke et al., 2019; West & Post, 2002). These studies provide confidence to the hypothesis of the present study that strategic changes in land management and land use in the western Free State can contribute to accumulation of SOC and further contribute to international obligations to carbon sequestration. In summary, grassland with moderate grazing that has low effect in production has the potential to store more carbon. This land management option is essential as carbon sequestration has been observed to reduce carbon in the atmosphere, which in turn reduce the effects of greenhouse gas that leads to global warming, and which leads to climate change.

#### **4.9 Conclusion**

This chapter aimed to determine which land management option is suitable for storing more carbon, and three objectives were derived to achieve the aim. The first objective was to determine the amount of carbon and nitrogen in the western Free State LC. To achieve this objective the soils sampled in 2019 from different sites in Free State were used. Results have showed that grassland can store more carbon than cultivated land. The cultivated land in Free State is mainly in the Arenosols and Luvisols and grassland is mainly in Calcisols and Lixisols. Studies have shown that Arenosols can also store more carbon like other soils if they are not continuously disturbed. Evidence shows that in Free State these types of soils are excessively used for agricultural purposes resulting to loss of more carbon to the atmosphere. Lixisols and Calcisols are shown to be used for grassland with reduced disturbance of C sequestration resulting to more carbon stored. The study then concluded that grassland can potentially store more carbon than cultivated land due to reduced disturbance.

The second objective was to determine the role of soil texture and grain size distribution in storing nutrients. To answer this objective again the soils sampled in 2019 from different sites in Free State were analysed using Malvern Mastersizer 2000. Based on the results it was apparent that soil texture plays a vital role in storing carbon. The results illustrated that silt sand

soils store more carbon than sand silt soils. The findings of this objective builds to the findings of the first objective which showed the LC and soil type that has a potential to store more nutrients. Results indicated that Lixisols have the high silt content and Arenosols have high sand silt content and Lixisols were observed to store more carbon and Arenosols to store less carbon. Generally, soils with high sand content are used for cultivation and this means these soils are regularly disturbed, thus they are observed to store less nutrients than soils with high silt content which are mostly used for grassland. Results further showed that more carbon is stored in top layers of soil and decrease with increasing depth. Grass roots are found in the top layers (0-2 cm and 2-5 cm) of the soil which explains why more carbon is stored in these depths, whereas with cultivated lands carbon gets used by plants during respiration. These findings match with other studies which found that organic carbon is consistently low in Arenosols of Southern Africa because of their regularly disturbance. The present study then concluded that soils with high silt content can accumulate more carbon because of being less disturbed whereas soils with high sand content mostly store less carbon because of their regularly disturbance, which further makes them more vulnerable to soil erosion.

The third objective for this chapter was to establish which land management is suitable to store more carbon. To achieve this objective DAYCENT carbon model was used. Ten land management scenarios were created and DAYCENT carbon model was used to simulate C in these different land management scenarios. The scenarios were formed around soil type, LC type (grassland or cultivated land), and land management option (herbivory applied or not applied). The results showed that grassland with moderate herbivory is the best land management strategy to store more carbon. Results and literature showed that even though grassland is the best LC to sequesterate C, it does not infinitely do so when the grass becomes morbid carbon storage also stops. Therefore, grazing is recommended but in moderation, because excessive grazing will also lead to excessive disturbance of C sequestration. It is evident that the semi-arid and arid soils are ideal for capturing carbon when they are in their native or converted to grassland state. Research also showed that less carbon in the soil can be associated with high dust because when dust occurs it mostly moves fine particles which include carbon. Therefore, to mitigate the current problem faced in Free State of losing a substantial amount of carbon due to agricultural practices and occurrence of dust, farmers should consider reversing the cultivated lands to native grassland. Farmers of these regions should invest in converting cultivated lands to grasslands and not only abandon the cultivated lands but make sure they restore grass in them. Furthermore, in the cultivated lands farmers



can practise minimal or no till to prevent loss of nutrients from the soils. Future land management strategies or scenarios that can be considered to potentially capture more carbon are grassland with moderate grazing and cultivated land with no till. This initiative will benefit the entire ecosystem by leading to a balanced ecosystem. Loss of carbon to the atmosphere result into high greenhouse gases in the atmosphere which in turn accelerate global warming. Therefore, it is important to properly manage the ecosystem for the benefit of present and the future.

### **Study limitations**

The major limitation to the study was data collection period; during the collection of AGB data, grass was not clipped at the beginning of growth season and that might have produced biased results. It is therefore recommended that future studies take into consideration cutting the grass at the beginning of the growth cycle before the AGB measurements are taken, to have much more reliable results.

## **Chapter 5: Synopsis of the study, overall conclusion, and recommendations**

### **5.1 Synopsis of the study**

The central part of South Africa, including most of Free State as well as part of the Northern Cape and North West, represent some of the most rainfed crop production areas in the world. Free State is dominated by agricultural practices and is known to produce maize or corn for South Africa and further export to other parts of Africa. Free State is characterized by summer rainfall with average of (400- 500 mm) and is mostly dominated by Arenosols and Luvisols types of soils. Due to these characteristics Free State has been observed to be one of the regions that can produce record breaking yields of maize or corn. Literature illustrate that this region was previously dominated by grassland but due to the increased economic demand some parts of the region were converted to cultivated land. The development however took place during the colonial era when Europeans arrived in this region and since then the land was substantially used for ploughing crops including but not limited to maize, sunflower, and groundnuts.

Farmers have since then invested significantly in crop production and thus make decision every year whether to plough or not. There are several factors that farmers consider when they make decisions about ploughing; those factors include but are not limited to economic demand (international maize price) and environmental factors (drought, onset and cessation of rainfall, temperatures, and frost variation). Drought and climate variability play a vital role in the decision making about which crop to plant and when to commence planting, however appetite for risk and the forecast maize price for the next season are found to mostly drive these decisions.

This study noted some of the patterns and indices of land degradation and the ecosystem services that were being lost because of the changes that had taken place since colonization. Grasslands were reported by early travelers in this area (Reitz, 1929) and when European farmers colonized the area, the grasslands were then rapidly converted into dryland for crop production. Cultivated land rapidly increased because of the ideal soil types for crop production in this region (Arenosols and Luvisols) and annual average rainfall that the region receives. These types of soils can be tilled rapidly, and crops can be planted immediately after significant spring rain, simultaneously fertilized, and then treated with herbicides to control weeds.

Annual ploughing is known globally to result in a loss of SOC, and increase in soil and wind erosion (Jones et al., 2005). The apparent increase in wind erosion, as evidenced by the high incidence of dust storms detectable by MSG, prompted an investigation of the origin of these dust storms, and to determine whether their occurrence could be associated to land management. Moreover, the study wanted to explore if there was any link between cultivation practices (e.g., frequency of ploughing, type of crop, post-harvesting practices, field abandonment and post-harvest herbivory) and the incidence of dust storms. Economic (international maize price, currency fluctuations) and environmental (rainfall amount and seasonality) are the main drivers of land use within the region. Lambin *et al.*, (2001) argued that economic demand prompts the land to be converted from grassland to cultivated land in many regions. It is also possible that deteriorating conditions in climate (e.g., changes in the amount and timing of rainfall) may affect land-use within the region.

The study therefore explored regional land-use and land cover trends using the 2000 and 2013-2014 national Land Cover data available. Furthermore, with the view of being able to offer farmers alternative options for land management, this study explored the use of biogeochemical models to predict the likely carbon storage options associated with the range of soil types encountered in this region. The data collected in the process of model parameterization provided evidence of the levels of SOC available under both intensively ploughed lands as well as those sites that had been subjected to moderate livestock grazing. This study showed that soil carbon levels are very high in the dense clay soils (Lixisols), and these should be preserved.

The outcomes of the research further indicated that there are recent trends in land use which point towards an increase in area under cultivation, and that this is taking place in relation with a decrease in native grassland. This is a regional trend that has been described elsewhere in land under commercial/small hold land. Studies such as Costa et al., (2003); Falcucci et al., (2007); Popovici et al., (2013); Tekle & Hedlund, (2000) also noted that cultivated land increases or remain unchanged. In contrast, this trend has not been detected in land under communal tenure in other parts of South Africa (e.g. former Transkei and rural areas of Kwa-Zulu Natal) where the farmers have little or no access to credit as well as a lower appetite for risk, and this has reduced interest in annual crop cultivation (van der Waal et al., 2018). Small scale farmers of these regions and other regions in Africa are not well supported by infrastructure to process and transport agricultural products and they also not well informed about the seasonal forecast Kgosikoma et al., (2018), which makes them lose interest in crop production.

It has been already noted that economic demand is the major driver of LC change in this region. However, the land is likely to change given the future climate drivers. According to the observations from this study it is evident that the land is likely to be left fallow due to climate constraints such as increase in temperatures and decrease in rainfall. Farmers depend on rainfall to decide whether to plant or not plant in a specific year. When temperatures increase and rainfall decrease crops are subjected to fail and if farmers take risk and plant under these conditions, they risk losing tons of crop yields. Engelbrecht *et al.*, (2015) projected a future increase in semi-arid and arid temperatures. This study also noted an increase of 1-2°C in temperature which results to decrease in frost. Rainfall has been observed to decrease with number of rain days shifting to late summer. This trend has also been described by Davis *et al.*, (2016) who found a slight decrease in SA rainfall and number of rainfall days.

This study has also noted that shift of LC from grassland to cultivated land may lead to land being susceptible to dust if the land is left fallow. Dust is a symptom of land degradation and has become a major problem in Free State and neighbouring regions. This problem dates back from 2006, according to the Meteosat Second Generation (MSG) Southern African dust events have become frequent and significant in extent (Vickery, Eckardt, & Bryant, 2013). The frequency of dust events was observed to be severe in 2015 and 2016 in Free State. This follows the severe drought that occurred during these years as shown by the SPEI data and the land was then left fallow. The conditions in Free State are therefore like the conditions of the Dust Bowl Era. During the Dust Bowl Era the US Great Plains were hit by severe drought and excessive wind-driven soil erosion of overgrazed rangeland and soil exposed by the use of farming practices that were not suitable for the semiarid region (Baumhardt, 2014; Hansen & Libecap, 1940). Both in the US Great Plains and Free State, the crop production is accompanied by a reduction in biodiversity and soil organic carbon, soil retention as well as the loss of micro-nutrients through wind and water erosion.

The conversion of grassland to cultivated land has also been observed to result in the loss of soil organic carbon in Free State due to soil degradation. There is globally published evidence on the impact of conversion of native grassland to cultivated land that points to an increase in the atmospheric CO<sub>2</sub> emission, and thus lead to decrease in soil carbon storage. This tells us that cultivated lands have become the source of atmospheric CO<sub>2</sub> emission and if mitigation measures are not taken the matter will further contribute to climate change as CO<sub>2</sub> is the major GHG that results to global warming. The increase in land under cultivation in the study area is therefore of great concern, and efforts would be made to reverse this trend if South Africa is to

attempt to achieve global emission targets and avoid further loss of the existing carbon store. The ultimate target is to have the land as a carbon sink rather than a carbon source in this region. This can be done by converting cultivated land back to native grassland with moderate herbivory, considering climate smart agriculture (CSA) and regenerative agriculture (RA).

Regenerative agriculture is viewed as a practice that can enhance the storage of SOC. However, according to Schreefel et al., (2020) RA still lacks a clear scientific definition as it mainly focus on the environmental dimension of sustainability such as soil health, resource management, water quality and availability. Therefore, farmers should be cautious when using this approach. Climate smart agriculture is another approach that can enhance the storage of soil organic carbon. Campbell et al., (2014) defined CSA as an approach that increase agricultural productivity to support increased incomes, food security and development, also increase adaptive capacity at multiple levels and decrease greenhouse gas emissions and increase carbon sinks. This approach consist of practices that include soil, water and nutrient management, livestock and forest and grassland management techniques (Scherr, Shames, & Friedman, 2012). Some of the practices (such as minimum till or no till, minimum grazing, planting cover crops and leaving crops residues) that CSA promotes are already being practiced by some of the Free State farmers which means they are aware of climate change and taking measures to promote mitigation or adaptation.

Following the current issue of soil organic carbon loss due to soil degradation, proper land management strategies that would aid with substantial storage of carbon are crucial. DAYCENT carbon model is a biogeochemical model that is suitable to simulate soil carbon. DAYCENT model was parameterized using the 2019 soil data collected in Free State to enable us to predict the likely SOC storage options available with changes in land use and changes in the intensity of herbivory on the four dominant soil types within the region. Both heavily cultivated soil types (Arenosols and Luvisols) were found to have lower than expected SOC level. However, the model presents an opportunity for carbon sequestration if extensive cultivation can be withdrawn from these soils. Del Grosso *et al.*, (2002) agree that dry soils can store more carbon when converted to no till and decrease fallow periods or reverse to natural grassland. Simple abandoning or stopping cultivation is not sufficient to achieve the storage of more SOC but farmers should make sure they revert the land to grassland. Abandoning the land is observed to result in the occurrence of dust and further lead to climate change because if the land is left fallow it acts as a source of carbon.

Some farmers in this region are livestock farmers and only use the land for livestock grazing and others use the land for game farming. Scenarios such as grassland with herbivory and grassland with no herbivory were taken into consideration when running the DAYCENT model. From the model simulation output grassland with moderate herbivory was found to be the best land management strategy to store more carbon. This research therefore recommends that national policies should be put in place to provide incentives for farmers to move from high intensity grazing to low intensity rates with indigenous herbivores, and to enable re-vegetation of marginal soils. This will enhance soil carbon stocks as well as increase biodiversity. Restoring of abandoned cultivated land has many benefits such as reducing runoff, sequestering more carbon, and reducing wind erosion Jiao et al., (2009); Qiu et al., (2011) and it is therefore promoted throughout the globe. This is an exceptional opportunity for local landowners to also adopt and apply these principles within coordinated reverting efforts. These will increase SOC, reduce CO<sub>2</sub> and CH<sub>4</sub> emissions, and enhance biodiversity. They will also mitigate against the effects of climate change which are likely to affect this region.

## **5.2 Overall conclusion**

The main essence of this research was to characterise the impact of rainfall and temperature in crop production, determine the LCLU changes in association with dust and lastly establish the suitable land management practices that can store more carbon in Free State. To achieve this research was conducted in Bultfontein area and later expanded the findings to the whole of Free State. Rainfall and temperature are major factors that affect crop production. Changes in LCLU have become a growing concern locally, regionally, and globally, thus it was vital for this study to explore them and further discover their contribution to the occurrence of dust. Moreover, SOC is a consequence of an important ecosystem service that is being neglected in many areas, therefore it was essential for this study to acquire knowledge about it in semi-arid regions like Free State. This was important because the knowledge will provide guidance to the suitable land management strategies that can be implemented to store more carbon in the future. Based on the results from different objectives in this study, the following were concluded:

1. To achieve the first aim of the study which was to ascertain whether LC is shifting from grassland towards cultivated land and causing dust three objectives were derived. The first objective to achieve the first aim was to determine the spatial and temporal changes of LC in Free State. The 2000 and 2013-2014 land cover maps derived from Agricultural Research Council were analysed using ArcMap. Based on the results I obtained, according to the 2000 and 2013-2014 LC maps there is an observed change in LC. Cultivated land from 2000 and 2013 – 2014 has increased but its spatial extent still does not exceed grassland. Cultivated land has increased by approximately 26 % and grassland has decreased by 22 %. The study however acknowledges that these may not be real changes but rather changes or errors in the two LC data products. According to the literature several studies have also noted that cultivated land increases or remain unchanged in semi-arid and arid regions and the change is mainly due to economic demand. These findings rather match with the findings of the present study; therefore, I concluded that cultivated land is becoming a dominant LC in dryland areas.
2. The second objective to achieve the first aim was to determine the role of vegetation in the occurrence of dust. To answer this objective MODIS EVI data for the sites of the start of dust was used. MODIS EVI around each dust source was clipped and based on the results it was apparent that vegetation plays a significant role on the occurrence of dust. This was evident because around most dust sources there was sparse vegetation; EVI was ranging between 0 and 0.18 which is a clear indication of poor vegetation. Sparse vegetation is directly proportional to dust production; the sparser the vegetation, the more dust events become. Findings also illustrated that dust mainly occur in cultivated land and the events are becoming prominent over the years (2015 and 2016). Therefore, cultivated bare land were found to be the major sources of dust and the events are becoming frequent as fallow lands are observed to increase over the years. Farmers are abandoning the cultivated lands due to changes in climate; rainfall is observed to decrease and temperatures to increase. The MODIS EVI data was also compared with the weather data for the sites of the start of dust to determine if weather patterns have any role in the occurrence of dust. Based on the results it was observed that dust events correspond with low rainfall, high temperature and high wind speed periods. Several other studies have also found that vegetation is a vital factor for the occurrence of dust, however factors like rainfall, temperature, humidity, and wind speed also affect the occurrence of dust. The results of the present study correspond with other

research findings, and from these findings it was concluded that vegetation plays a significant role in the occurrence of dust, however it is not the only factor.

3. The third objective to achieve the first aim was to assess the dominating crop and LC around dust sources. Investigation was narrowed down to assess exactly the dominating crop and LC around each dust source. Now that it was clear that vegetation plays a significant role in dust production, the study wished to understand under which crops and LC are we likely to get dust. To answer this investigation crop and land cover data obtained from Department of Agriculture, Forestry and Fisheries was used. The results showed that each dust source is likely to have plus minus nine crops and land cover, but maize, fallow and pasture lands always dominate around each dust source. Some dust events are dominated by all three mentioned crop and land cover types, some are dominated by one of them but generally around each dust source one of the three crop and land cover types is always found dominating. The reason these three crop and land cover types results in dust occurrence is because i) during the period of high winds (Aug – Nov) maize is already harvested and land is either left bare or with crop residues which are later grazed by livestock making the area susceptible to dust, ii) when area is covered by pasture and there is overgrazing, vegetation becomes sparse thus resulting to dust and iii) when the land is left fallow with no wind breaks the soil particles can easy become eroded when high wind occurs. Other studies have found that excessive bare land results to more dust and these findings rather match with the findings of the present study, as many dust sources were found to correspond with fallow land. Based on the results, it was concluded that surface roughness plays a vital role in controlling soil erosion and the type of crop cover is the major identifier of the areas vulnerable to dust. Fallow land is identified as the hotspot of dust.
4. The second aim of this study was to determine the climate constraints to Free State crop production. To achieve this aim three objectives were formulated with the first one trying to determine the variation of rainfall in Free State. To answer this objective CHIRPS, ARC and SPEI data were used. SPEI data showed that drought is becoming prominent and severe over the years. Based on the investigated years; some years had moderate, and some had severe drought and others were normal years. Drought has



been observed to be the consequences of low rainfall, high temperatures, high wind, and low relative humidity. Both CHIRPS and ARC data showed that there is a seasonal shift on the onset of rainfall; rainfall has shifted to late summer by approximately 62 days on average from 1981-2019 in Free State. Furthermore, ARC showed a slight increase (357-408 mm/year) in rainfall from 2005- 2016 and CHIRPS showed a slight decrease (458-404 mm/year). Other studies have observed that there is a slightly decrease in SA rainfall and number of rainfall days. These results correspond with the results of the present study even though ARC results are showing a slight increase. The slight difference from the results is expected since the compared two datasets are completely different from each other; CHIRPS data has a spatial resolution of 0.05 and ARC data is in a point data format and has missing values. Missing values in a dataset are recognised as a limitation because they might result to unrealistic or biased findings. However, based on the findings it was concluded that rainfall is slightly decreasing in semi-arid and arid regions with droughts reoccurring and thus negatively affecting crop production. The farmers depend on these factors to decide on planting times and crop types. Extreme weather conditions further results in a decrease of crop yields as some crops cannot withstand undesirable weather conditions.

5. The second objective to achieve the second aim was to determine temperature and frost variation and how they affect crop production in Free State. To achieve this objective ARC temperature data was used. The results showed that temperatures have increased by  $\sim 1-2^{\circ}\text{C}$  in Free State and frost has decreased, and its onset has shifted by  $\sim 11$  days. Frost normally starts occurring in April but according to the results it has shifted to May and low in extent, some years had not received frost at all (i.e., 2016). This is evidence that temperatures are increasing. These results are supported by other studies who projected a future increase in semi-arid and arid temperatures. Decrease in frost is an advantage to plants especially if they are planted late. With the observed decrease in frost variation farmers can still plant maize as late as January and get to harvest time without crops being killed by frost. However, an increase in temperatures might result to plants losing massive amount of water especially if evaporative demand is greater than water supply and thus resulting to crop failure. Increase in temperatures require farmers to continuously irrigate their crops if they want them to retain enough moisture.

Irrigation is not certainly feasible in FS as crops usually gets planted over thousands of hectares making it difficult to continuously irrigate them, hence farmers use the rainfed technique. The ARC data had missing data which made it less reliable, however the results still agreed with other people's results, and it was then concluded that temperatures are increasing leading to decrease in frost.

6. The third objective to achieve the second aim was to determine how wind speed affects the occurrence of dust. To achieve this objective ARC and ERA5 data were used. Both datasets showed that there is no constant trend; in some years wind increases and some decreases. The ARC maximum wind speed was 10 – 15 m/s and ERA5 maximum wind speed was 10 m/s. Both datasets showed that high wind speed occurs from August-November. Other studies done in FS have also observed high winds between August and November which is a major contributor to dust production, matching with the findings of the current study. The limitation of the two datasets is that ARC is in a point data format and ERA5 has a spatial resolution of 30 km, which makes these datasets completely different and not easy to compare. However, based on the results it was concluded that high wind corresponds with dry months and thus stimulates the production of dust in FS drylands. To mitigate the occurrence of dust during dry months farmers can make sure they don't leave the fields completely bare; they can either leave crop residues, stubbles, or plant winter crops to avoid bare fields. It has been evident from the present study that surface roughness plays a vital role in dust production, therefore crop residues, stubbles and winter crops can act as wind breaker and prevent soil particles from moving.
7. To achieve the third aim which was to determine which land management option is suitable for improving soil ecosystem services., three objectives were derived. The first objective to achieve the third aim was to determine the amount of carbon and nitrogen in the western Free State LC. To achieve this objective the soils sampled in 2019 from different sites in Free State were used. Results have showed that grassland can store more carbon than cultivated land. The cultivated land in Free State is mainly in the Arenosols and Luvisols and grassland is mainly in Calcisols and Lixisols. Studies have shown that Arenosols can also store more carbon like other soils if they are not

continuously disturbed. Evidence shows that in Free State these types of soils are excessively used for agricultural purposes resulting to them losing more carbon to the atmosphere. Lixisols and Calcisols are shown to be used for grassland with reduced disturbance of C sequestration resulting to more carbon stored. The study then concluded that grassland can potentially store more carbon than cultivated land due to reduced disturbance.

8. The second objective to achieve the third aim was to determine the role of soil texture and grain size distribution in storing nutrients. To answer this objective again the soils sampled in 2019 from different sites in Free State were analysed using Malvern Mastersizer 2000. Based on the results it was apparent that soil texture plays a vital role in storing carbon. The results illustrated that silt sand soils store more carbon than sand silt soils. The findings of this objective builds to the findings of the first objective which showed the LC and soil type that has a potential to store more nutrients. Results indicated that Lixisols have the high silt content and Arenosols have high sand silt content and Lixisols were observed to store more carbon and Arenosols to store less carbon. Generally, soils with high sand content are used for cultivation and this means these soils are regularly disturbed, thus they are observed to store less nutrients than soils with high silt content which are mostly used for grassland. Results further showed that more carbon is stored in top layers of soil and decrease with increasing depth. Grass roots are found in the top layers (0-2 cm and 2-5 cm) of the soil which explains why more carbon is stored in these depths, whereas with cultivated lands carbon gets used by plants during respiration. These findings match with the results of other studies which found that organic carbon is consistently low in Arenosols of Southern Africa because of their regularly disturbance. The present study then concluded that soils with high silt content can accumulate more carbon because of being less disturbed whereas soils with high sand content mostly store less carbon because of their regularly disturbance, which further makes them more vulnerable to soil erosion.
9. The third objective to achieve the third aim was to establish which land management is suitable to store more carbon. To achieve this objective DAYCENT carbon model was used. Ten land management scenarios were created and DAYCENT carbon model was

used to simulate C in these different land management scenarios. The scenarios were formed around soil type, LC type (grassland or cultivated land), and land management option (herbivory applied or not applied). The results showed that grassland with moderate herbivory is the best land management strategy to store more carbon. Results and literature showed that even though grassland is the best LC to sequester C, it does not infinitely do so, when the grass becomes morbid carbon storage also stops. Therefore, grazing is recommended but in moderation, because excessive grazing will also lead to excessive disturbance of C sequestration. It is evident that the semi-arid and arid soils are ideal for capturing carbon when they are in their native or converted to grassland state. Research also showed that less carbon in the soil can be associated with high dust because when dust occurs it mostly moves fine particles which include carbon. Therefore, to mitigate the current problem faced in Free State of losing a substantial amount of carbon due to agricultural practices and occurrence of dust, farmers should consider reversing the cultivated lands to native grassland with moderate herbivory. Farmers of these regions should invest in converting cultivated lands to grasslands and not only abandon the cultivated lands but make sure they restore grass in them. By restoring grass most carbon can be sequestered, and the farmers can in return get carbon credits. Furthermore, in the cultivated lands farmers can practise minimal or no till to prevent loss of nutrients from the soils. Future land management strategies or scenarios that can be considered to potentially capture more carbon are grassland with moderate grazing and cultivated land with no till. This initiative will benefit the entire ecosystem by leading to a balanced ecosystem. Dust emission not only results to movement of important soil particles but also results to air pollution. Air pollution might cause several diseases to human such as asthma. On the other hand, loss of carbon to the atmosphere results into high greenhouse gases in the atmosphere which in turn accelerate global warming. Therefore, it is important to properly manage the ecosystem for the benefit of present and the future.

### 5.3 Recommendations

Continuous management of changes in land cover or land use is recommended to monitor if the land is changing to the better or worse. The findings of this study can be further improved by incorporating the 1990, 2018 and 2020 national land cover maps. These maps were not used because the study was only interested in the changes that occurred from 2006 – 2016. The study therefore recommends future studies to use the 1990, 2000, 2013-2014, 2018 and 2020 national land cover maps to better understand the long term spatial and temporal land cover/land use changes.

The weather data had missing data in some days which would have made it difficult to draw proper conclusions about the impact of rainfall on crop production if CHIRPS data was not available for gap filling. Therefore, better monitoring and maintenance of weather stations is recommended to improve the quality of the data. Installing more weather stations with reliable data will also improve the accuracy of the data but it would take several decades for such data to depict viable trends.

Future studies can also improve on the data collection period especially when investigating the suitable land management strategies to store carbon. During the collection of aboveground biomass data, grass was not clipped at the beginning of growth season and that might have produced biased results. Sufficient data collection time is thus important so that all the necessary data can be collected to provide nonbiased results. According to this study it is vital to protect the ecosystem to promote positive sustainable environment for the benefit of present and future generation. Factors such as climate change, land cover or land use change and agricultural practices affect the ecosystem and are interconnected, with the consequences of one factor resulting to the occurrence of the other. Therefore, these factors need to be continuously studied to have a balanced ecosystem.

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## Appendices

### Appendix 2.1: Example of Java script used to extract MODIS EVI for dust sources

```
// Plot MODIS EVI band value means in a section of SADust MSG
// demonstrate interactive charts.

var a200608291 = ee.Geometry.Rectangle(26.182,-28.1699,26.186,-28.1659);

var modisLAI = ee.ImageCollection('MODIS/MCD43A4_EVI')
  .filterDate('2000-01-01', '2018-06-30')
  .select('EVI');

// Create an image time series chart.
var chart = ui.Chart.image.series({
  imageCollection: modisLAI,
  region: a200608291,
  reducer: ee.Reducer.mean(),
  scale: 200
});

// Add the chart to the map.
chart.style().set({
  position: 'top-left',
  width: '500px',
  height: '300px'
});
Map.add(chart);

// Outline and center area on the map.
var sfLayer = ui.Map.Layer(a200608291, {color: 'FF0000'}, 'SF');
Map.layers().add(sfLayer);
Map.setCenter(26.186, -28.1679);
.....
```

Appendix 2.2: Summary table of the growth conditions, as reflected by the EVI, for the sites of dust storm events during 2006-2016

| No. of events | Date      | Max EVI | Average EVI | No. of years of below average EVI before dust event | Land cover type                     | Soil type |
|---------------|-----------|---------|-------------|-----------------------------------------------------|-------------------------------------|-----------|
| 1             | 200608291 | 0.37    | 0.17        | 0                                                   | Cultivation                         | Arenosols |
| 2             | 200608292 | 0.39    | 0.23        | 4                                                   | Riparian zone                       | Lixisols  |
| 3             | 200609251 | 0.34    | 0.21        | 5                                                   | Riparian zone                       | Lixisols  |
| 4             | 200609252 | 0.38    | 0.18        | 0                                                   | Cultivation                         | Arenosols |
| 5             | 200611101 | 0.38    | 0.23        | 5                                                   | Riparian zone                       | Lixisols  |
| 6             | 200611102 | 0.31    | 0.18        | 3                                                   | Cultivation                         | Arenosols |
| 7             | 200611103 | 0.47    | 0.25        | 5                                                   | Riparian zone                       | Lixisols  |
| 8             | 200612031 | 0.46    | 0.22        | 5                                                   | Cultivation                         | Arenosols |
| 9             | 200612032 | 0.33    | 0.21        | 3                                                   | Cultivation                         | Arenosols |
| 10            | 200612033 | 0.34    | 0.22        | 2                                                   | Cultivation                         | Arenosols |
| 11            | 200612034 | 0.40    | 0.21        | 4                                                   | Cultivation                         | Arenosols |
| 12            | 200612035 | 0.54    | 0.28        | 5                                                   | Riparian zone                       | Lixisols  |
| 13            | 200612036 | 0.37    | 0.22        | 1                                                   | Cultivation                         | Arenosols |
| 14            | 200612037 | 0.39    | 0.23        | 5                                                   | Grassland                           | Lixisols  |
| 15            | 200612038 | 0.44    | 0.25        | 5                                                   | Riparian zone                       | Calcisols |
| 16            | 200612169 | 0.36    | 0.21        | 5                                                   | Grassland                           | Calcisols |
| 17            | 200706251 | 0.09    | 0.08        | 0                                                   | Bare land                           | Calcisols |
| 18            | 200707271 | 0.25    | 0.14        | 0                                                   | Riparian zone with patches of grass | Lixisols  |
| 19            | 200707272 | 0.57    | 0.21        | 4                                                   | Cultivation                         | Arenosols |
| 20            | 200707273 | 0.35    | 0.19        | 4                                                   | Cultivation                         | Arenosols |

|    |           |      |      |   |                                      |           |
|----|-----------|------|------|---|--------------------------------------|-----------|
| 21 | 200707274 | 0.36 | 0.21 | 0 | Urban development                    | Luvisols  |
| 22 | 200707275 | 0.37 | 0.20 | 0 | Bare land close to patches of trees  | Luvisols  |
| 23 | 200708141 | 0.27 | 0.18 | 1 | Bare land                            | Calcisols |
| 24 | 200708142 | 0.22 | 0.15 | 0 | Cultivation                          | Arenosols |
| 25 | 200708143 | 0.29 | 0.17 | 0 | Bare land                            | Lixisols  |
| 26 | 200708234 | 0.23 | 0.14 | 0 | Bare land                            | Calcisols |
| 27 | 200708232 | 0.27 | 0.15 | 0 | Bare land                            | Calcisols |
| 28 | 200708233 | 0.32 | 0.16 | 0 | Grassland                            | Lixisols  |
| 29 | 200708231 | 0.27 | 0.15 | 0 | Cultivation                          | Luvisols  |
| 30 | 200708235 | 0.19 | 0.14 | 0 | Bare land                            | Calcisols |
| 31 | 200709071 | 0.25 | 0.17 | 0 | Cultivation                          | Arenosols |
| 32 | 200709072 | 0.43 | 0.27 | 2 | Cultivation                          | Arenosols |
| 33 | 200709111 | 0.17 | 0.13 | 2 | Bare land                            | Luvisols  |
| 34 | 200709231 | 0.45 | 0.17 | 1 | Cultivation                          | Arenosols |
| 35 | 200709232 | 0.42 | 0.18 | 1 | Cultivation                          | Arenosols |
| 36 | 200709233 | 0.26 | 0.18 | 0 | Riparian zone                        | Arenosols |
| 37 | 200709261 | 0.26 | 0.19 | 3 | Bare land with patches of vegetation | Calcisols |
| 38 | 200709262 | 0.28 | 0.18 | 2 | Bare land with patches of vegetation | Arenosols |
| 39 | 200711261 | 0.28 | 0.16 | 0 | Bare land                            | Calcisols |
| 40 | 200711262 | 0.30 | 0.17 | 0 | Cultivation                          | Arenosols |
| 41 | 200711263 | 0.28 | 0.17 | 0 | Riparian zone                        | Calcisols |
| 42 | 200809231 | 0.32 | 0.19 | 3 | Grassland                            | Calcisols |

|    |           |      |      |   |               |           |
|----|-----------|------|------|---|---------------|-----------|
| 43 | 200809232 | 0.30 | 0.18 | 1 | Cultivation   | Arenosols |
| 44 | 200809233 | 0.21 | 0.15 | 1 | Bare land     | Calcisols |
| 45 | 201008221 | 0.33 | 0.22 | 5 | Cultivation   | Luvisols  |
| 46 | 201008222 | 0.47 | 0.25 | 5 | Riparian zone | Luvisols  |
| 47 | 201008291 | 0.10 | 0.07 | 2 | Bare land     | Calcisols |
| 48 | 201011081 | 0.31 | 0.18 | 5 | Riparian zone | Calcisols |
| 49 | 201011082 | 0.31 | 0.18 | 3 | Cultivation   | Luvisols  |
| 50 | 201108231 | 0.38 | 0.19 | 3 | Cultivation   | Arenosols |
| 51 | 201108232 | 0.31 | 0.19 | 3 | Riparian zone | Lixisols  |
| 52 | 201108233 | 0.47 | 0.20 | 3 | Cultivation   | Arenosols |
| 53 | 201108234 | 0.44 | 0.20 | 3 | Cultivation   | Arenosols |
| 54 | 201208111 | 0.54 | 0.23 | 3 | Cultivation   | Luvisols  |
| 55 | 201208112 | 0.40 | 0.22 | 0 | Riparian zone | Luvisols  |
| 56 | 201208113 | 0.34 | 0.21 | 1 | Bare land     | Lixisols  |
| 57 | 201208114 | 0.30 | 0.17 | 1 | Riparian zone | Lixisols  |
| 58 | 201208115 | 0.28 | 0.19 | 0 | Riparian zone | Lixisols  |
| 59 | 201208116 | 0.34 | 0.21 | 0 | Grassland     | Lixisols  |
| 60 | 201208117 | 0.35 | 0.19 | 2 | Bareland      | Calcisols |
| 61 | 201208151 | 0.44 | 0.19 | 2 | Cultivation   | Arenosols |
| 62 | 201208152 | 0.31 | 0.18 | 0 | Riparian zone | Calcisols |
| 63 | 201208153 | 0.31 | 0.18 | 0 | Riparian zone | Lixisols  |
| 64 | 201208154 | 0.25 | 0.14 | 0 | Cultivation   | Luvisols  |
| 65 | 201209201 | 0.55 | 0.23 | 5 | Cultivation   | Arenosols |
| 66 | 201209202 | 0.26 | 0.16 | 1 | Riparian zone | Lixisols  |
| 67 | 201209281 | 0.24 | 0.15 | 0 | Grassland     | Calcisols |
| 68 | 201209282 | 0.60 | 0.20 | 1 | Cultivation   | Luvisols  |

|    |           |      |      |   |                                               |           |
|----|-----------|------|------|---|-----------------------------------------------|-----------|
| 69 | 201209283 | 0.29 | 0.17 | 0 | Bareland                                      | Lixisols  |
| 70 | 201209284 | 0.32 | 0.18 | 0 | Bare land                                     | Luvisols  |
| 71 | 201210081 | 0.22 | 0.15 | 0 | Bare land                                     | Calcisols |
| 72 | 201210082 | 0.45 | 0.18 | 2 | Cultivation                                   | Arenosols |
| 73 | 201210083 | 0.29 | 0.17 | 1 | Bare land                                     | Calcisols |
| 74 | 201210084 | 0.30 | 0.17 | 0 | Cultivation                                   | Arenosols |
| 75 | 201210211 | 0.30 | 0.17 | 0 | Cultivation                                   | Luvisols  |
| 76 | 201210212 | 0.28 | 0.17 | 0 | Cultivation                                   | Luvisols  |
| 77 | 201210301 | 0.33 | 0.16 | 0 | Bare land close to the pan                    | Calcisols |
| 78 | 201210302 | 0.25 | 0.15 | 0 | Bare land close to the pan                    | Calcisols |
| 79 | 201210303 | 0.56 | 0.21 | 5 | Cultivation                                   | Luvisols  |
| 80 | 201308111 | 0.13 | 0.11 | 0 | Bare land                                     | Luvisols  |
| 81 | 201308291 | 0.24 | 0.13 | 0 | Grassland                                     | Luvisols  |
| 82 | 201309191 | 0.19 | 0.13 | 0 | Bare land/pan                                 | Calcisols |
| 83 | 201309192 | 0.12 | 0.10 | 0 | Bareland                                      | Luvisols  |
| 84 | 201310071 | 0.26 | 0.16 | 0 | Cultivation                                   | Arenosols |
| 85 | 201310121 | 0.33 | 0.19 | 0 | Urban development                             | Luvisols  |
| 86 | 201310301 | 0.23 | 0.14 | 0 | Cultivated bareland with patches of grass     | Luvisols  |
| 87 | 201310302 | 0.25 | 0.16 | 0 | Riparian zone with patches of trees and grass | Luvisols  |
| 88 | 201311071 | 0.21 | 0.14 | 1 | Bare land with patches of grass               | Luvisols  |
| 89 | 201311072 | 0.24 | 0.15 | 0 | Bare land with bushes                         | Lixisols  |

|     |           |      |      |   |                                    |           |
|-----|-----------|------|------|---|------------------------------------|-----------|
| 90  | 201311121 | 0.28 | 0.16 | 0 | Cultivation                        | Luvisols  |
| 91  | 201407251 | 0.34 | 0.20 | 0 | Urban development                  | Luvisols  |
| 92  | 201407252 | 0.36 | 0.18 | 2 | Grassland                          | Luvisols  |
| 93  | 201408271 | 0.30 | 0.16 | 3 | Grassland                          | Luvisols  |
| 94  | 201408272 | 0.35 | 0.20 | 2 | Grassland                          | Luvisols  |
| 95  | 201408273 | 0.23 | 0.13 | 0 | Urban development                  | Calcisols |
| 96  | 201408274 | 0.48 | 0.23 | 4 | Riparian zone                      | Lixisols  |
| 97  | 201408291 | 0.38 | 0.20 | 0 | Bare land close to the river       | Luvisols  |
| 98  | 201409301 | 0.27 | 0.17 | 1 | Cultivation                        | Luvisols  |
| 99  | 201409302 | 0.27 | 0.17 | 1 | Cultivation/tree plantation        | Arenosols |
| 100 | 201410161 | 0.26 | 0.17 | 3 | Cultivation                        | Luvisols  |
| 101 | 201410162 | 0.43 | 0.19 | 4 | Cultivation                        | Arenosols |
| 102 | 201410163 | 0.28 | 0.17 | 3 | Grassland close to trees and river | Arenosols |
| 103 | 201410171 | 0.25 | 0.15 | 4 | Bare land next to the pan          | Calcisols |
| 104 | 201410172 | 0.27 | 0.16 | 1 | Grassland with patches of trees    | Arenosols |
| 105 | 201411151 | 0.36 | 0.19 | 2 | Grassland with trees               | Luvisols  |
| 106 | 201508131 | 0.40 | 0.21 | 0 | Bare land with patches of grass    | Lixisols  |
| 107 | 201508151 | 0.25 | 0.14 | 0 | Bare land                          | Arenosols |
| 108 | 201508152 | 0.27 | 0.17 | 0 | Cultivation                        | Arenosols |
| 109 | 201508201 | 0.29 | 0.18 | 0 | Grassland with patches of trees    | Luvisols  |

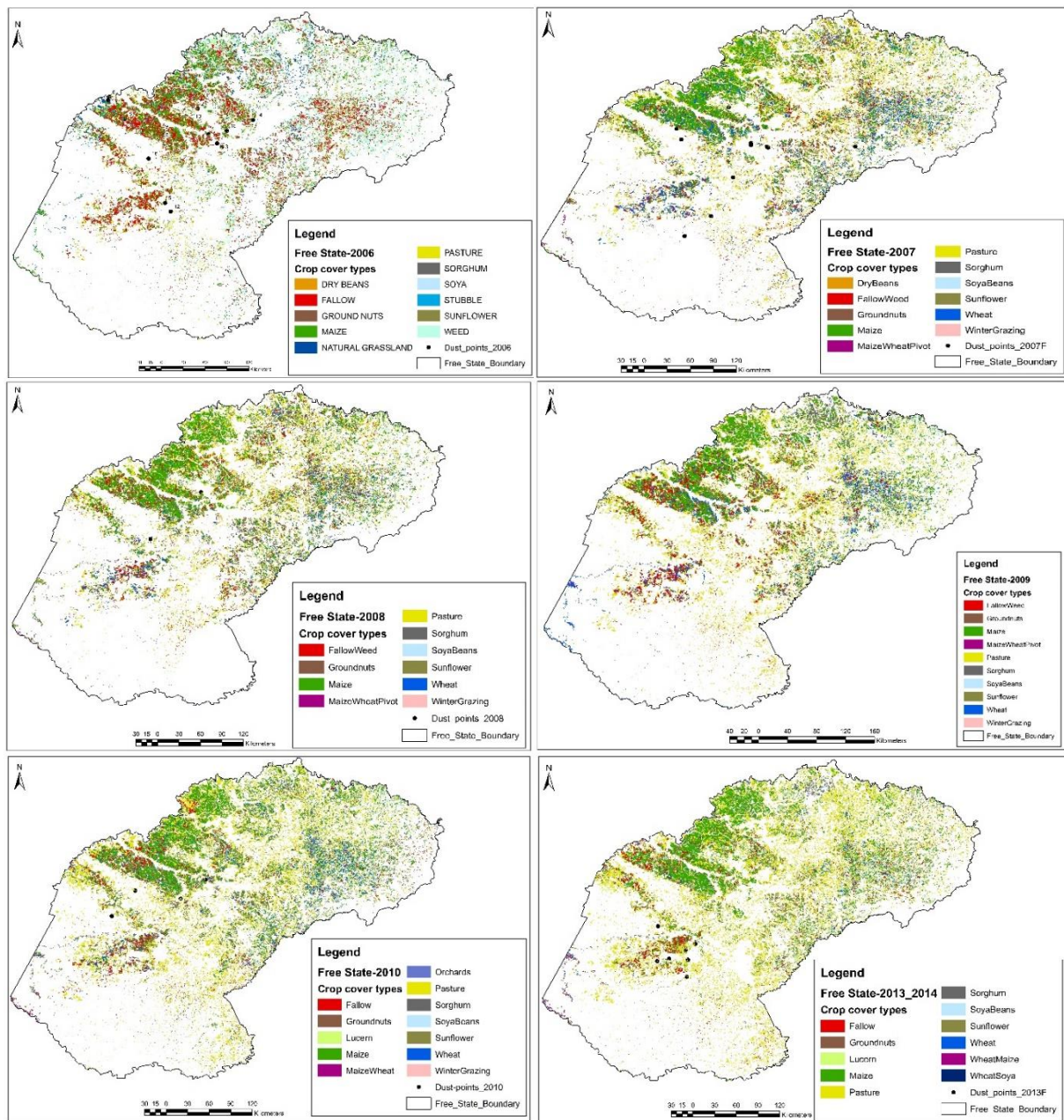
|     |           |      |      |   |                                         |           |
|-----|-----------|------|------|---|-----------------------------------------|-----------|
| 110 | 201510041 | 0.13 | 0.11 | 0 | Bare land                               | Luvisols  |
| 111 | 201510101 | 0.41 | 0.20 | 0 | Cultivation                             | Luvisols  |
| 112 | 201510102 | 0.31 | 0.17 | 2 | Grassland                               | Calcisols |
| 113 | 201510103 | 0.28 | 0.16 | 0 | Cultivation                             | Arenosols |
| 114 | 201510121 | 0.23 | 0.15 | 0 | Grassland close to trees and Vaal River | Arenosols |
| 115 | 201510122 | 0.33 | 0.16 | 1 | Cultivation                             | Arenosols |
| 116 | 201510141 | 0.56 | 0.19 | 0 | Cultivation                             | Arenosols |
| 117 | 201511011 | 0.32 | 0.17 | 0 | Cultivation                             | Arenosols |
| 118 | 201511012 | 0.28 | 0.16 | 0 | Riparian zone                           | Lixisols  |
| 119 | 201511021 | 0.61 | 0.21 | 5 | Cultivation                             | Arenosols |
| 120 | 201511022 | 0.20 | 0.13 | 0 | Cultivation                             | Luvisols  |
| 121 | 201511211 | 0.22 | 0.14 | 0 | Riparian zone                           | Luvisols  |
| 122 | 201511212 | 0.37 | 0.19 | 0 | Riparian zone                           | Lixisols  |
| 123 | 201511251 | 0.38 | 0.19 | 0 | Riparian zone                           | Lixisols  |
| 124 | 201511252 | 0.32 | 0.19 | 0 | Cultivation next to the river           | Luvisols  |
| 125 | 201511253 | 0.23 | 0.15 | 0 | Urban development                       | Luvisols  |
| 126 | 201511261 | 0.31 | 0.19 | 0 | Bare land                               | Lixisols  |
| 127 | 201511262 | 0.32 | 0.18 | 1 | Bare land with patches of grass         | Lixisols  |
| 128 | 201511263 | 0.33 | 0.19 | 0 | Bare land with patches of trees         | Lixisols  |
| 129 | 201512061 | 0.30 | 0.14 | 0 | Grassland                               | Luvisols  |
| 130 | 201512111 | 0.21 | 0.14 | 0 | Riparian zone                           | Lixisols  |
| 131 | 201512141 | 0.28 | 0.16 | 0 | Grassland                               | Luvisols  |
| 132 | 201512241 | 0.38 | 0.18 | 0 | Cultivation                             | Arenosols |

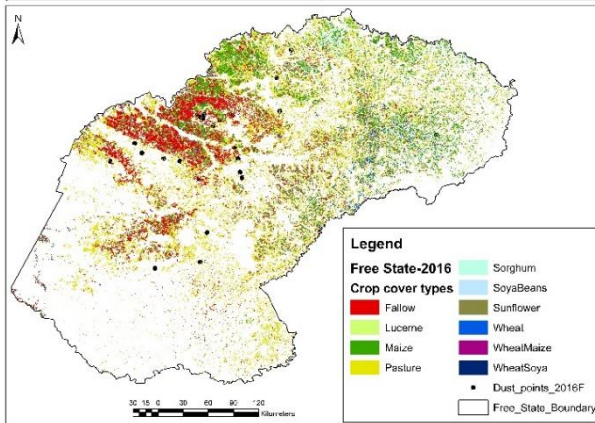
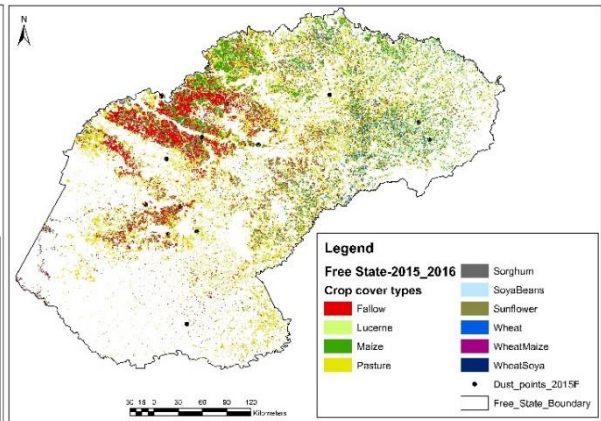
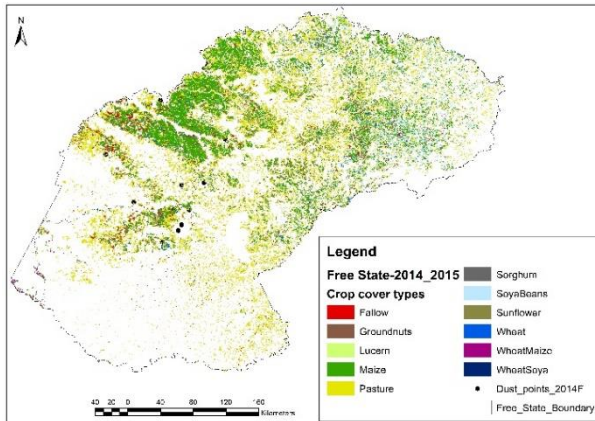
|     |           |      |      |   |                                 |           |
|-----|-----------|------|------|---|---------------------------------|-----------|
| 133 | 201601045 | 0.07 | 0.06 | 3 | Bare land                       | Calcisols |
| 134 | 201601046 | 0.06 | 0.05 | 0 | Bare land with patches of grass | Calcisols |
| 135 | 201601047 | 0.28 | 0.15 | 0 | Cultivation                     | Arenosols |
| 136 | 201601061 | 0.19 | 0.15 | 3 | Cultivation                     | Luvisols  |
| 137 | 201607311 | 0.30 | 0.19 | 2 | Riparian zone                   | Luvisols  |
| 138 | 201607312 | 0.36 | 0.17 | 1 | Cultivation                     | Luvisols  |
| 139 | 201608031 | 0.33 | 0.18 | 1 | Cultivation                     | Arenosols |
| 140 | 201608032 | 0.34 | 0.20 | 2 | Grassland with patches of trees | Luvisols  |
| 141 | 201608033 | 0.40 | 0.22 | 1 | Grassland                       | Lixisols  |
| 142 | 201609051 | 0.24 | 0.17 | 0 | Grassland                       | Calcisols |
| 143 | 201609052 | 0.33 | 0.22 | 4 | Riparian zone                   | Luvisols  |
| 144 | 201609111 | 0.27 | 0.18 | 0 | Grassland                       | Luvisols  |
| 145 | 201609112 | 0.22 | 0.14 | 0 | Cultivation                     | Arenosols |
| 146 | 201609113 | 0.39 | 0.19 | 3 | Cultivation                     | Luvisols  |
| 147 | 201609141 | 0.26 | 0.16 | 3 | Bare land                       | Luvisols  |
| 148 | 201609151 | 0.30 | 0.18 | 3 | Bare land with patches of grass | Luvisols  |
| 149 | 201609152 | 0.31 | 0.18 | 4 | Bare land                       | Calcisols |
| 150 | 201609261 | 0.24 | 0.17 | 3 | Bare land                       | Luvisols  |
| 151 | 201609262 | 0.34 | 0.19 | 5 | Bare land                       | Luvisols  |
| 152 | 201609263 | 0.25 | 0.17 | 4 | Bare land with patches of grass | Luvisols  |
| 153 | 201610111 | 0.24 | 0.17 | 4 | Bare land                       | Luvisols  |
| 154 | 201610112 | 0.21 | 0.15 | 0 | Grassland                       | Calcisols |
| 155 | 201610291 | 0.29 | 0.20 | 0 | Cultivation                     | Arenosols |
| 156 | 201610292 | 0.25 | 0.18 | 2 | Grassland                       | Lixisols  |



|     |           |      |      |   |                                 |           |
|-----|-----------|------|------|---|---------------------------------|-----------|
| 157 | 201610293 | 0.28 | 0.17 | 1 | Bare land                       | Calcisols |
| 158 | 201611011 | 0.27 | 0.18 | 4 | Bare land                       | Calcisols |
| 159 | 201611012 | 0.32 | 0.14 | 0 | Cultivation                     | Luvisols  |
| 160 | 201611031 | 0.28 | 0.19 | 0 | Cultivation                     | Arenosols |
| 161 | 201611032 | 0.30 | 0.19 | 3 | Bare land with patches of grass | Luvisols  |
| 162 | 201611171 | 0.23 | 0.18 | 3 | Grassland                       | Lixisols  |
| 163 | 201611172 | 0.22 | 0.13 | 0 | Cultivation                     | Arenosols |
| 164 | 201611173 | 0.28 | 0.20 | 3 | Bare land with sparse grass     | Luvisols  |
| 165 | 201611174 | 0.29 | 0.21 | 2 | Bare land                       | Lixisols  |
| 166 | 201611301 | 0.26 | 0.18 | 3 | Grassland                       | Lixisols  |
| 167 | 201611302 | 0.40 | 0.27 | 5 | Riparian zone                   | Lixisols  |
| 168 | 201612011 | 0.29 | 0.19 | 3 | Grassland                       | Luvisols  |
| 169 | 201612012 | 0.17 | 0.11 | 1 | Urban development               | Luvisols  |
| 170 | 201612013 | 0.43 | 0.18 | 2 | Bare land patches of shrubs     | Lixisols  |
| 171 | 201612051 | 0.20 | 0.15 | 3 | Grassland                       | Calcisols |
| 172 | 201612052 | 0.20 | 0.14 | 3 | Riparian zone                   | Calcisols |
| 173 | 201612053 | 0.14 | 0.12 | 1 | Bare land with patches of grass | Calcisols |
| 174 | 201612054 | 0.15 | 0.11 | 0 | Bare land                       | Luvisols  |
| 175 | 201612061 | 0.26 | 0.18 | 3 | Grassland                       | Lixisols  |
| 176 | 201612062 | 0.20 | 0.16 | 0 | Bare land                       | Luvisols  |
| 177 | 201612121 | 0.25 | 0.15 | 3 | Grassland                       | Calcisols |

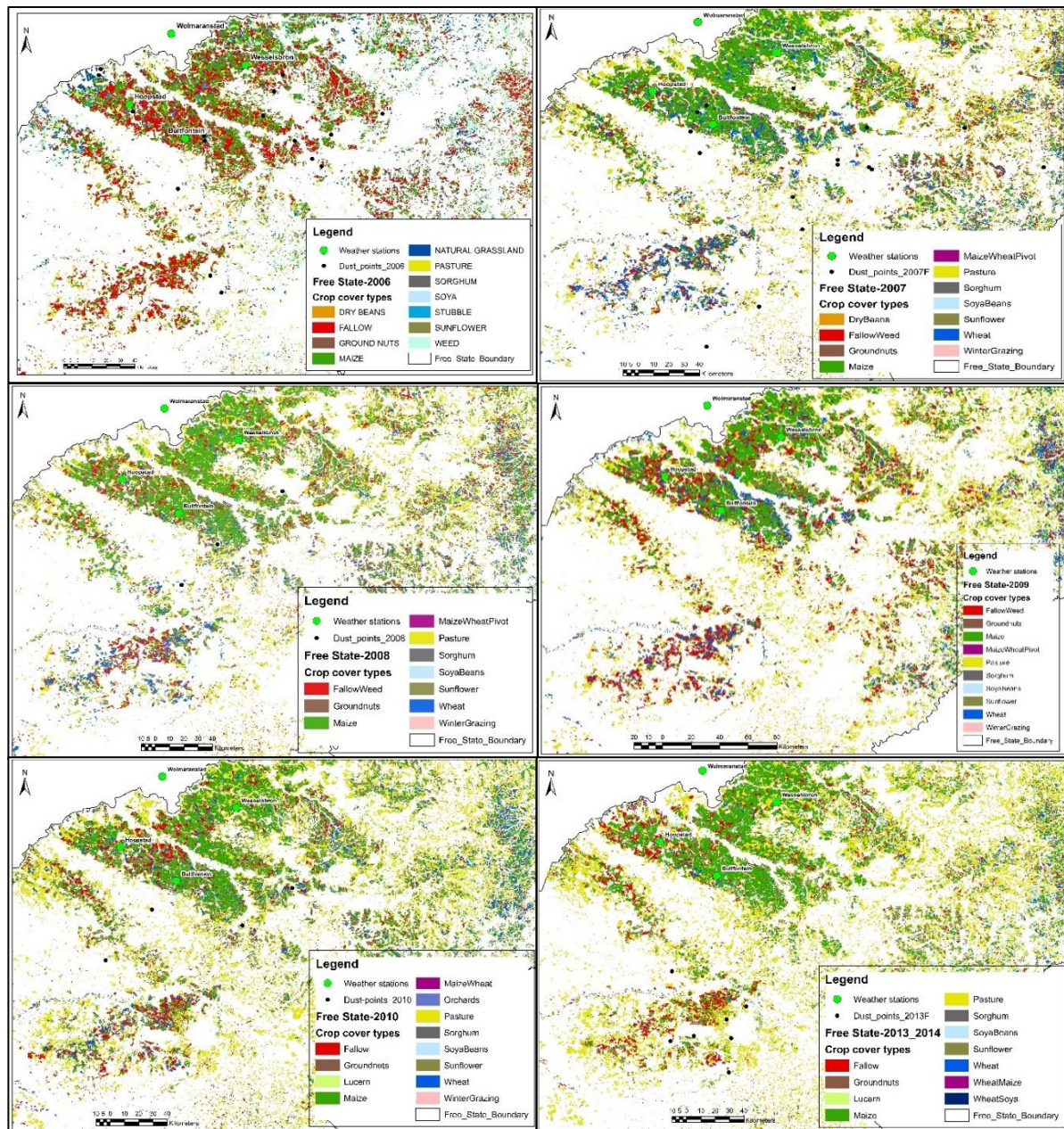
## Appendix 2.3: Spatial and temporal variation of crop and land cover types and dust sources in Free State from 2006-2016



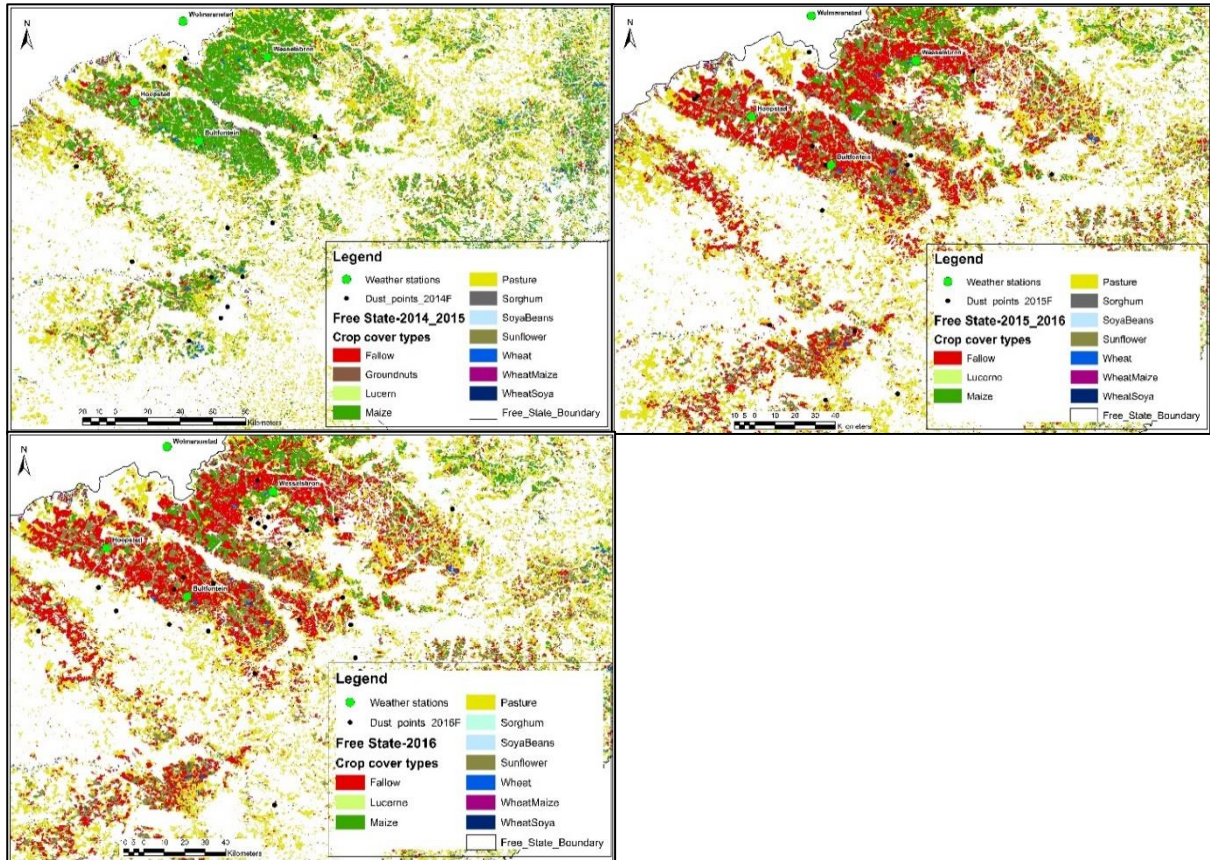




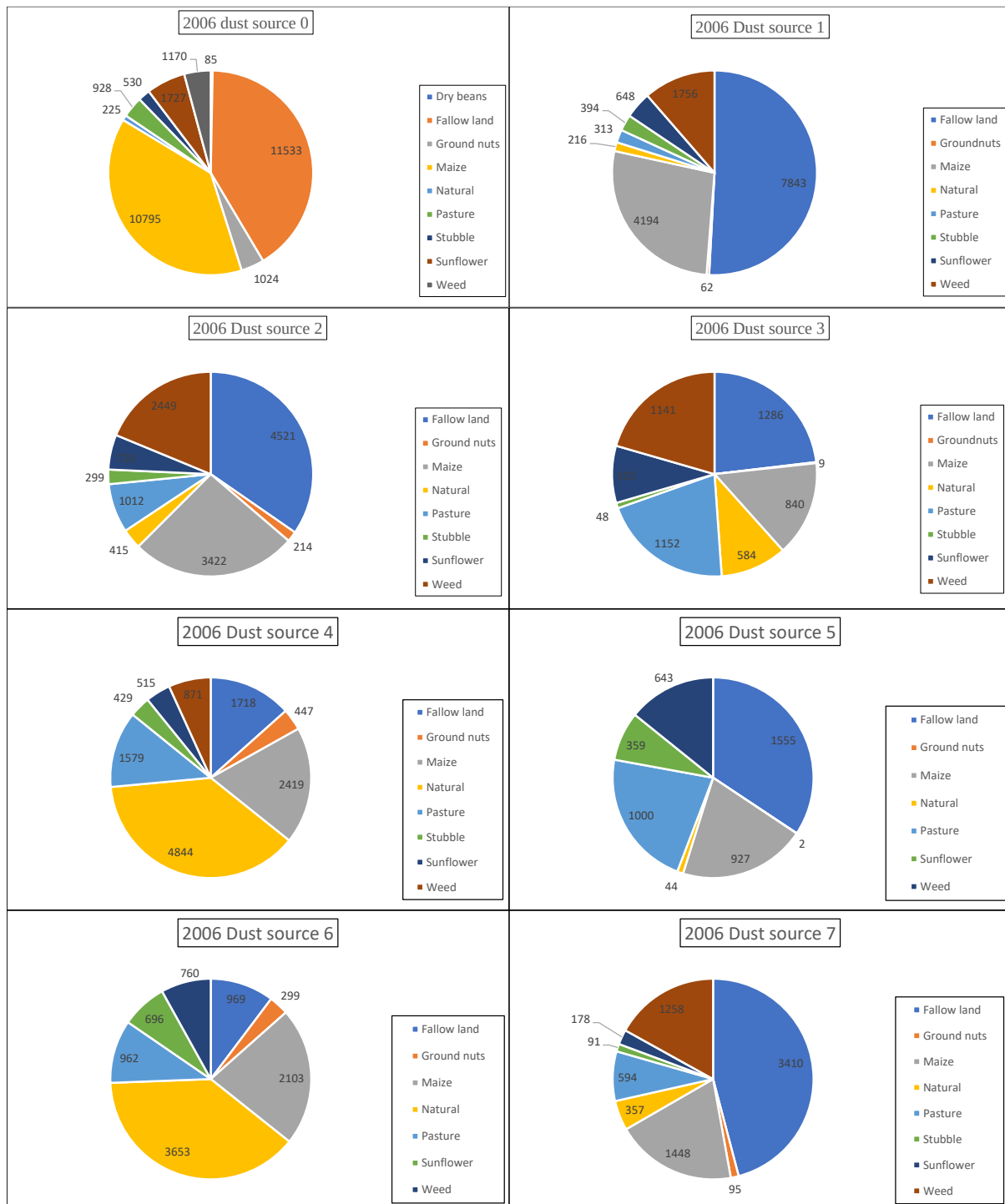
Appendix 2.4: Crop and land cover spatial and temporal variation, dust points and weather stations from 2006 – 2016 zoomed into the western part of Free State Province

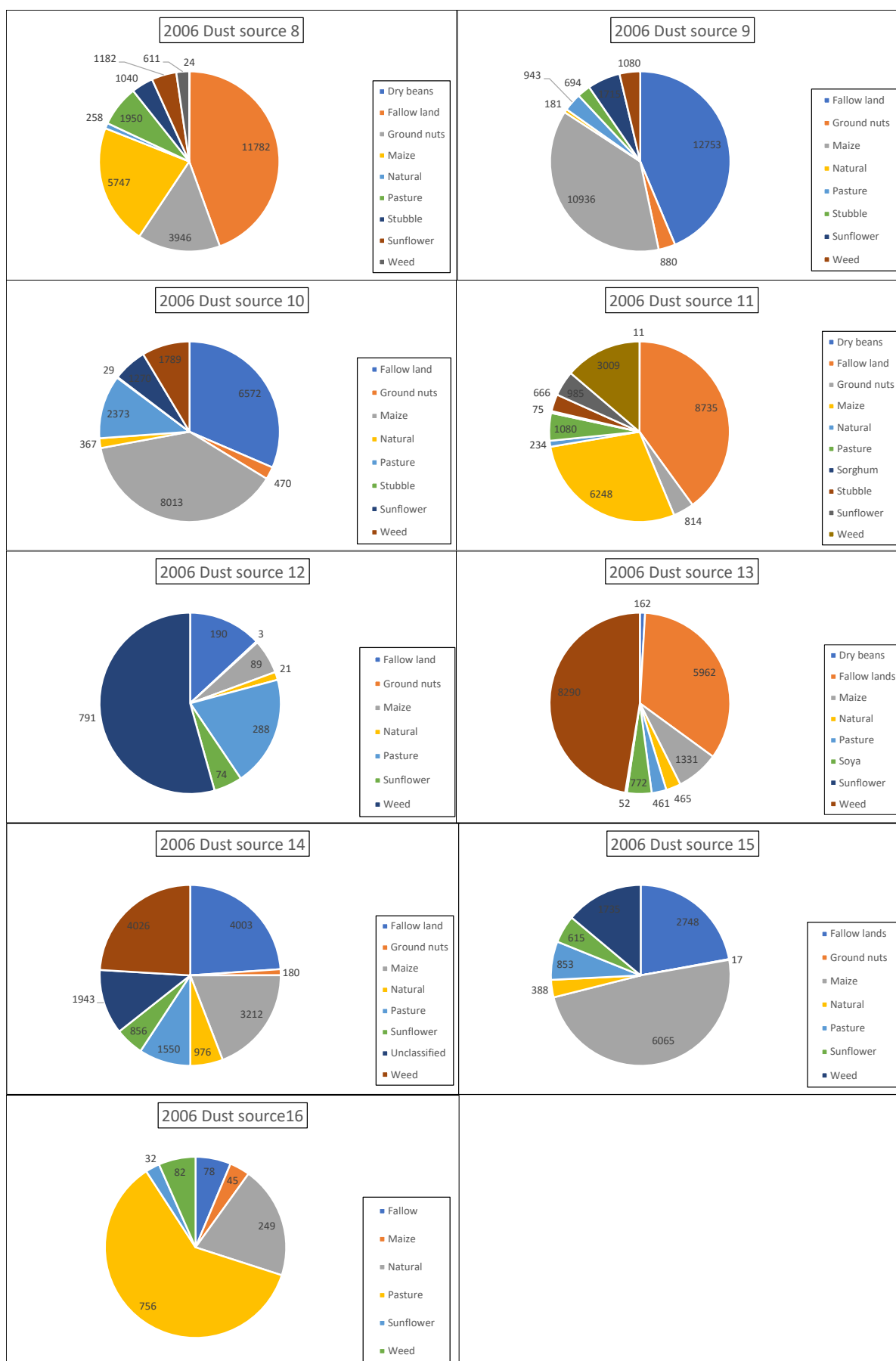




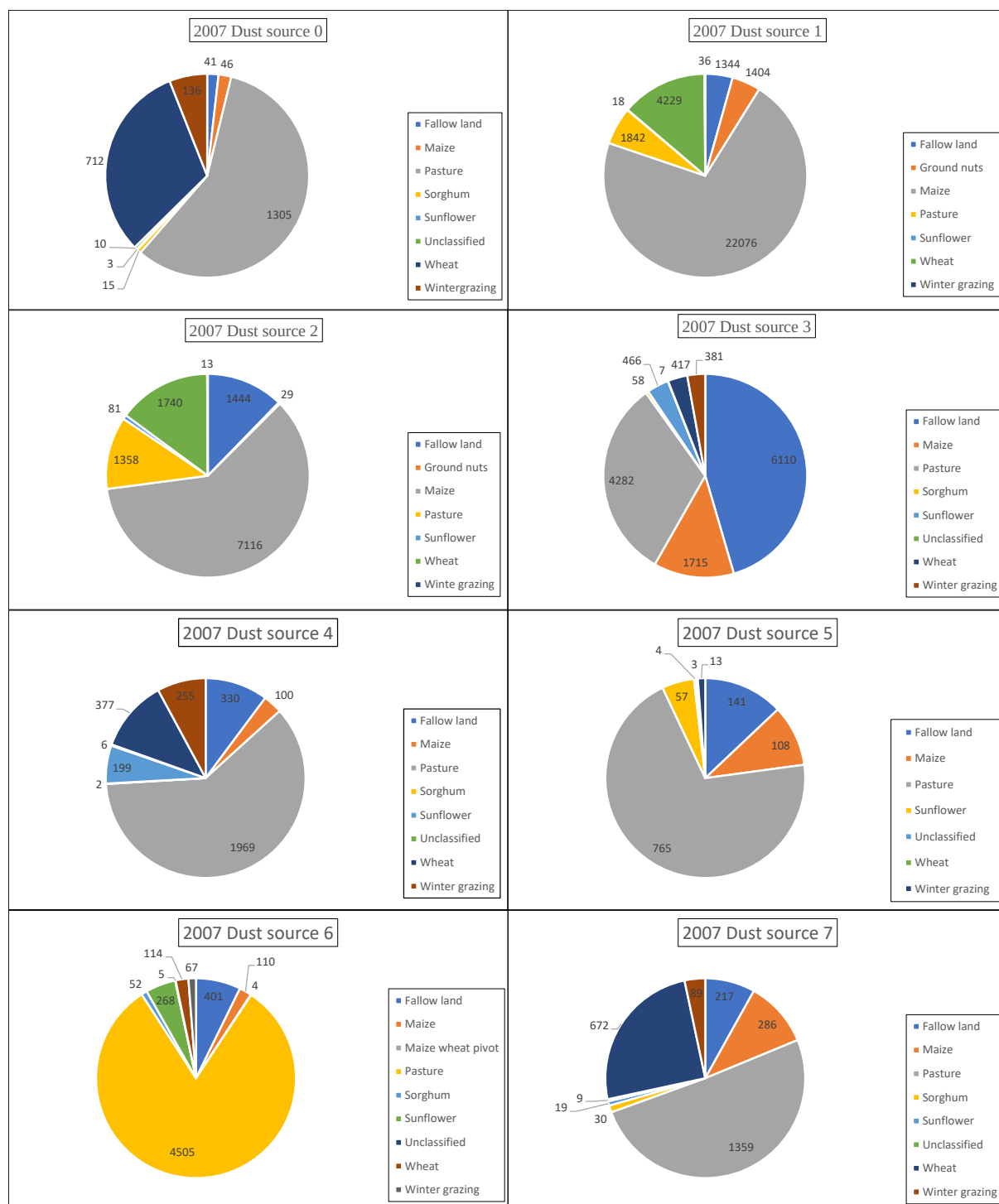


## Appendix 2.5: Dust sources area composition in 2006 in the Free State Province





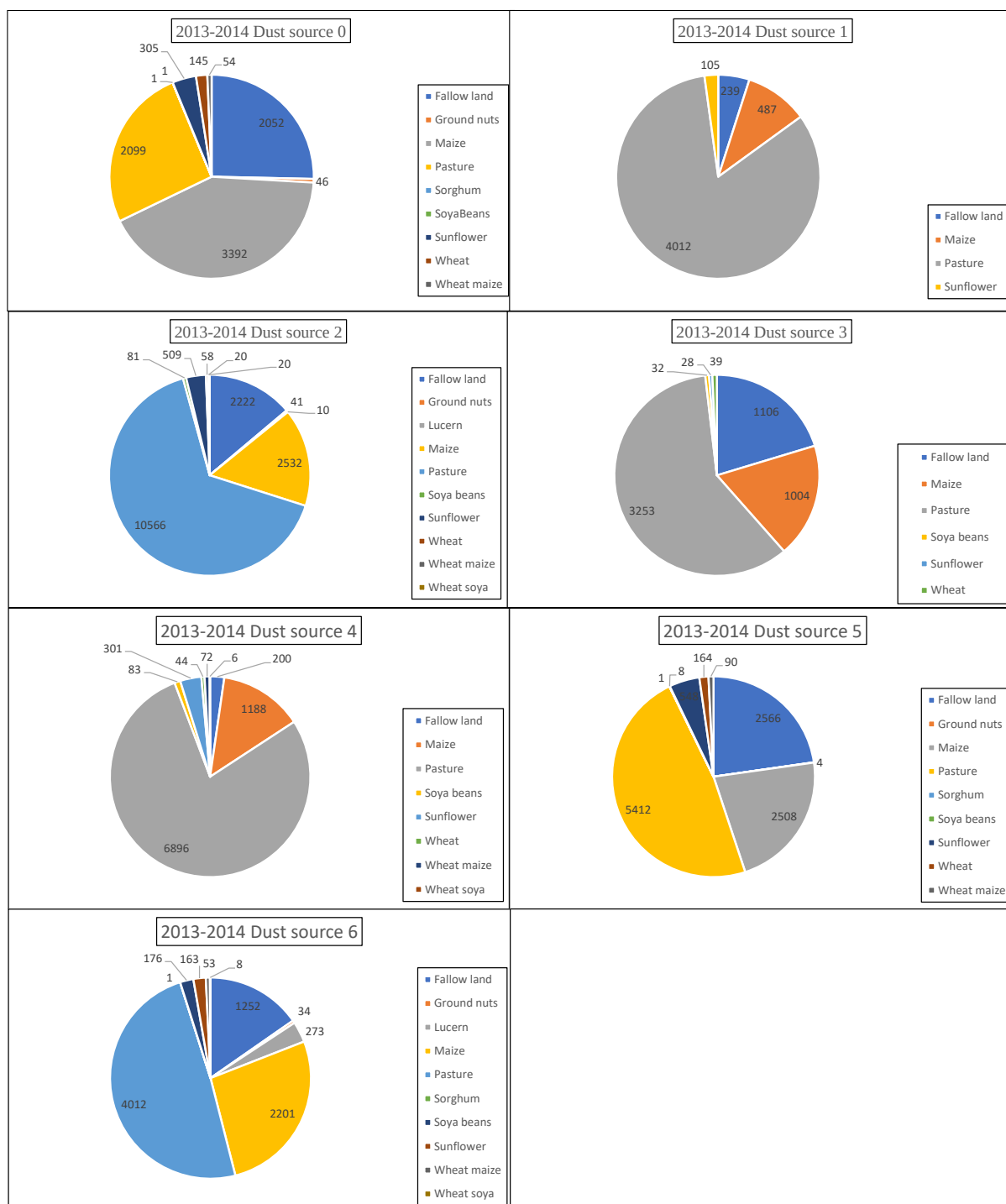
## Appendix 2.6: Dust sources area composition in 2007 in the Free State Province



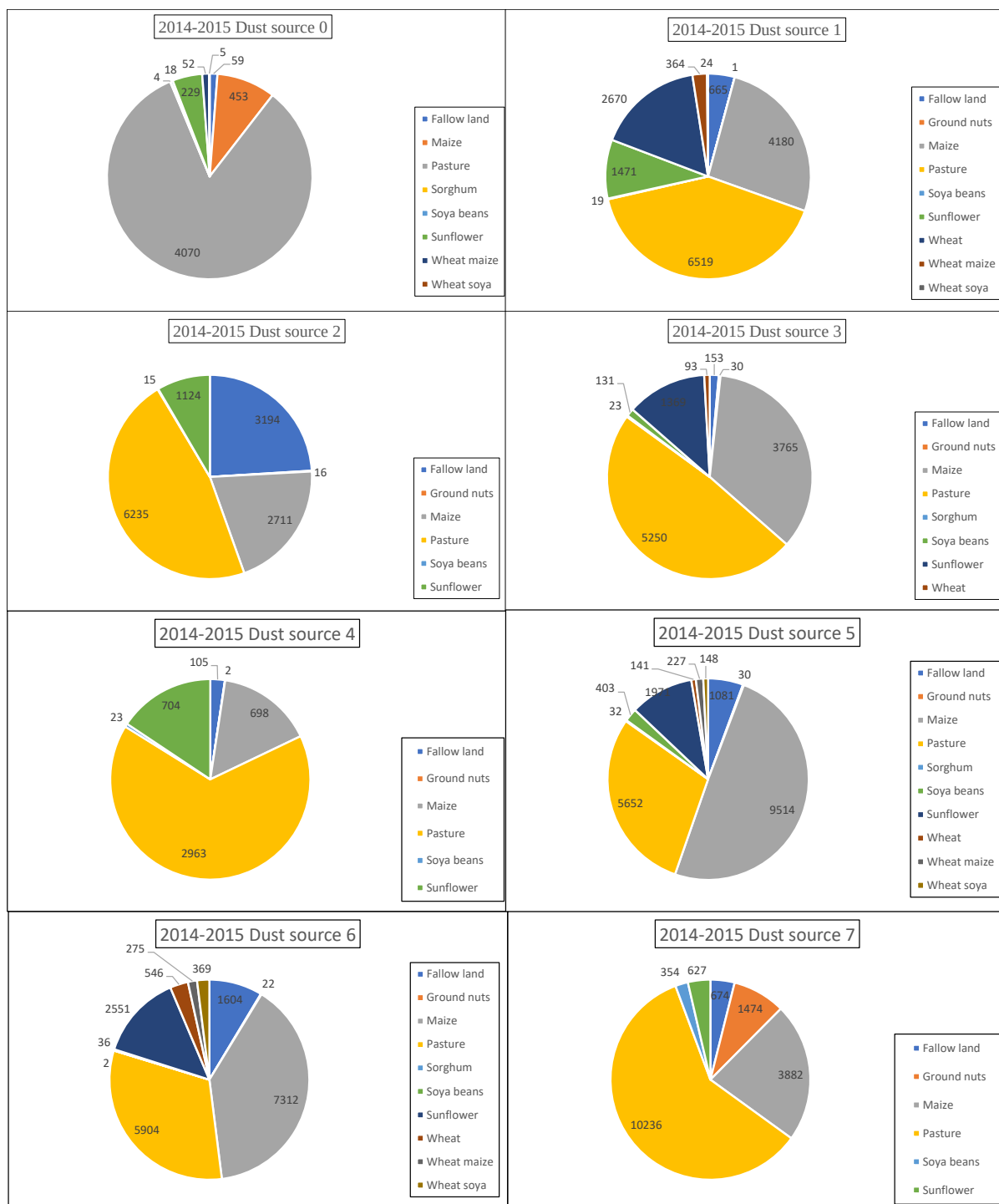


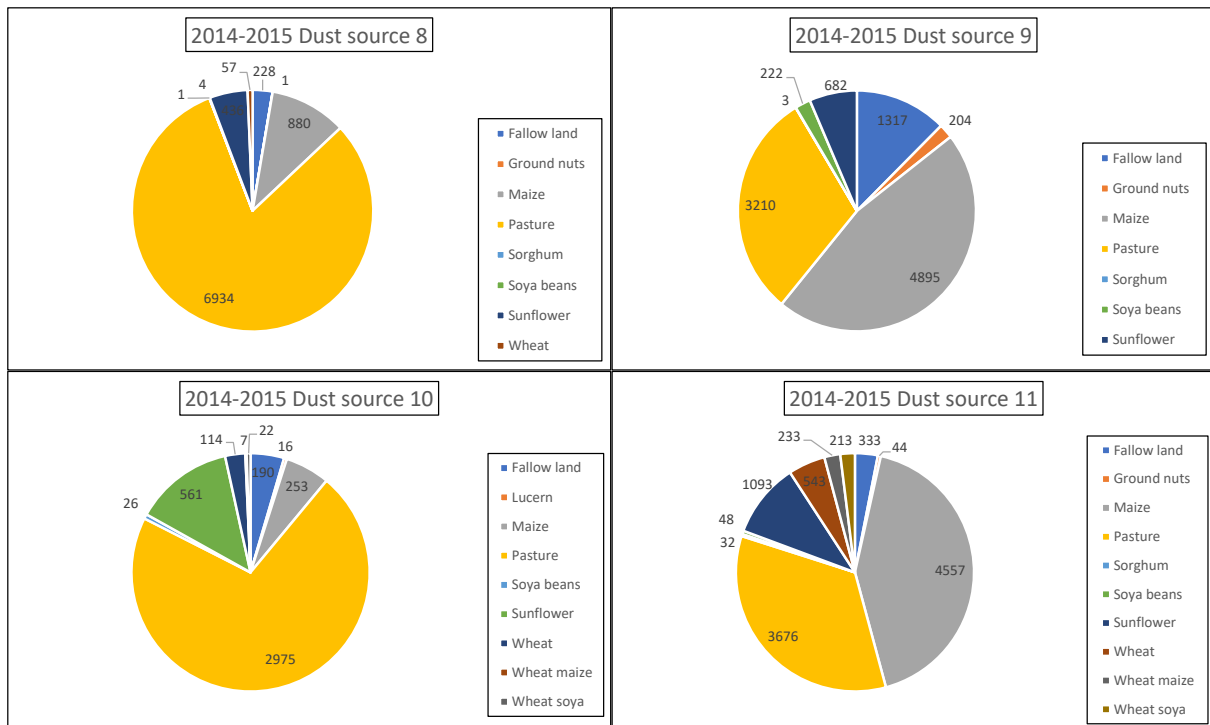


## Appendix 2.7: Dust sources area composition in 2013-2014 in the Free State Province

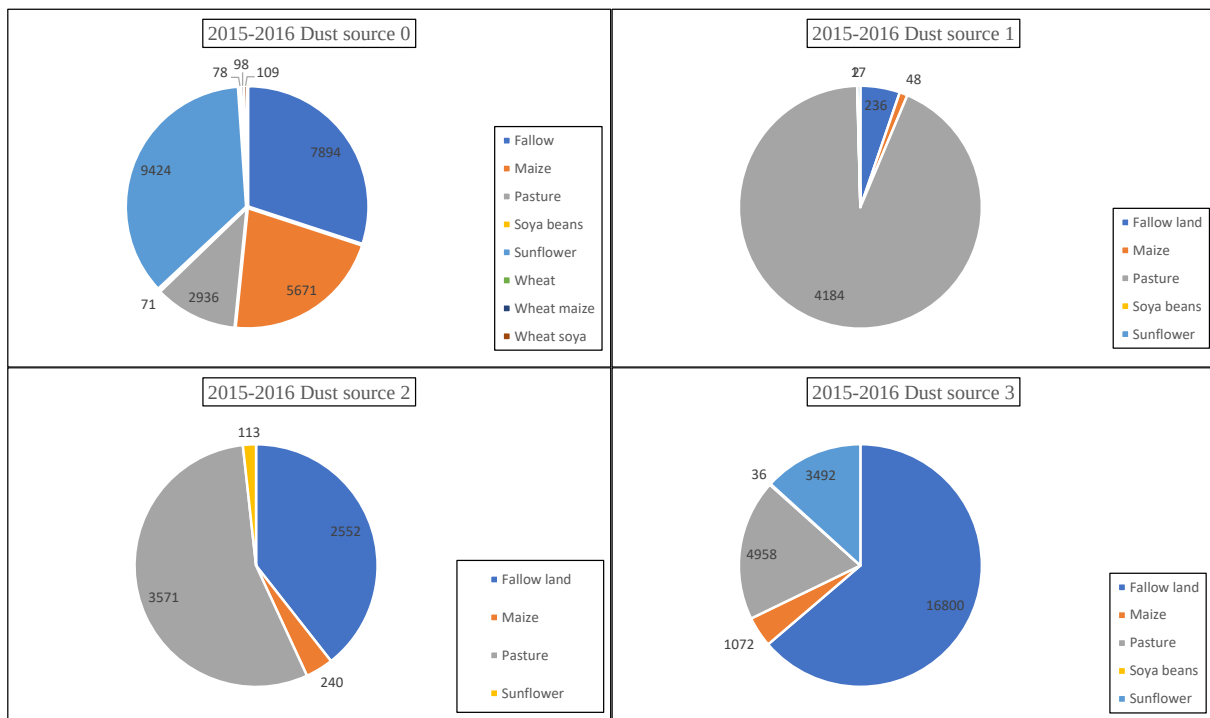


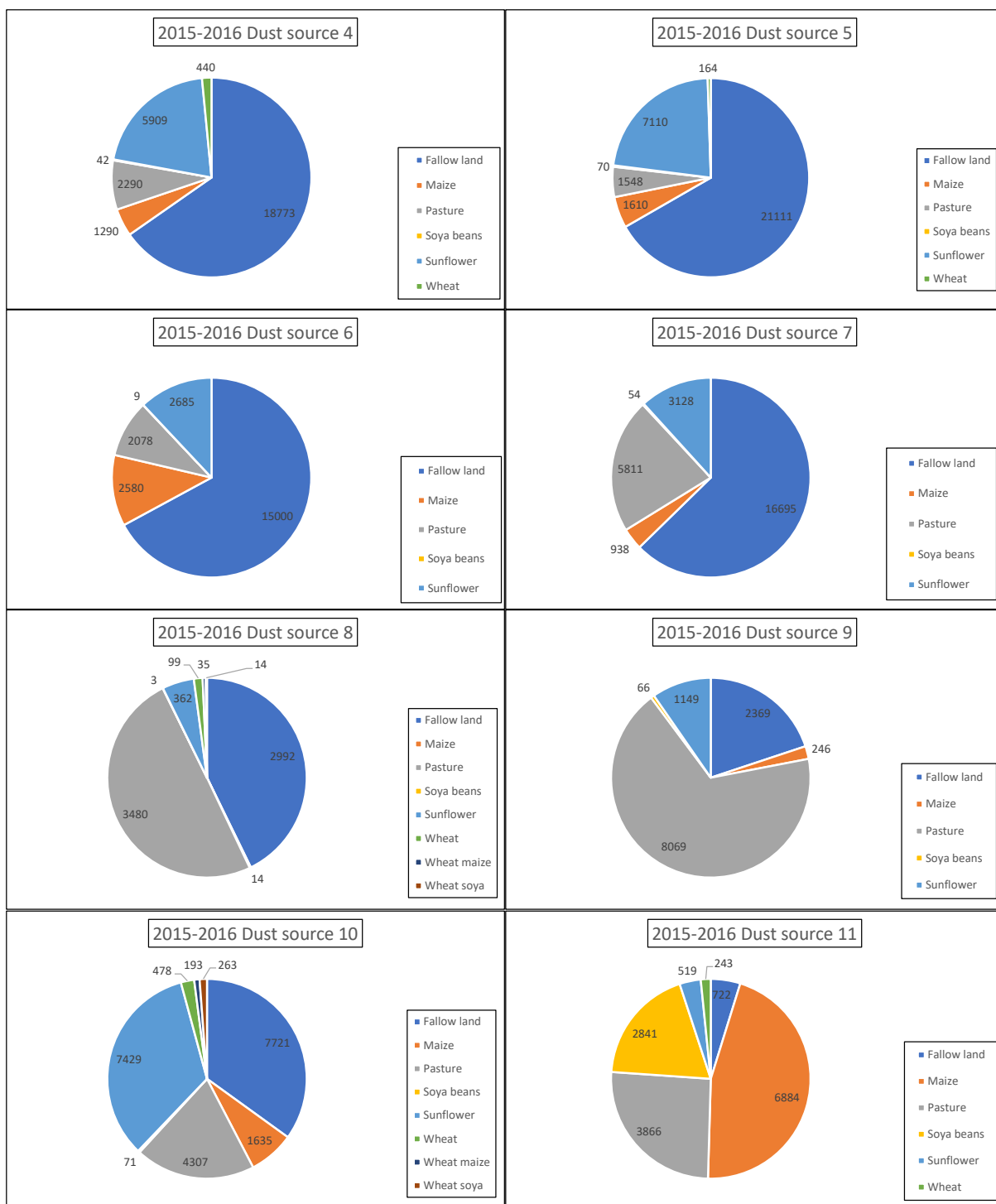
## Appendix 2.8: Dust sources area composition in 2014-2015 in the Free State Province

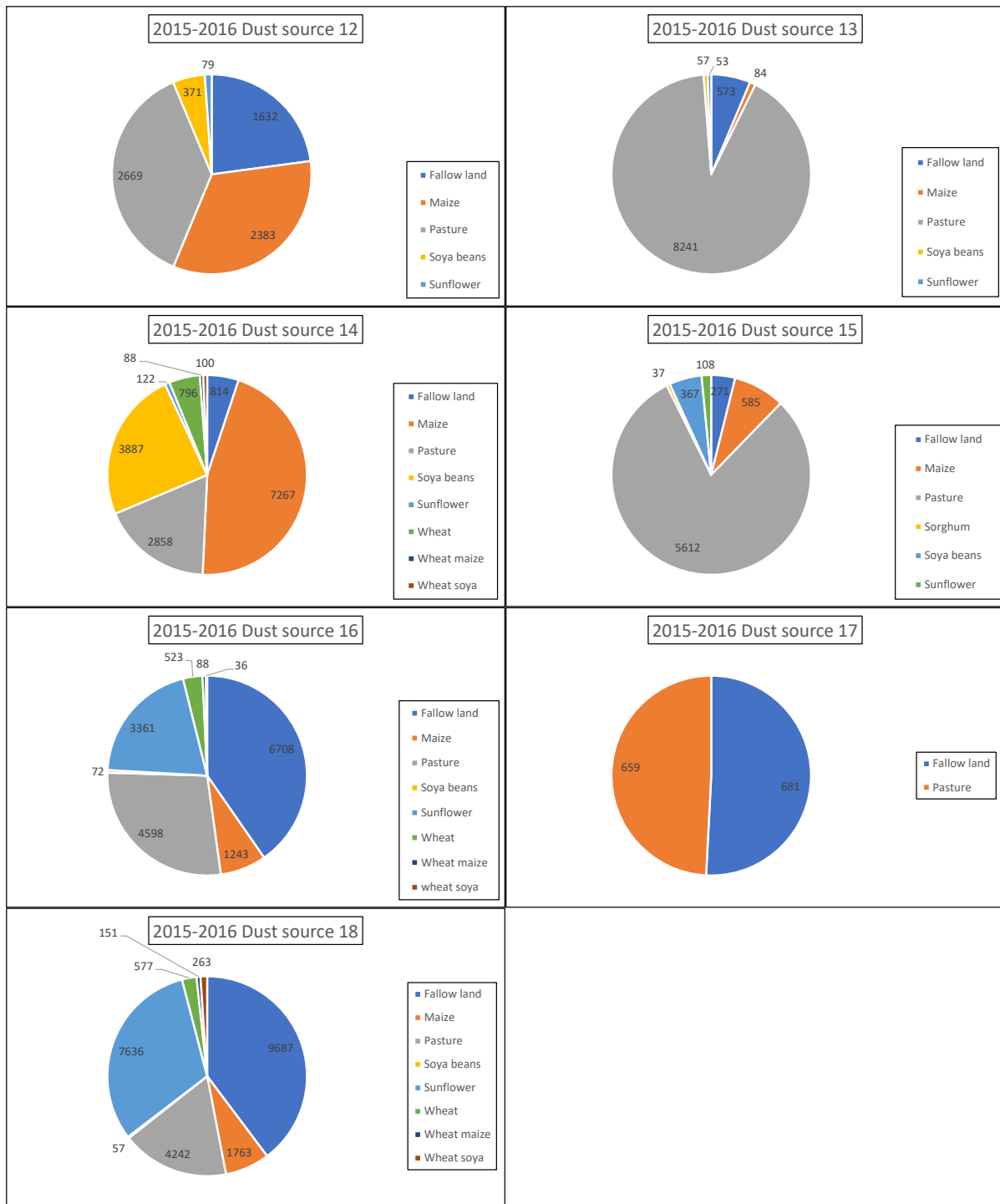




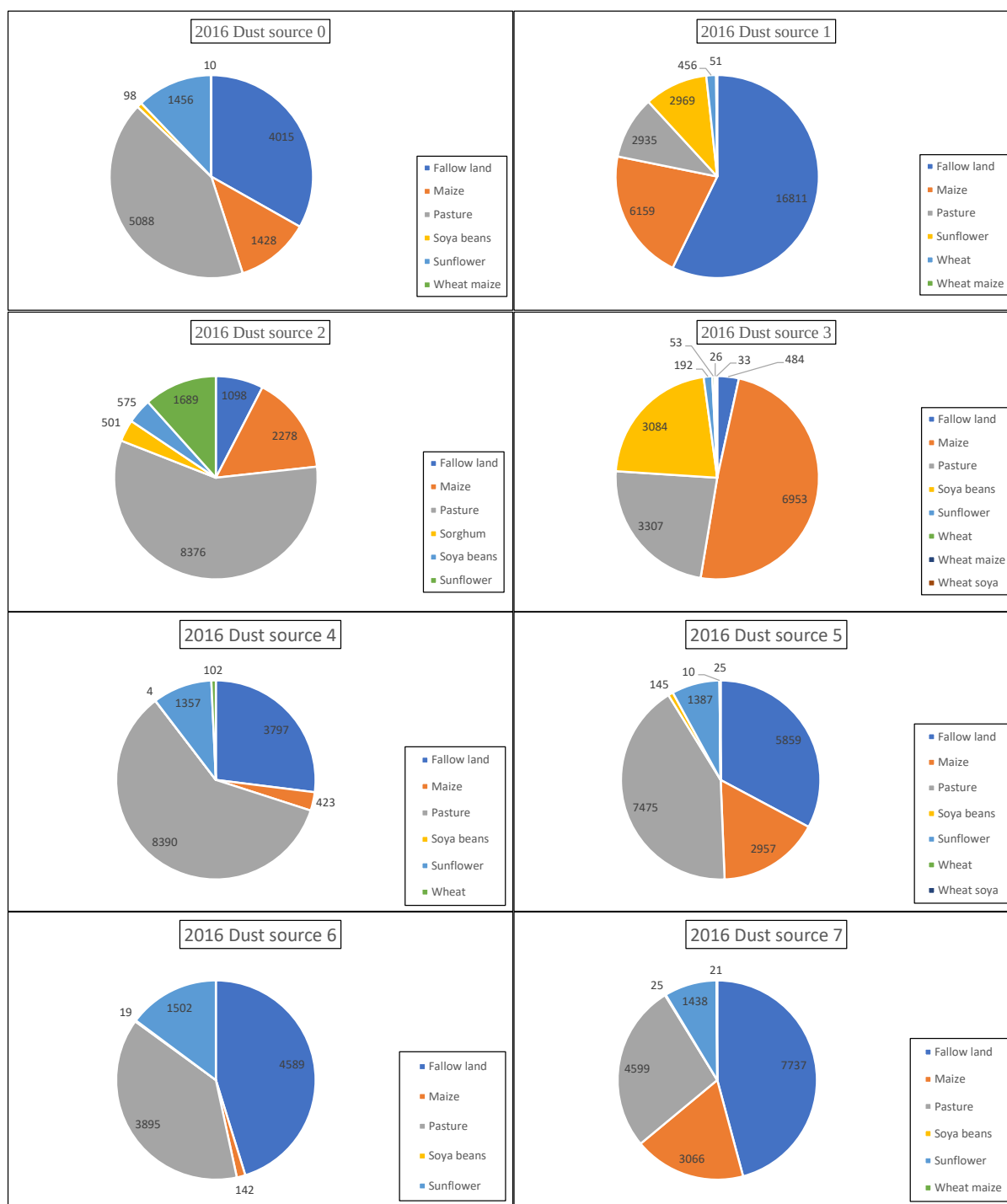
Appendix 2.9: Dust sources area composition in 2015-2016 in the Free State Province





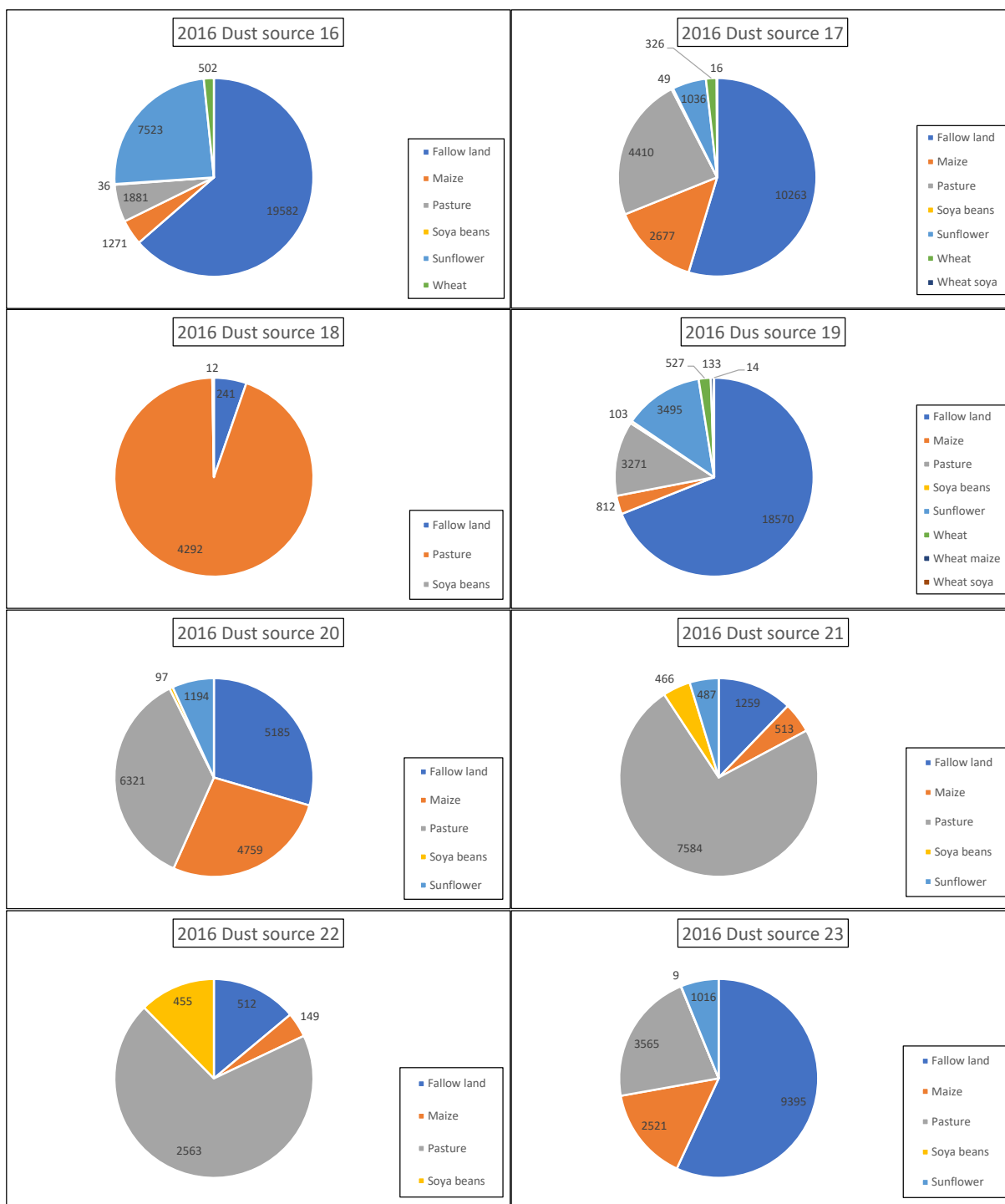


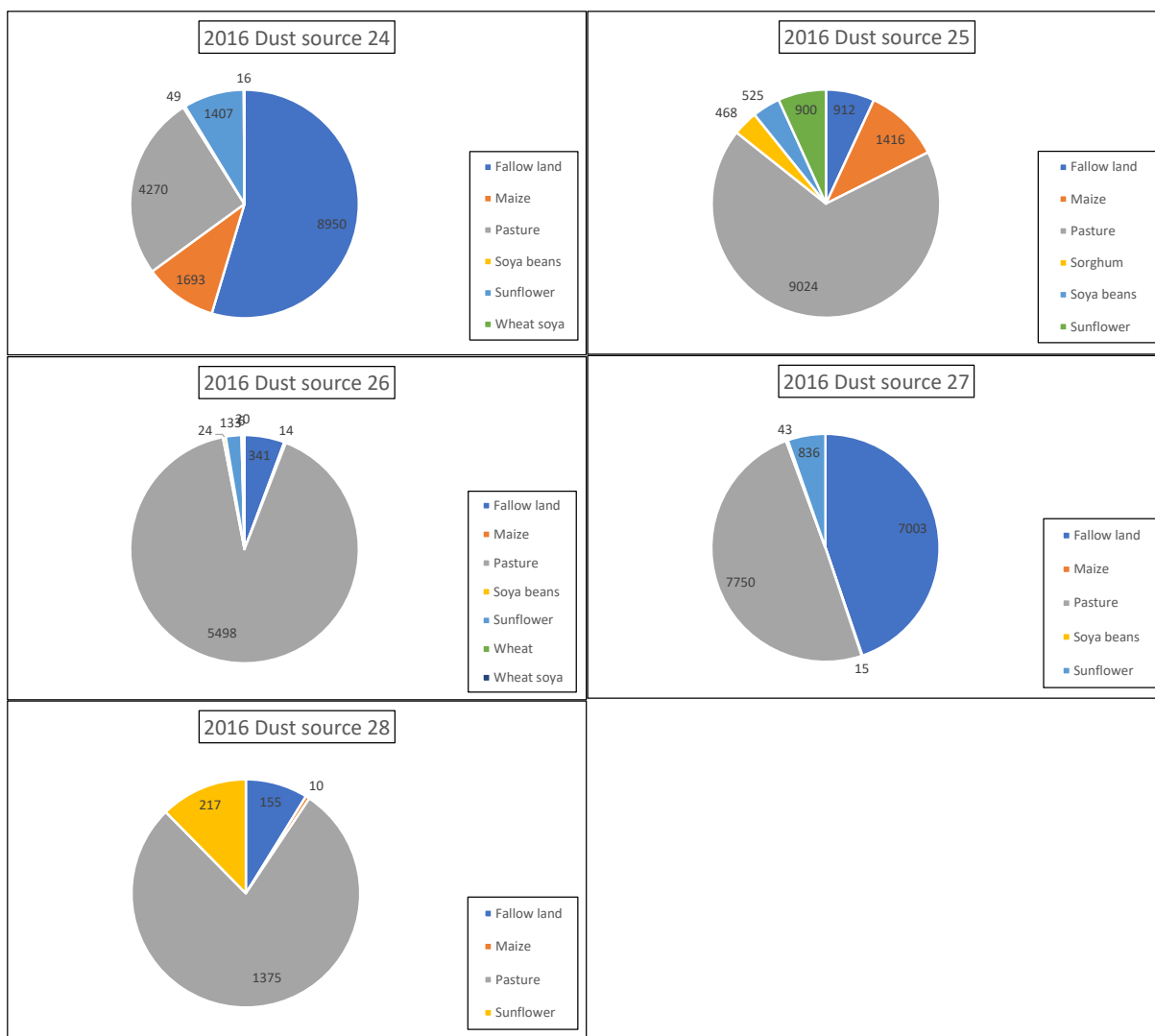
## Appendix 2.10: Dust sources area composition in 2016 in the Free State Province











### Appendix 3.1: Example of Java script used to extract CHIRPS for weather stations

```
// Plot CHIRPS band value means in a section of SADust MSG
// demonstrate interactive charts.

var a200608291 = ee.Geometry.Rectangle(26.06358,-28.15282,26.07235,-28.16246);

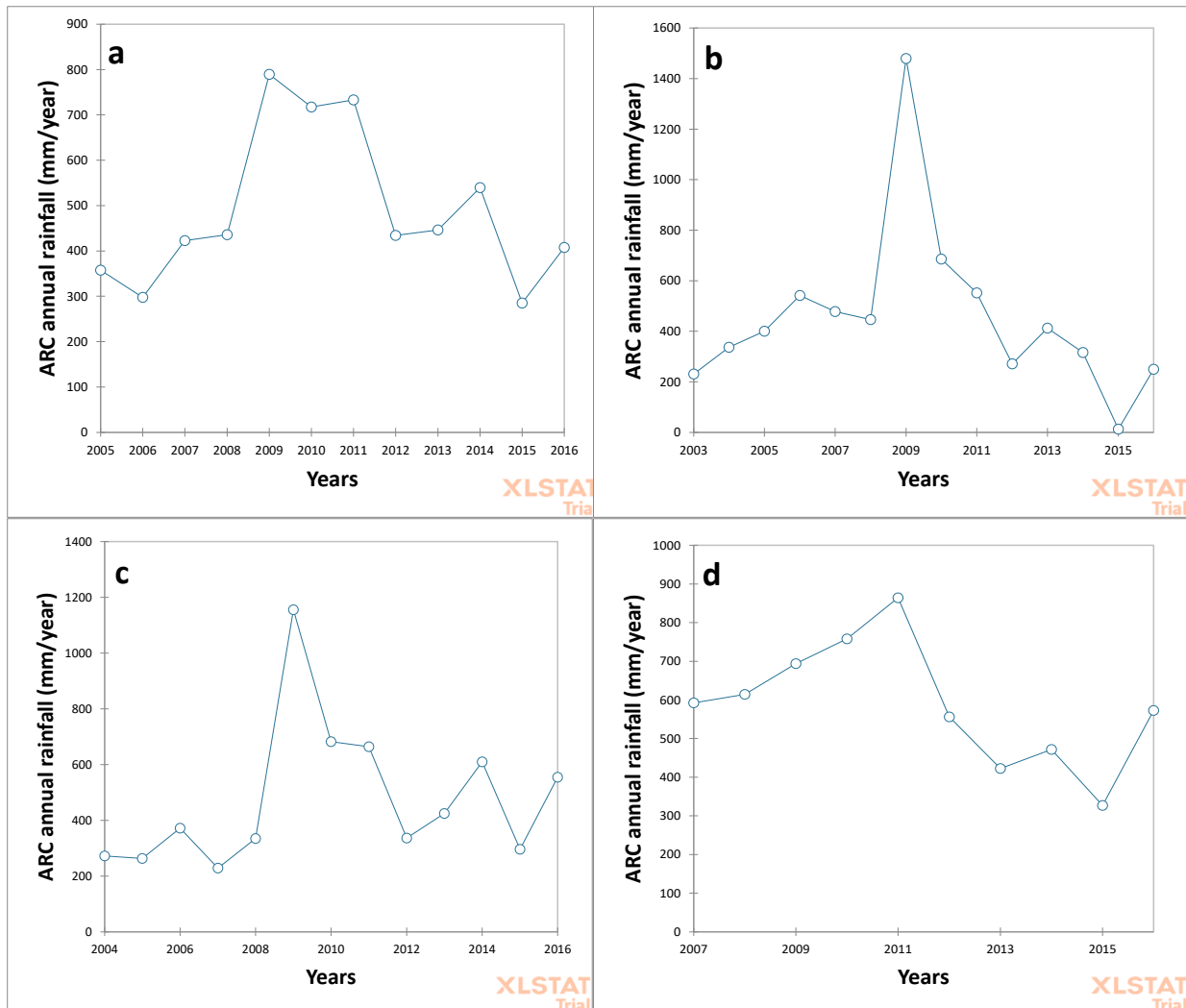
var modisLAI = ee.ImageCollection('UCSB-CHG/CHIRPS/DAILY')
  .filterDate('2005-01-01', '2005-12-31')
  .select('precipitation');

// Create an image time series chart.
var chart = ui.Chart.image.series({
  imageCollection: modisLAI,
  region: a200608291,
  reducer: ee.Reducer.mean(),
  scale: 200
});

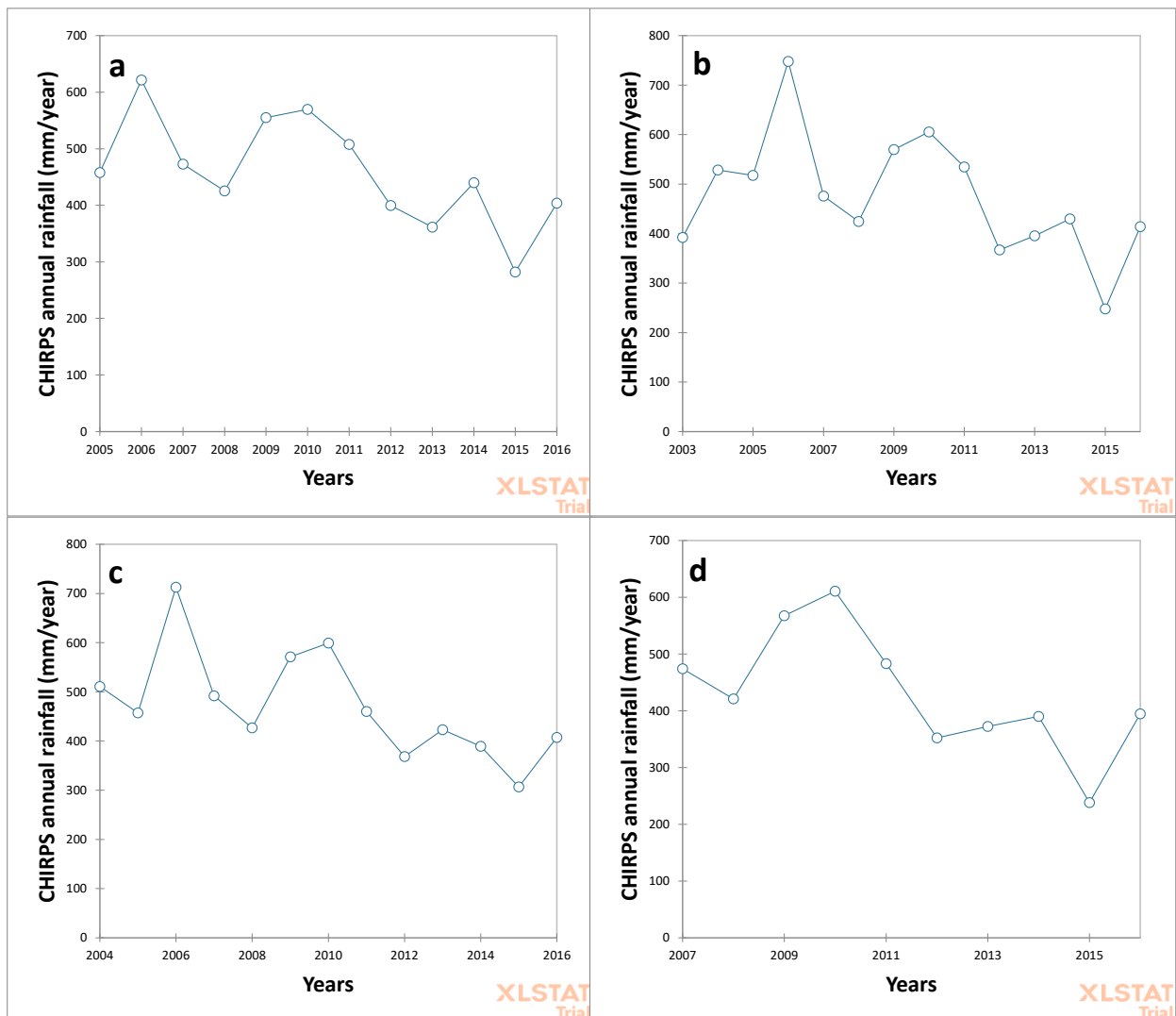
// Add the chart to the map.
chart.style().set({
  position: 'top-left',
  width: '500px',
  height: '300px'
});
Map.add(chart);

// Outline and center area on the map.
var sfLayer = ui.Map.Layer(a200608291, {color: 'FF0000'}, 'SF');
Map.layers().add(sfLayer);
Map.setCenter(26.063, -28.152);
```

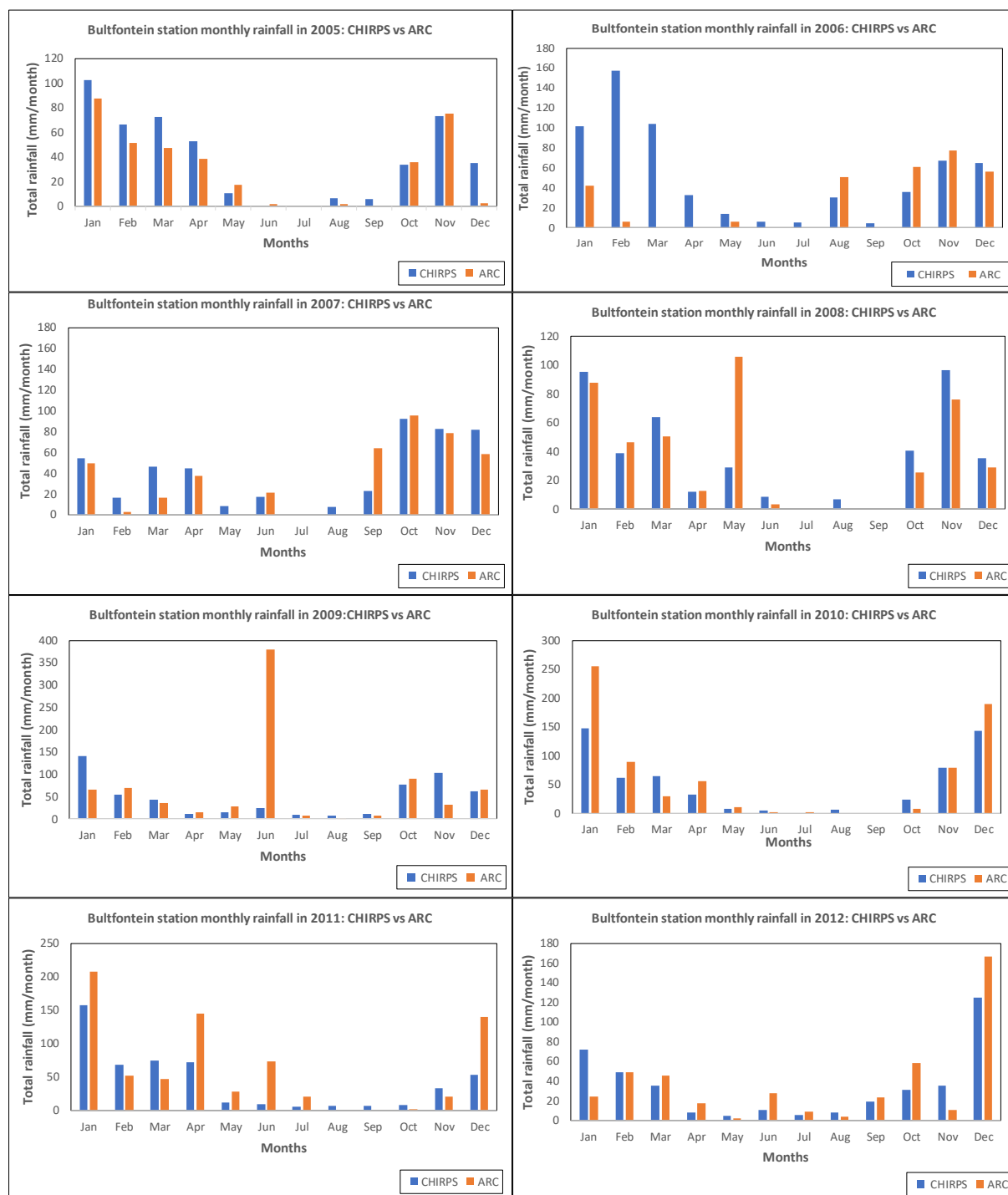
Appendix 3.2: Trend in ARC annual rainfall (a) Bultfontein, (b) Hoopstad, (c) Wesselsbron and (d) Wolmaranstad.

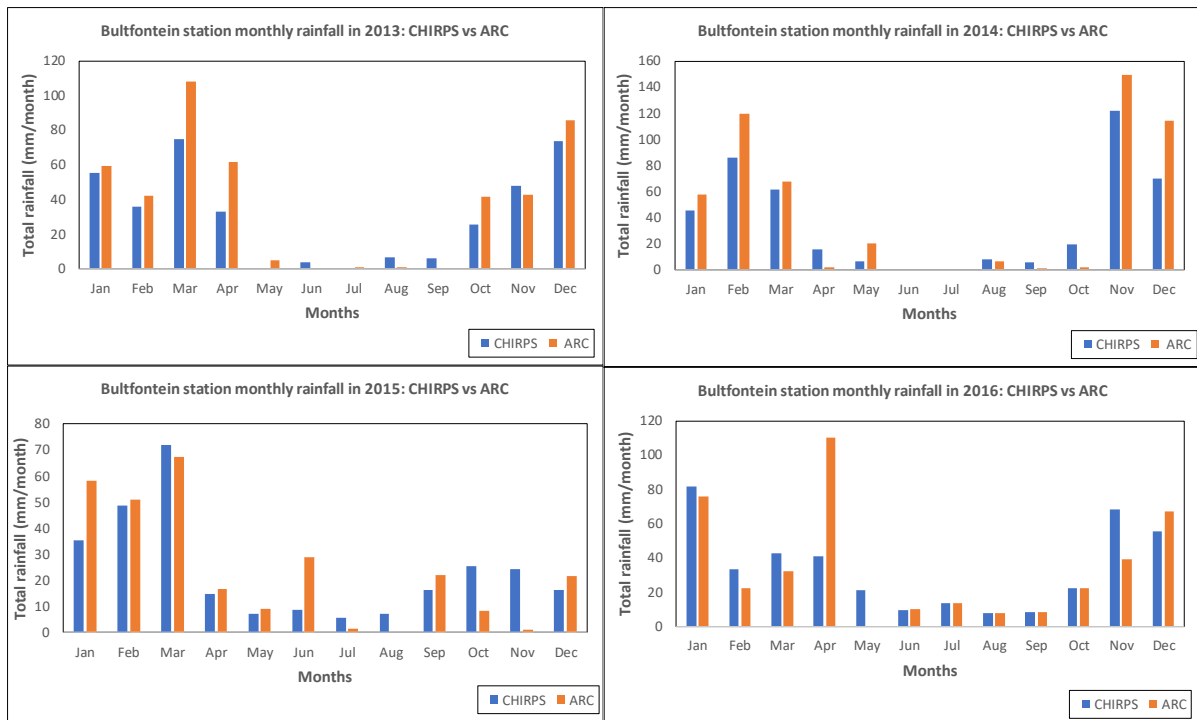


Appendix 3.3: Trend in CHIRPS annual rainfall (a) Bultfontein, (b) Hoopstad, (c) Wesselsbron and (d) Wolmaranstad.

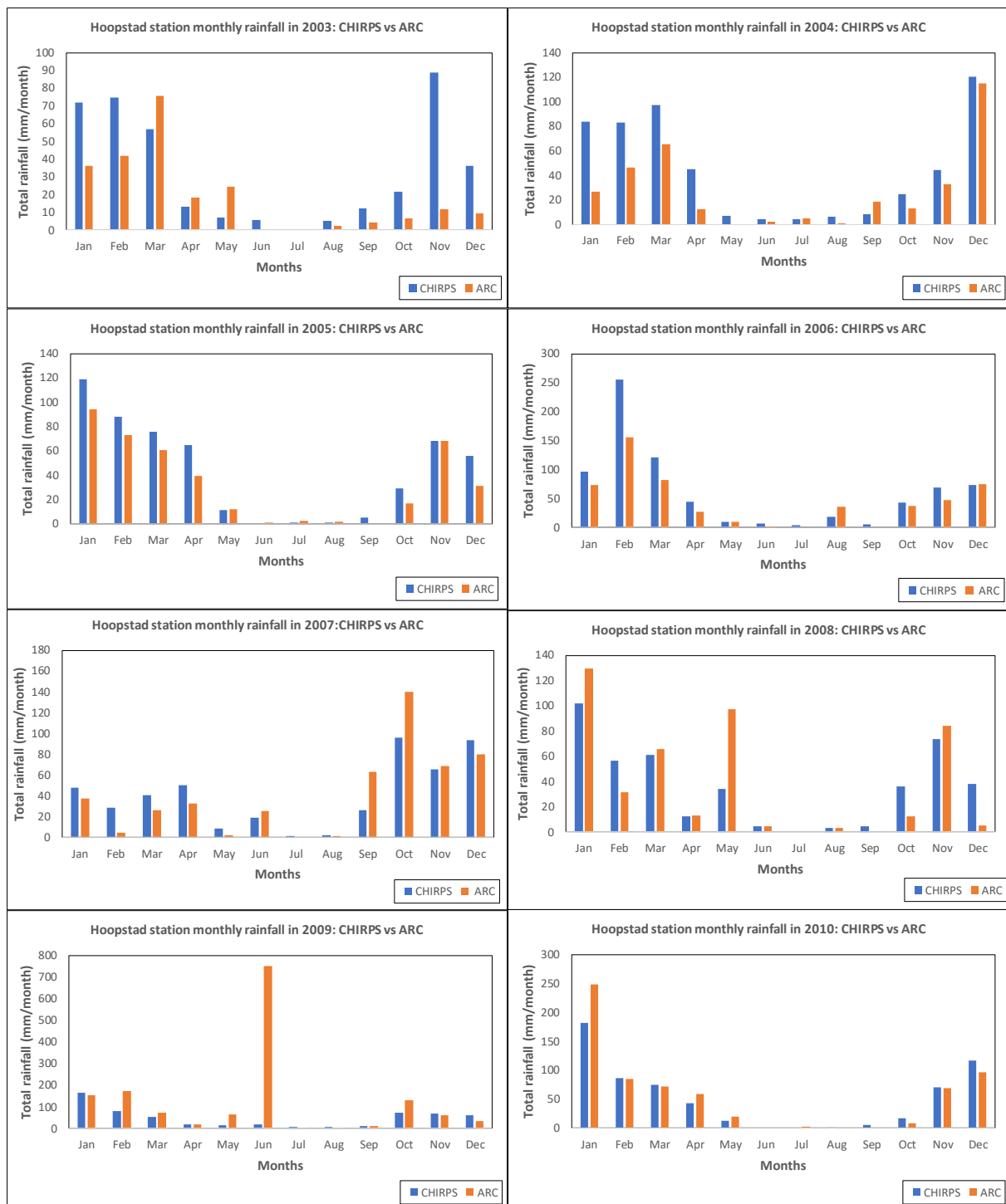


## Appendix 3.4: Total monthly rainfall from 2005-2016 in Bultfontein station: CHIRPS vs ARC

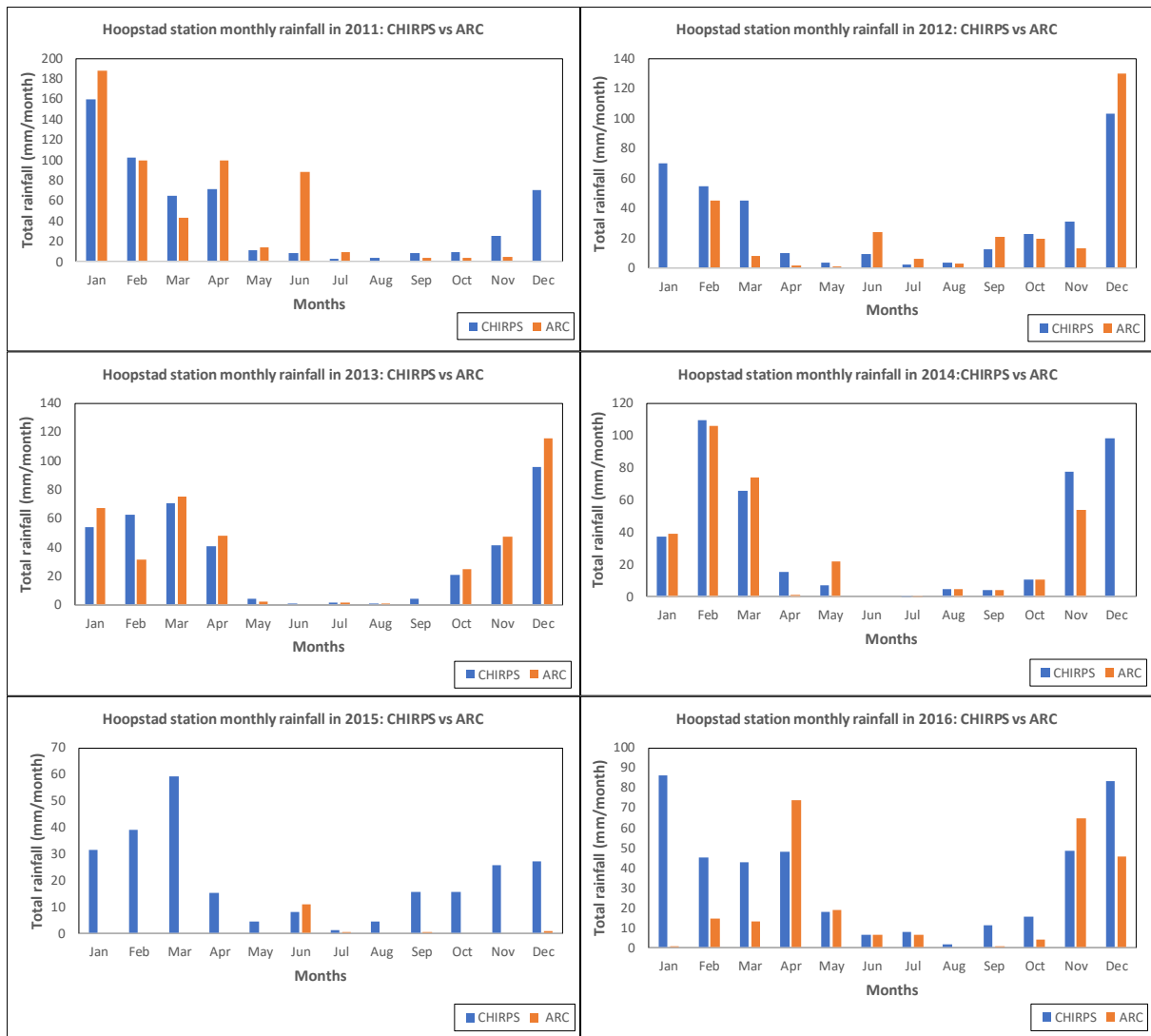




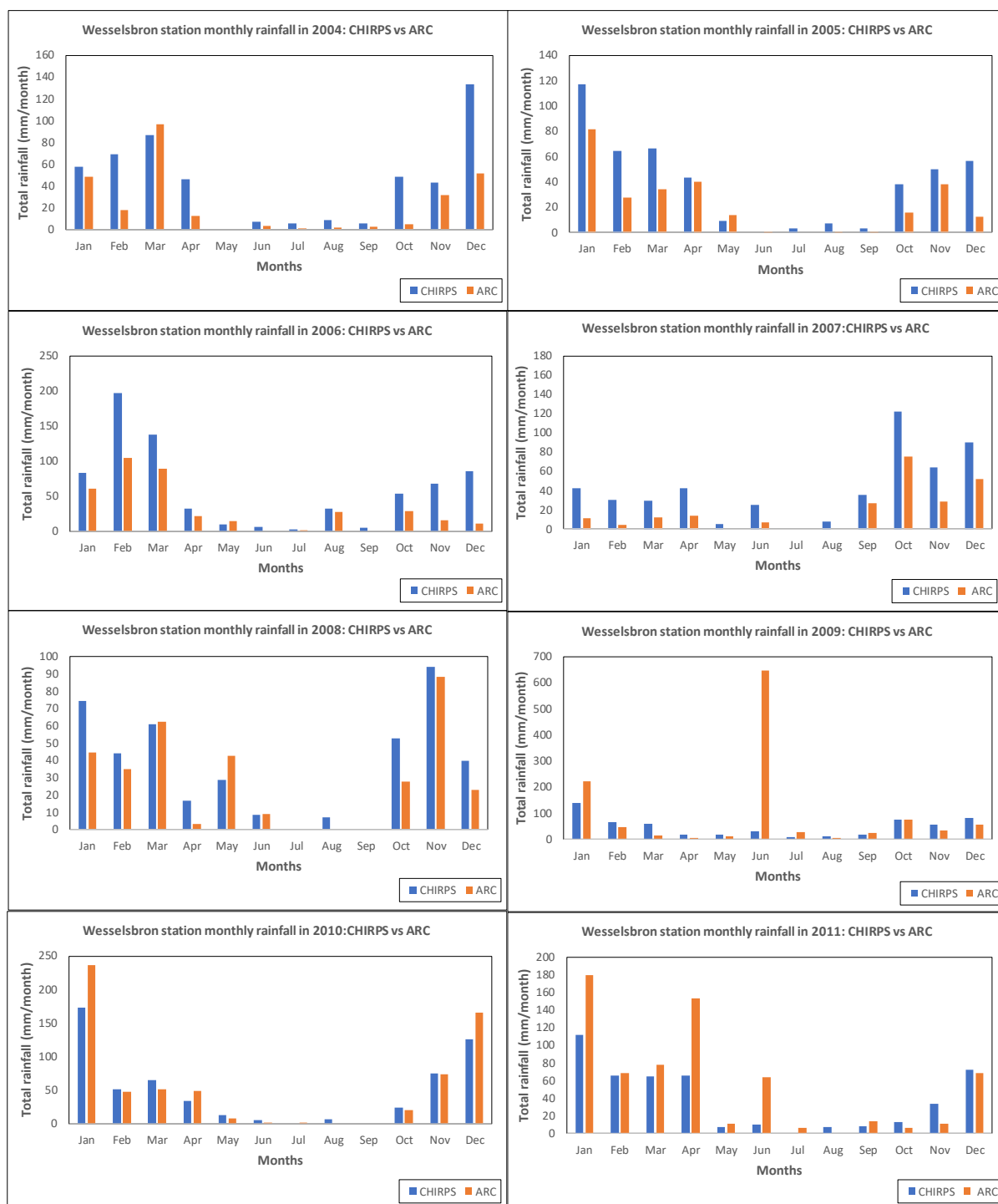
### Appendix 3.5: Total monthly rainfall from 2003-2016 in Hoopstad station: CHIRPS vs ARC

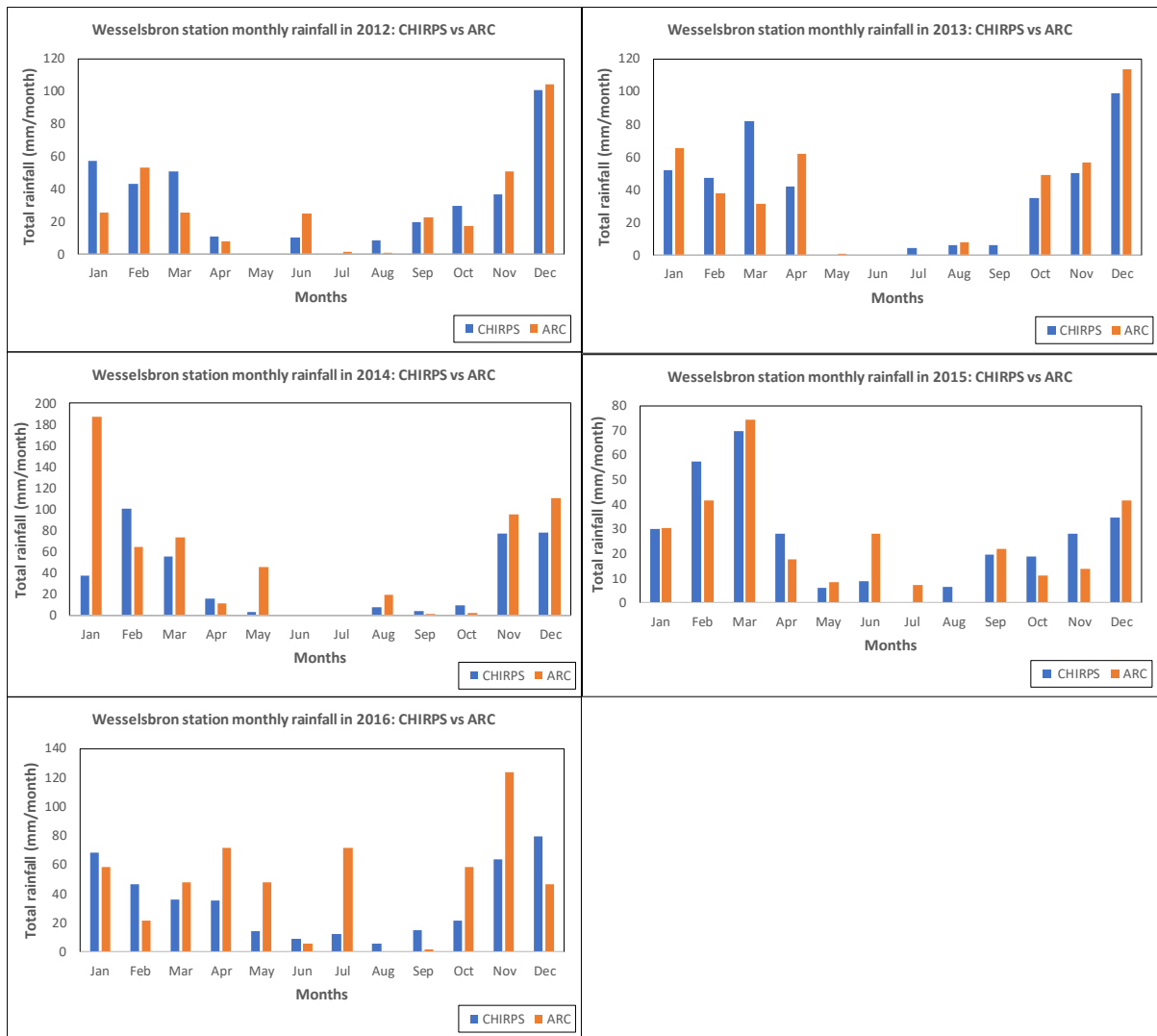




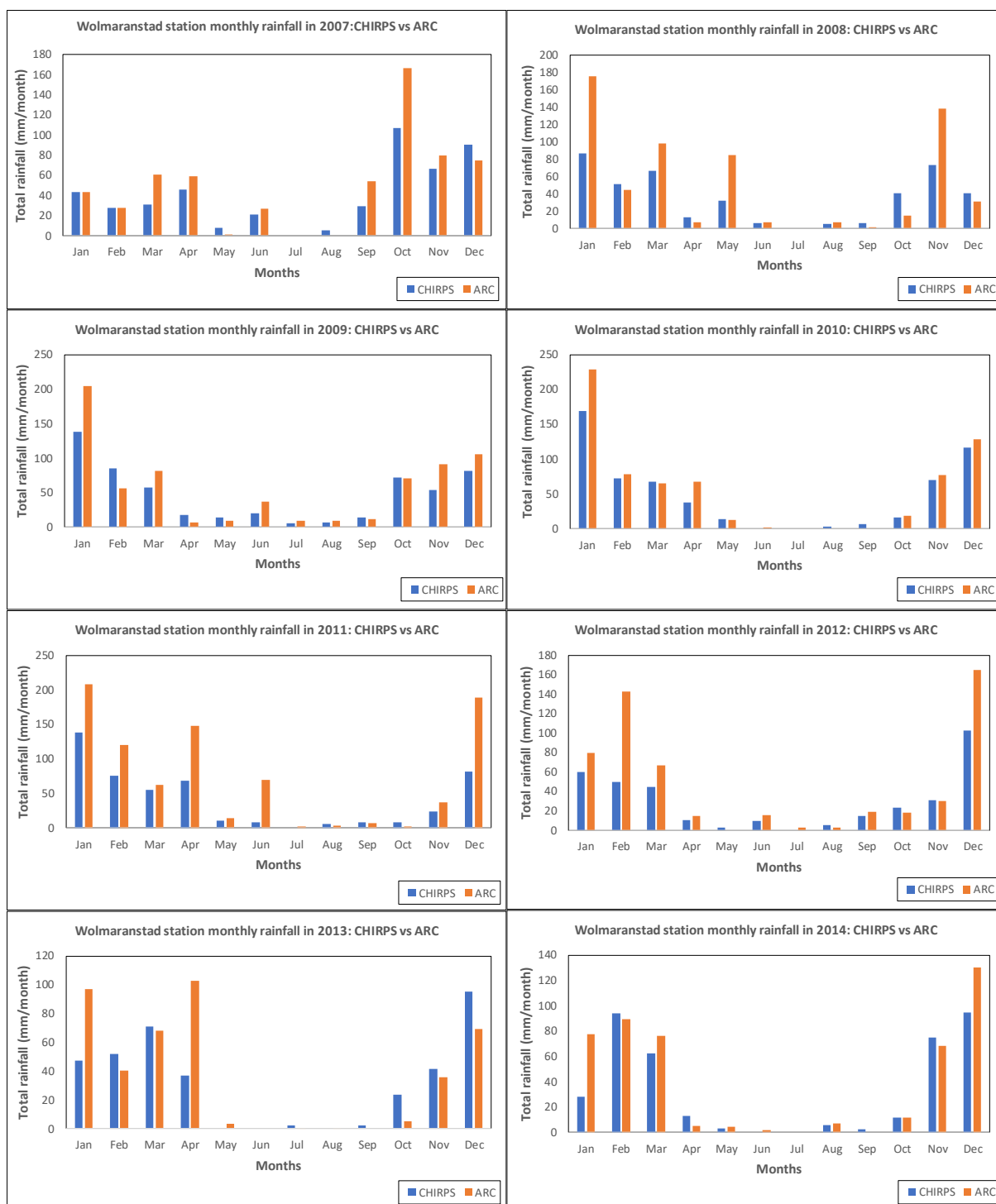


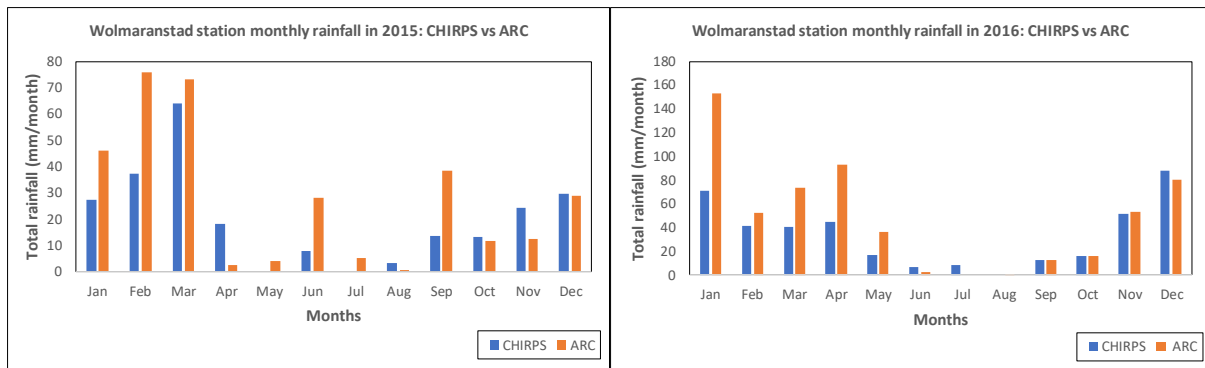
## Appendix 3.6: Total monthly rainfall from 2004-2016 in Wesselsbron station: CHIRPS vs ARC



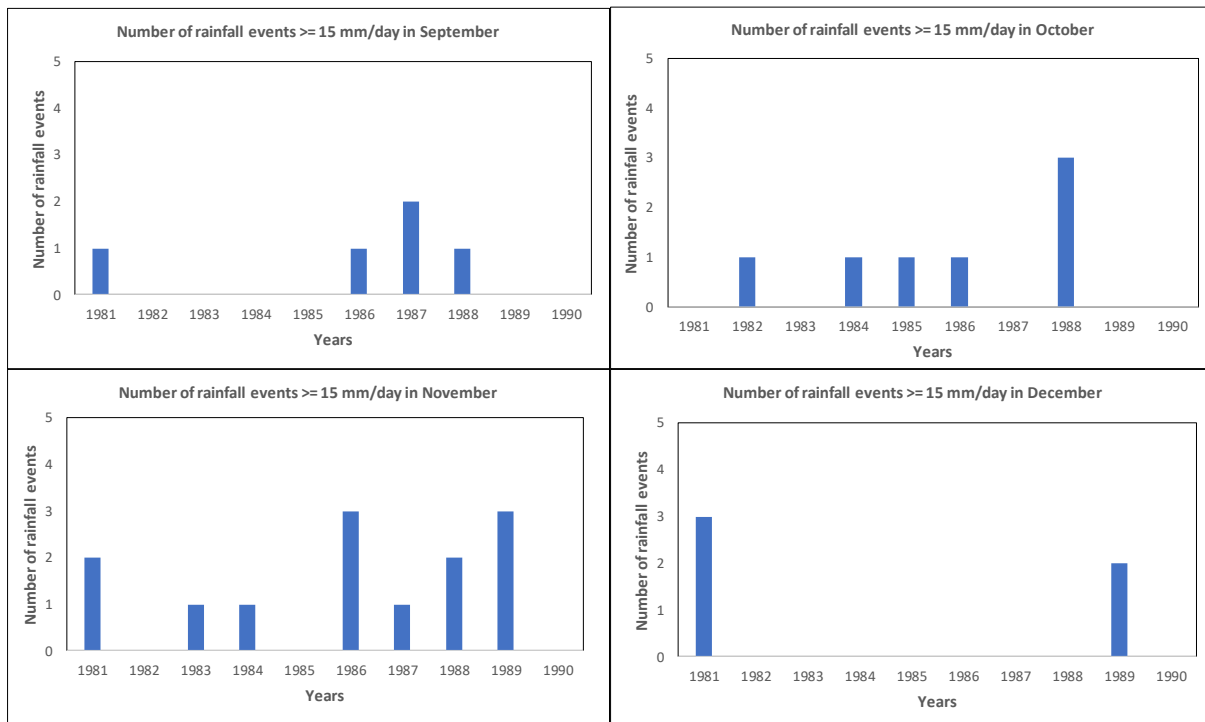


## Appendix 3.7: Total monthly rainfall from 2007-2016 in Wolmaranstad station: CHIRPS vs ARC

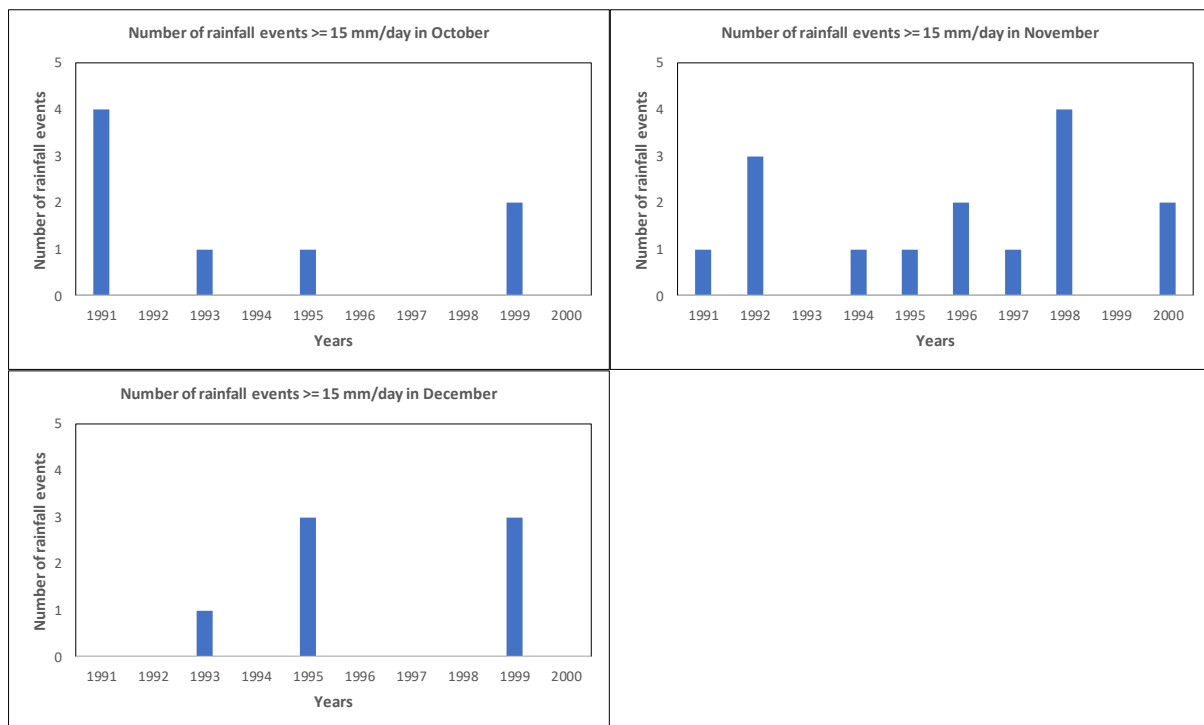




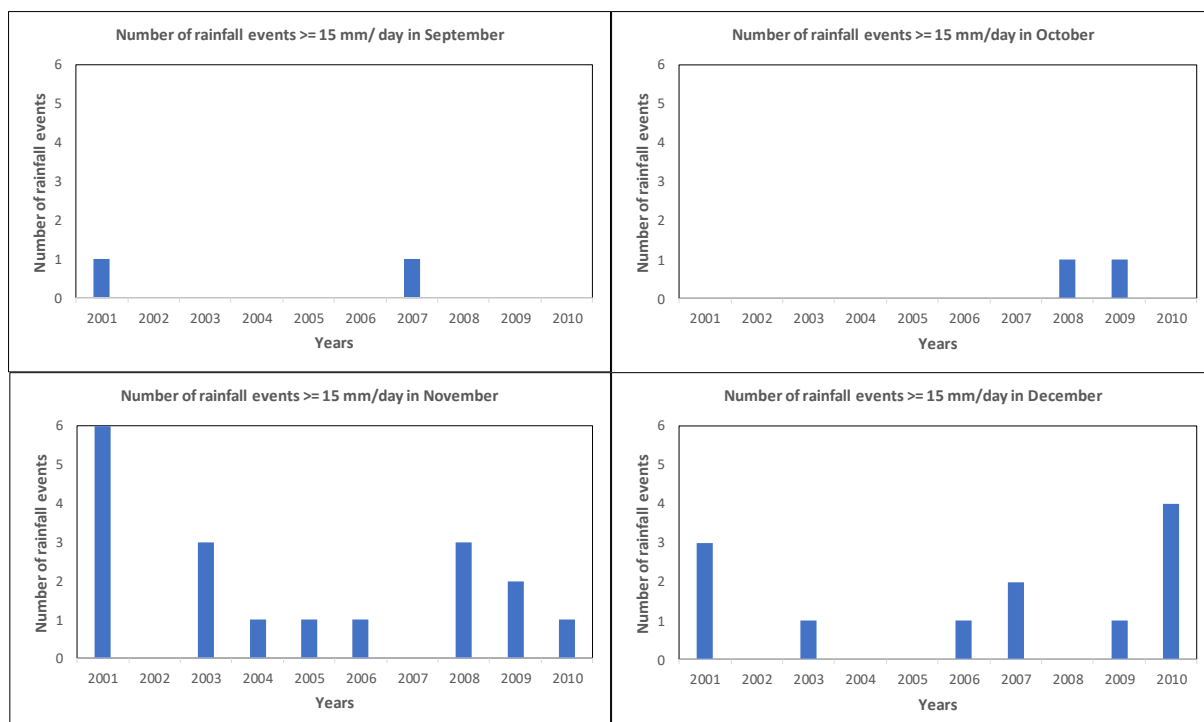
### Appendix 3.8: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Bultfontein



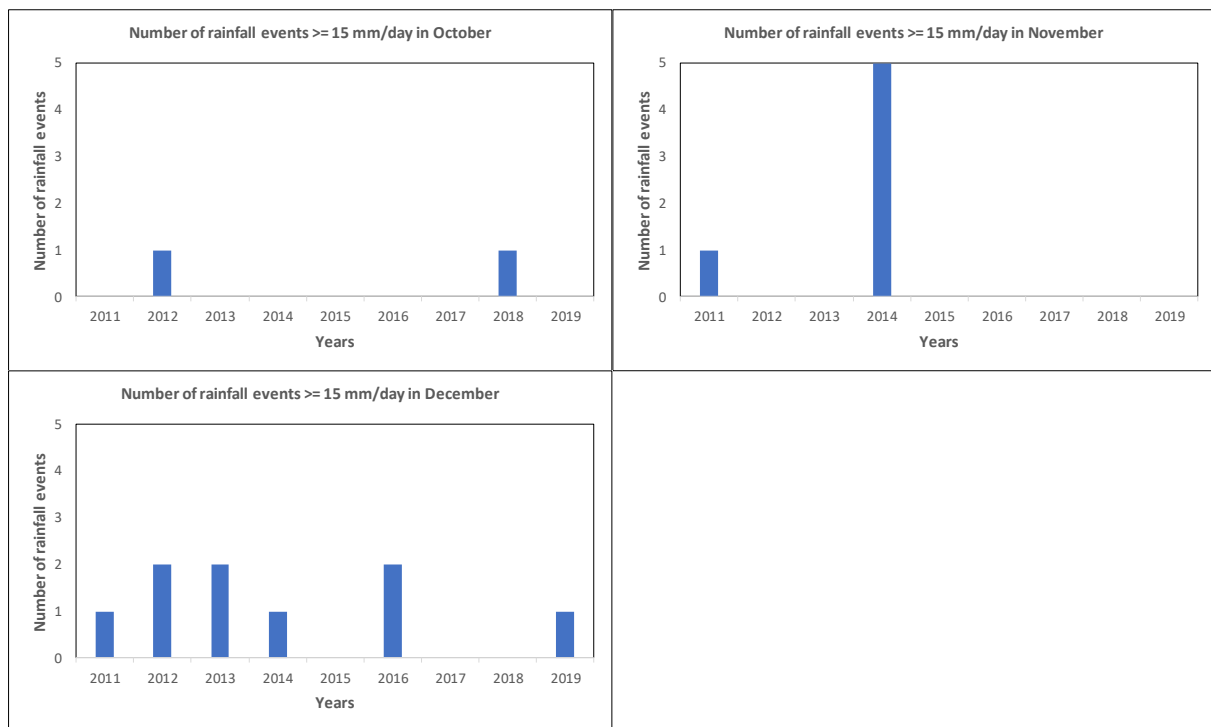
### Appendix 3.9: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Bultfontein



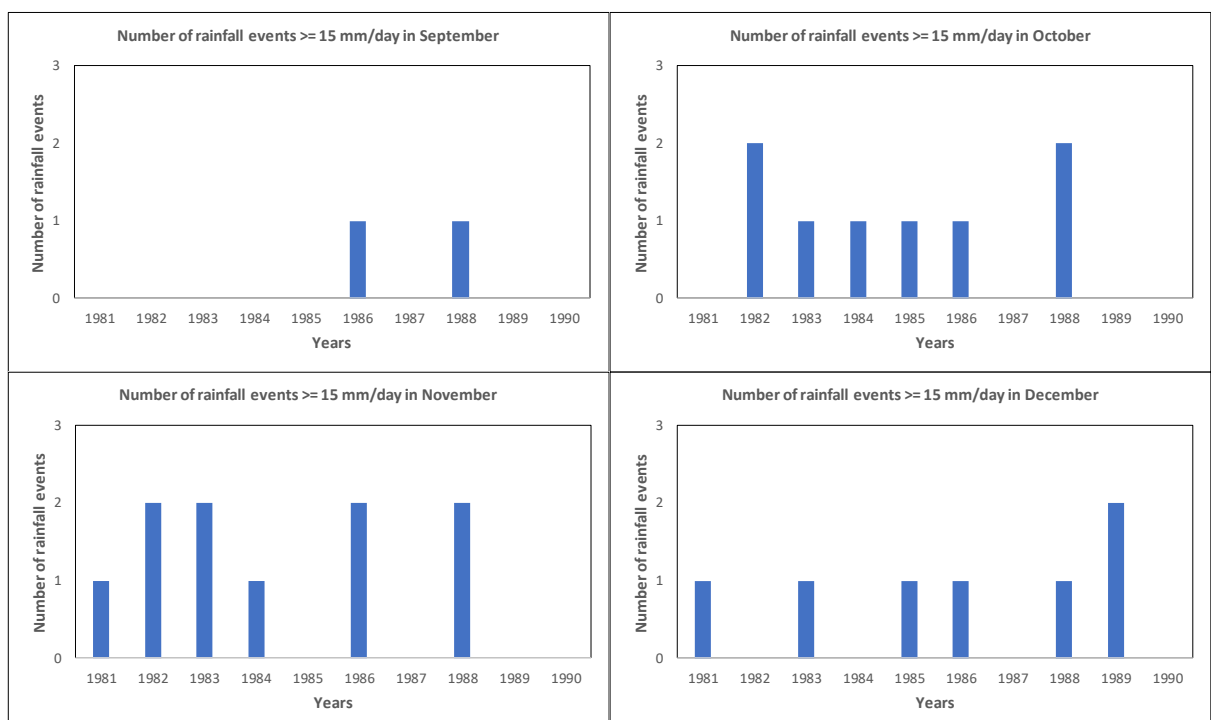
### Appendix 3.10: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Bultfontein



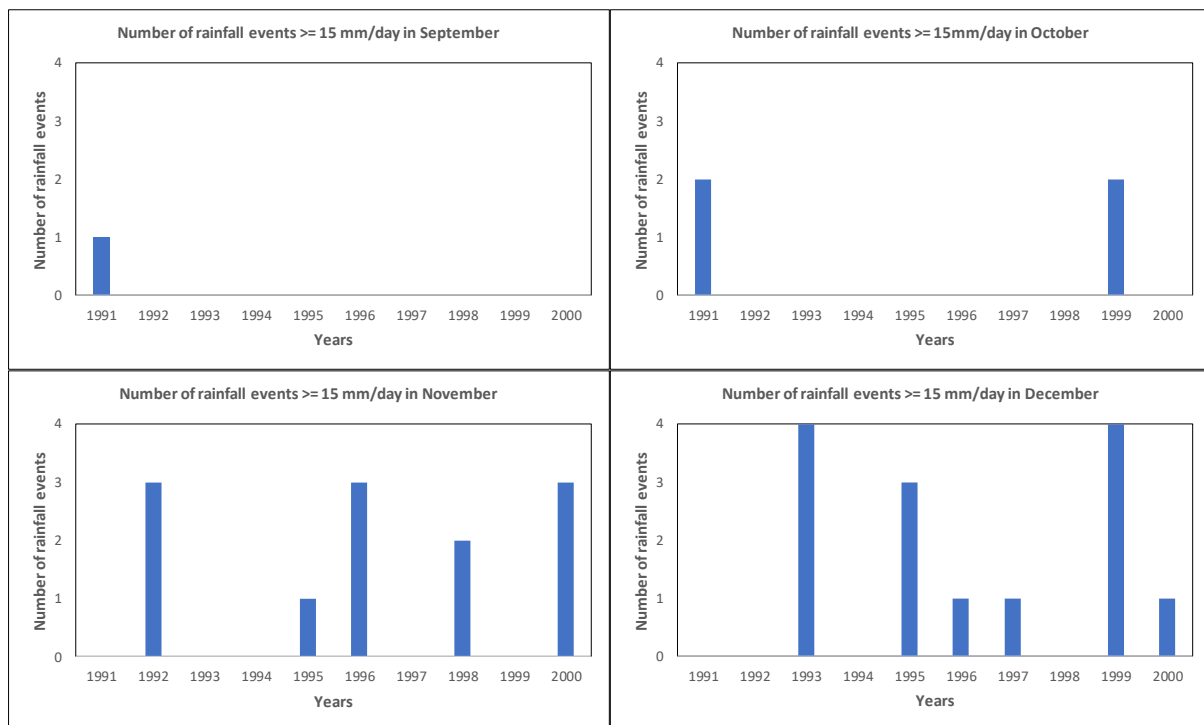
### Appendix 3.11: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Bultfontein



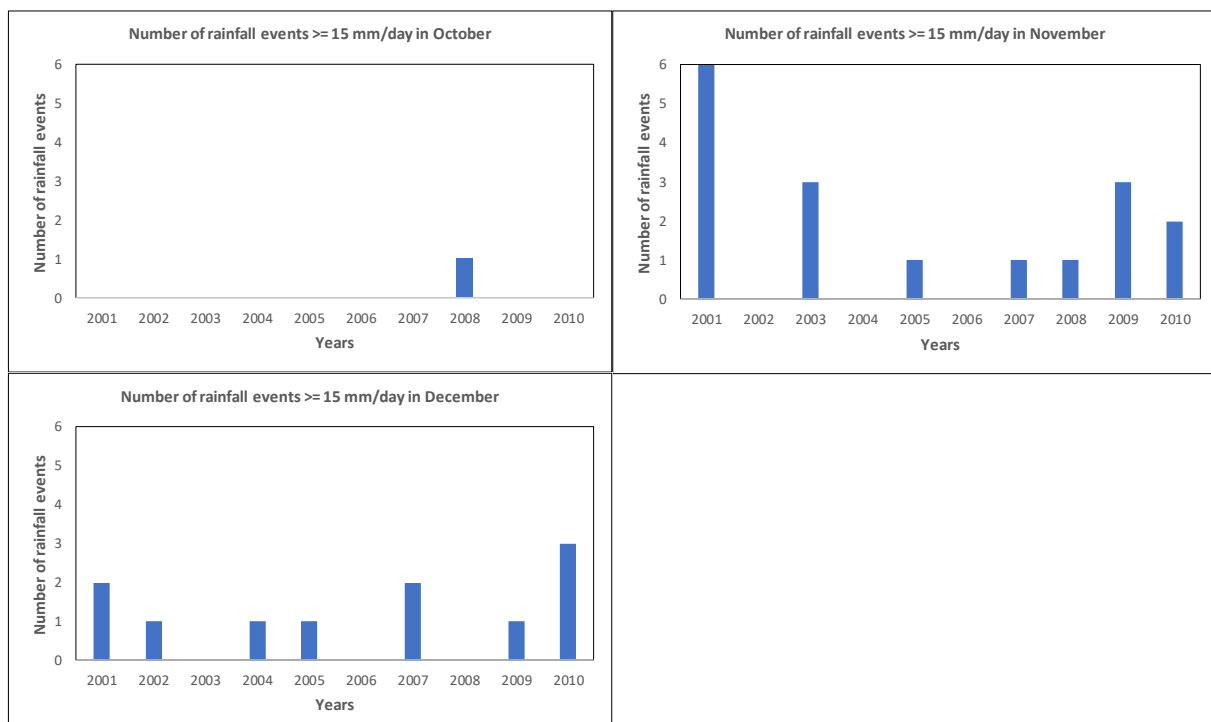
### Appendix 3.12: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Hoopstad



Appendix 3.13: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Hoopstad

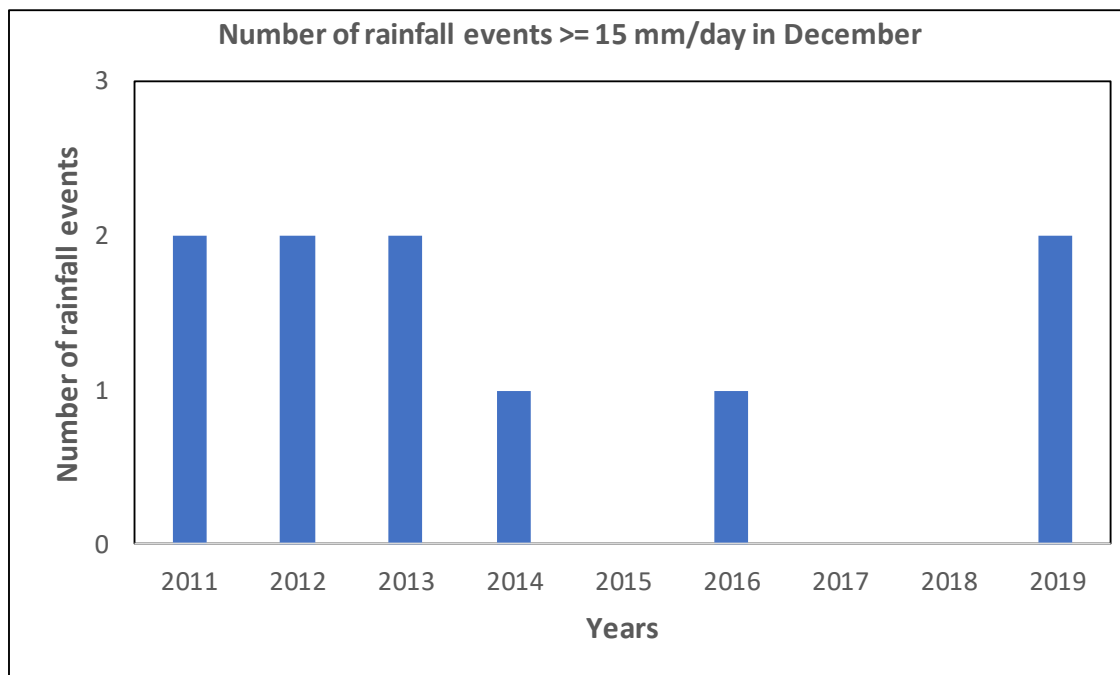


Appendix 3.14: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Hoopstad

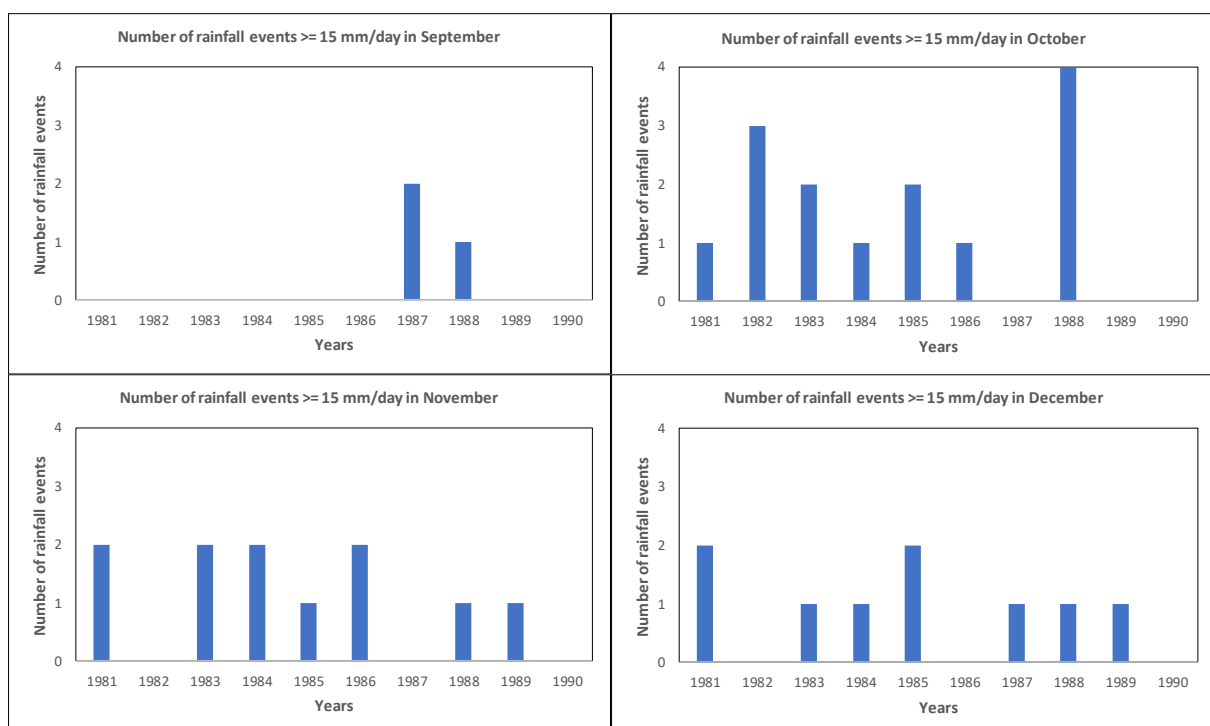




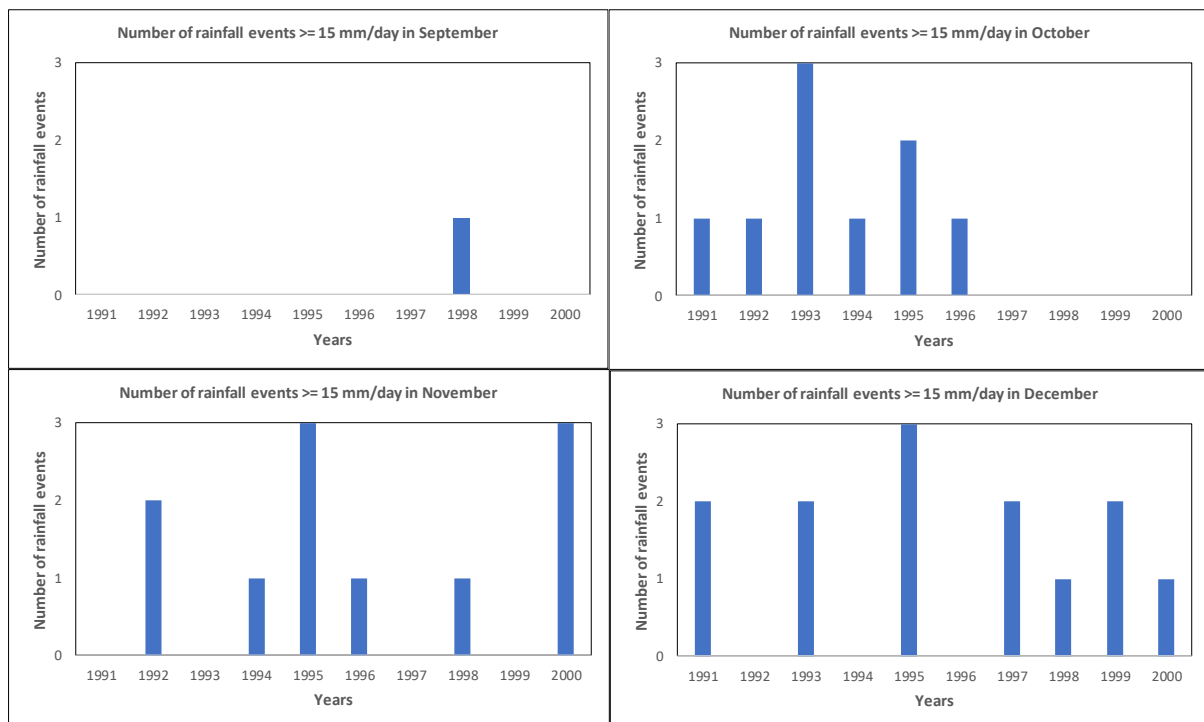
Appendix 3.15: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Hoopstad



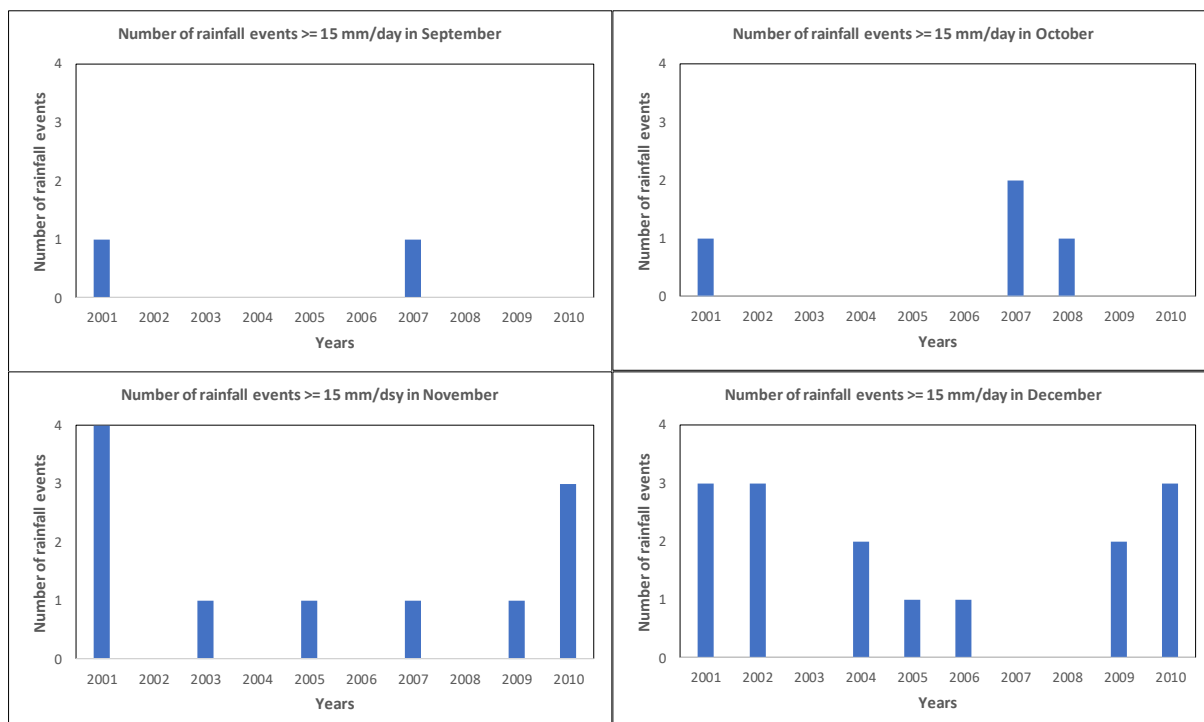
Appendix 3.16: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Wesselsbron



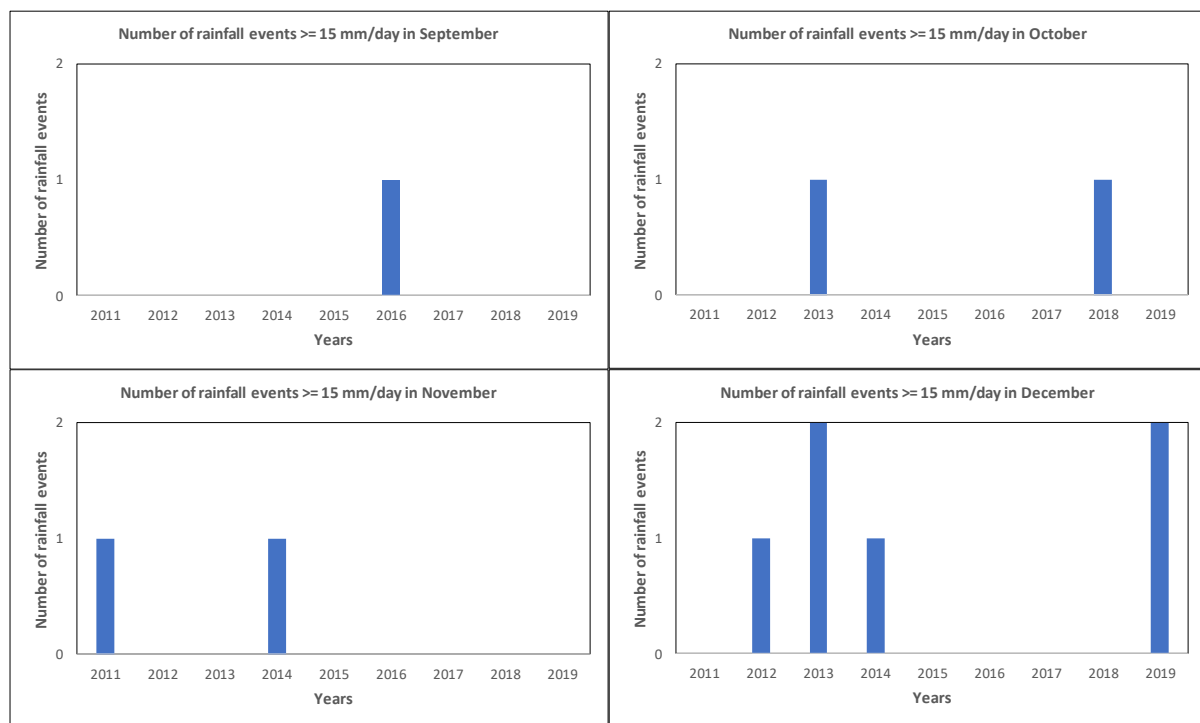
Appendix 3.17: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Wesselsbron



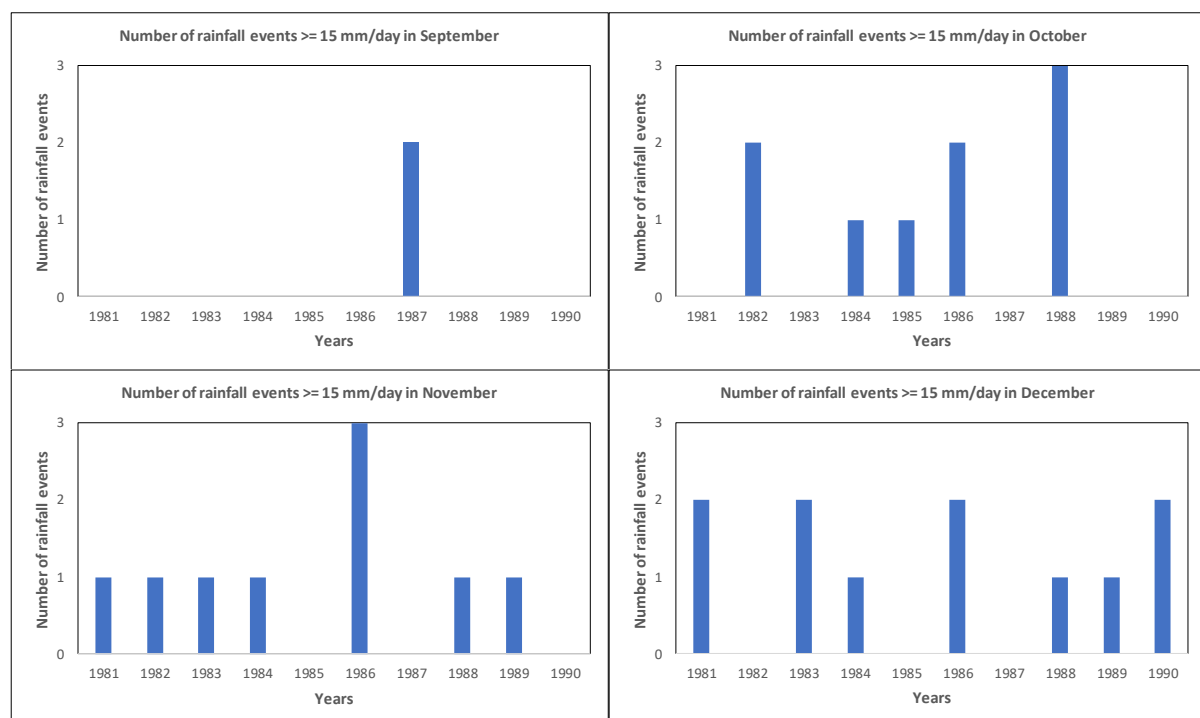
Appendix 3.18: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Wesselsbron



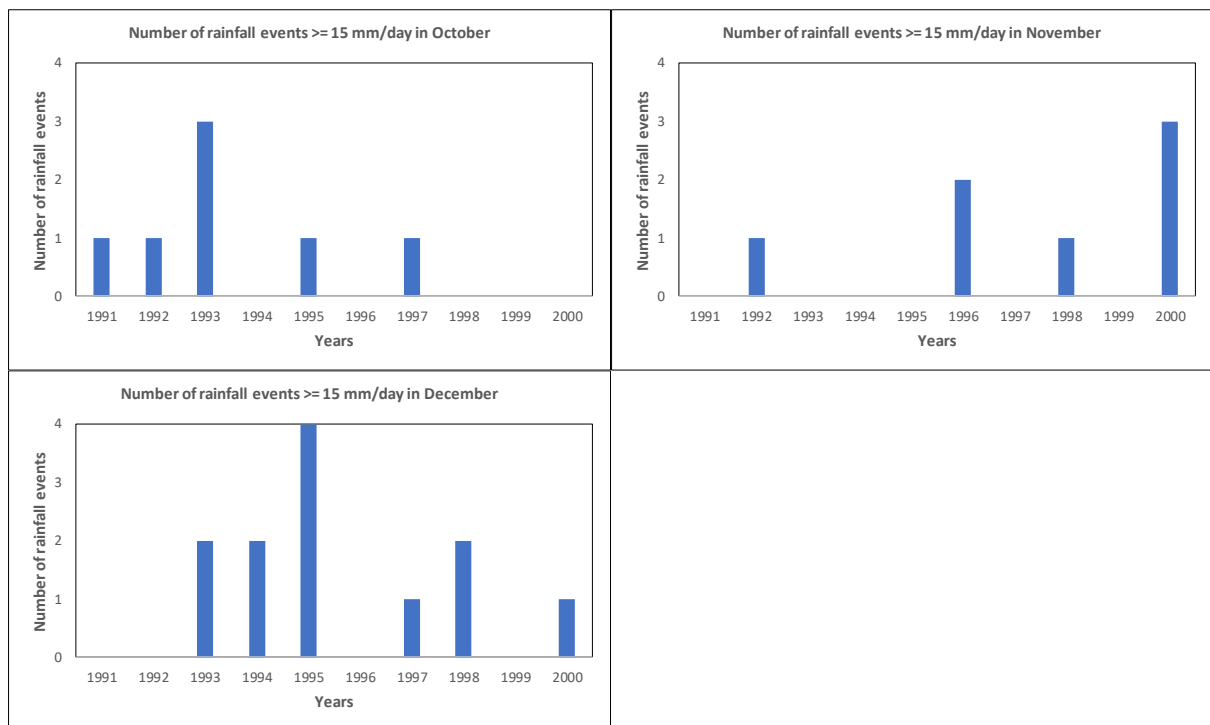
### Appendix 3.19: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Wesselsbron



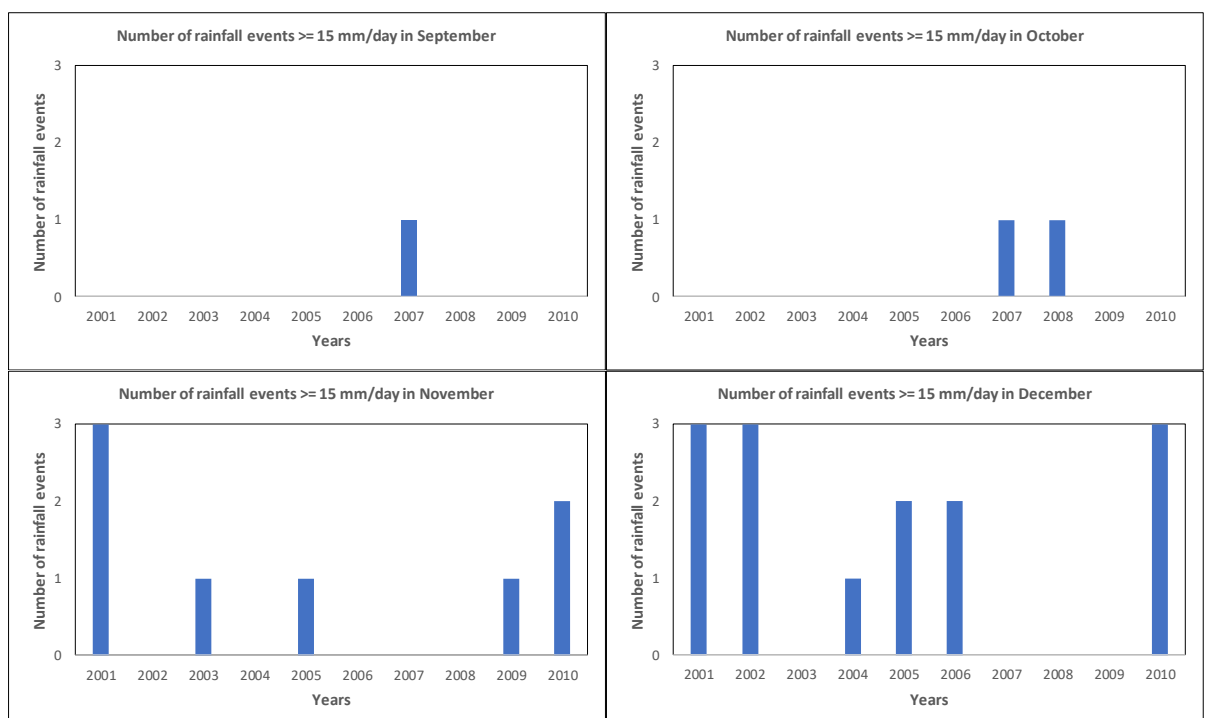
### Appendix 3.20: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1981-1990 Wolmaranstad



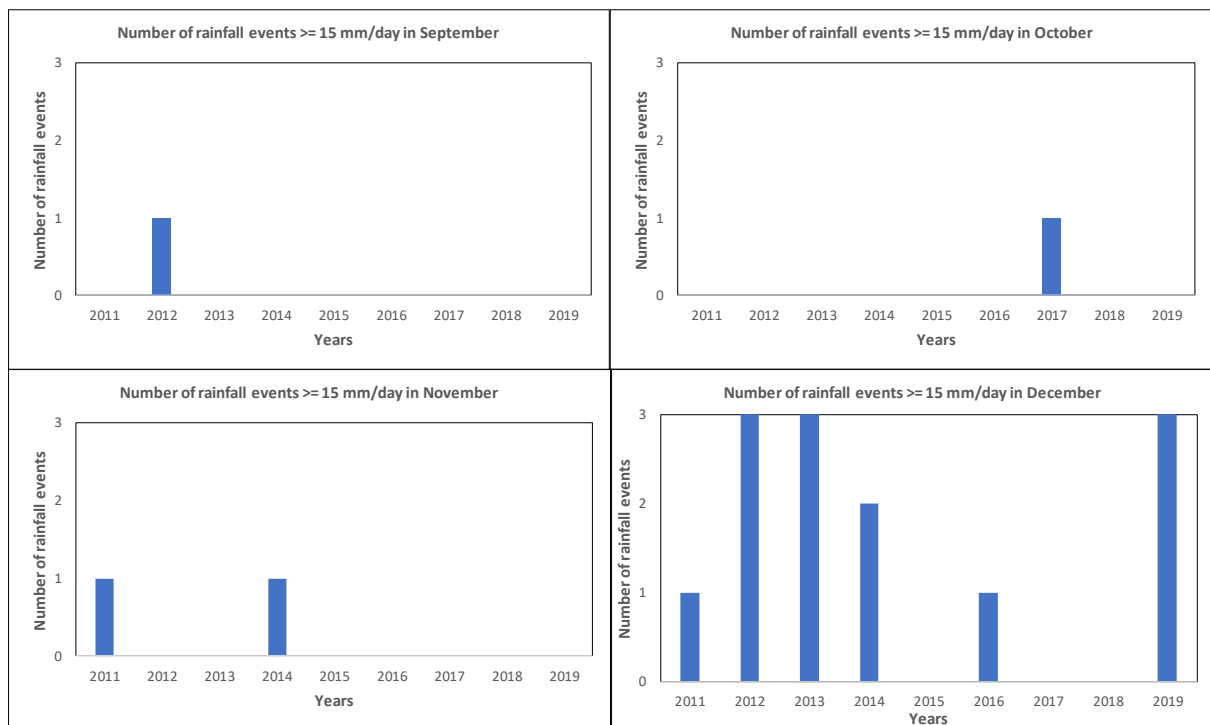
Appendix 3.21: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 1991-2000 Wolmaranstad



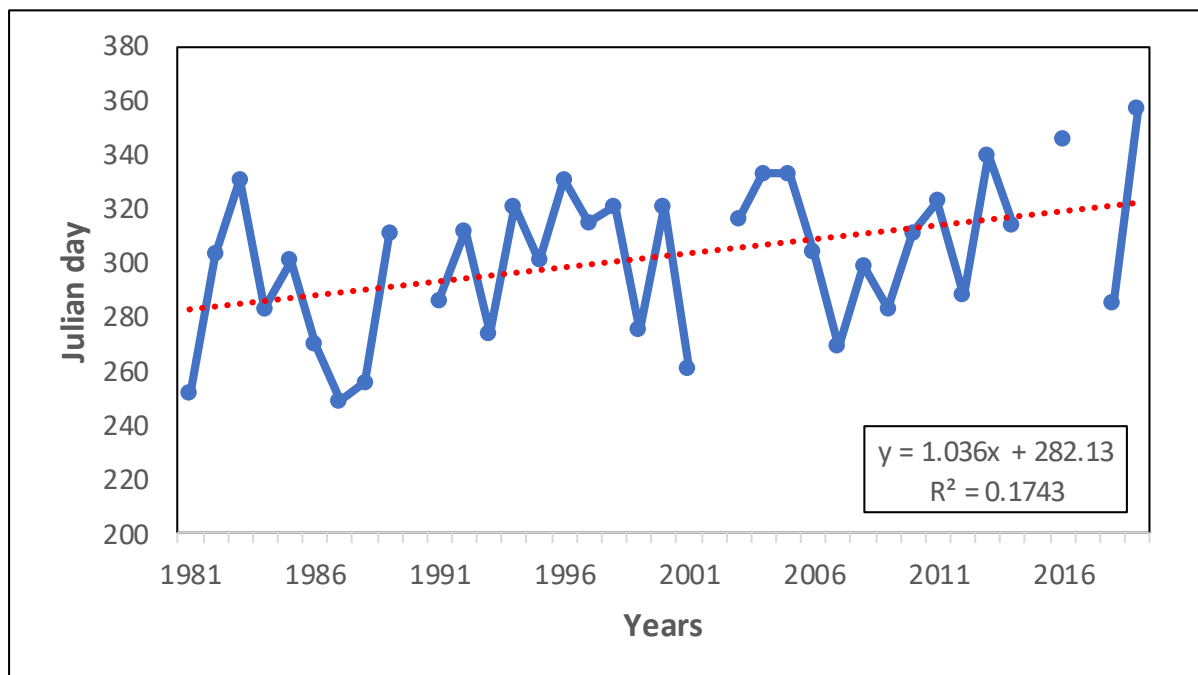
Appendix 3.22: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2001-2010 Wolmaranstad



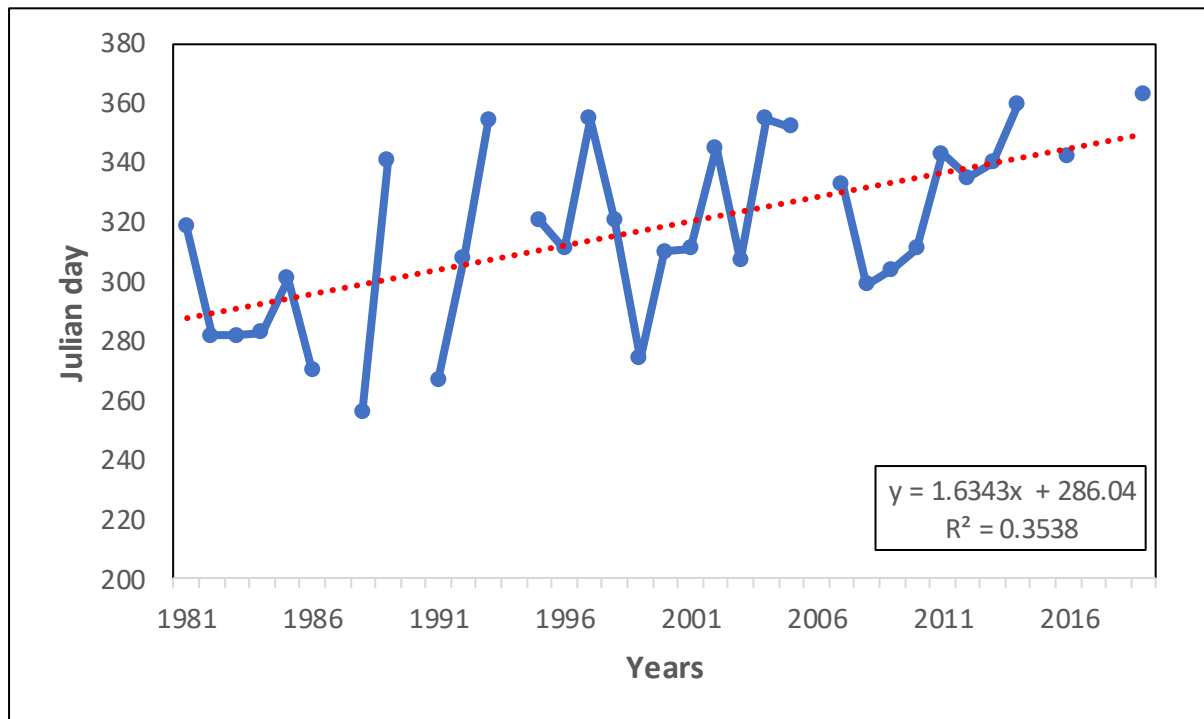
Appendix 3.23: Number of rainfall events greater or equal to 15 mm/ day in Free State rainfall season from 2011-2019 Wolmaranstad



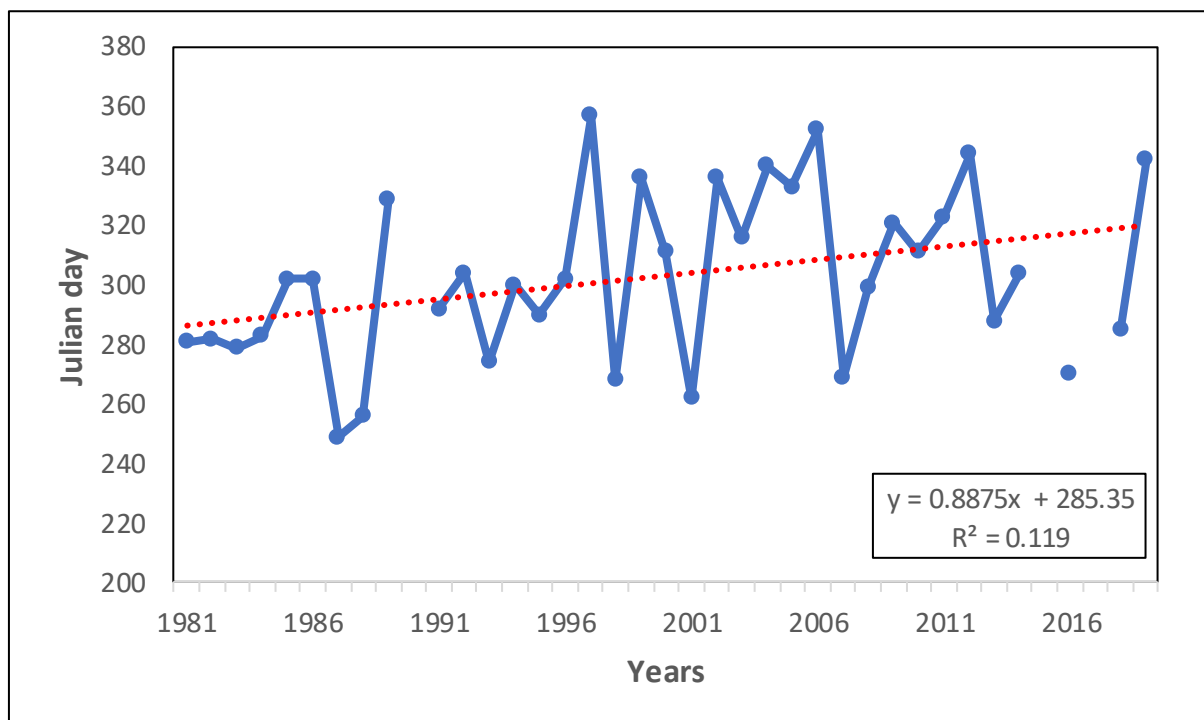
Appendix 3.24: Trend on the onset of rainfall in Bultfontein (1981-2019)



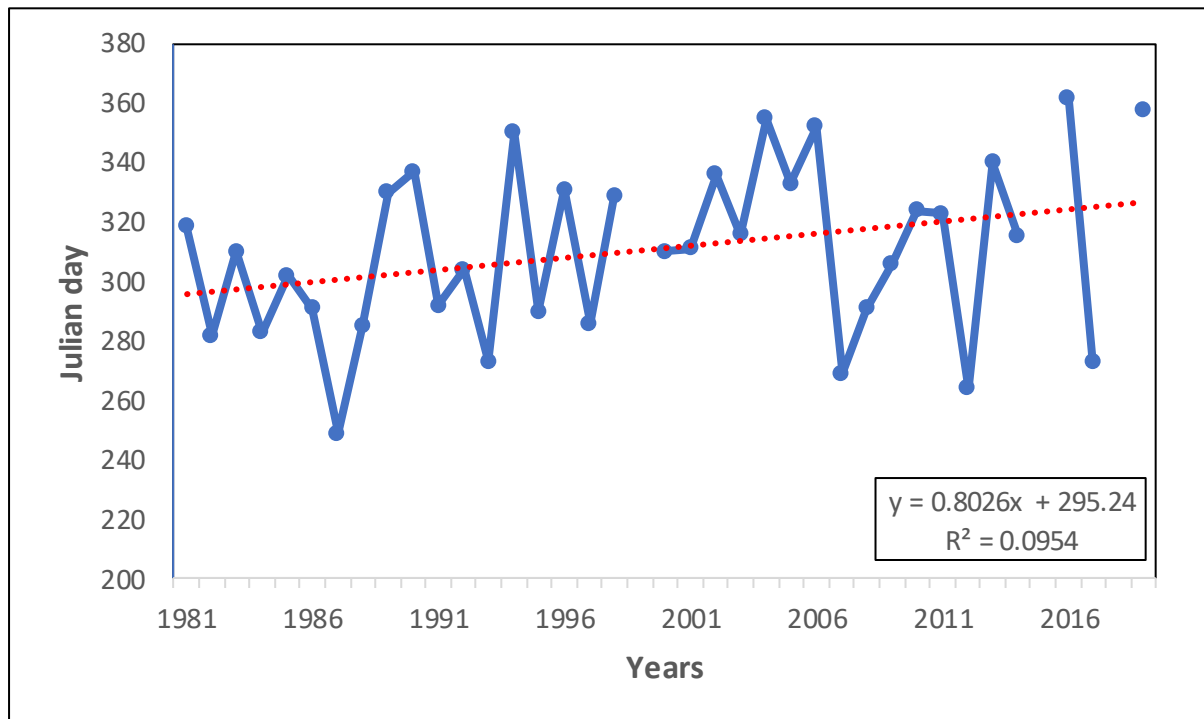
Appendix 3.25: Trend on the onset of rainfall in Hoopstad (1981-2019)



Appendix 3.26: Trend on the onset of rainfall in Wesselsbron (1981-2019)

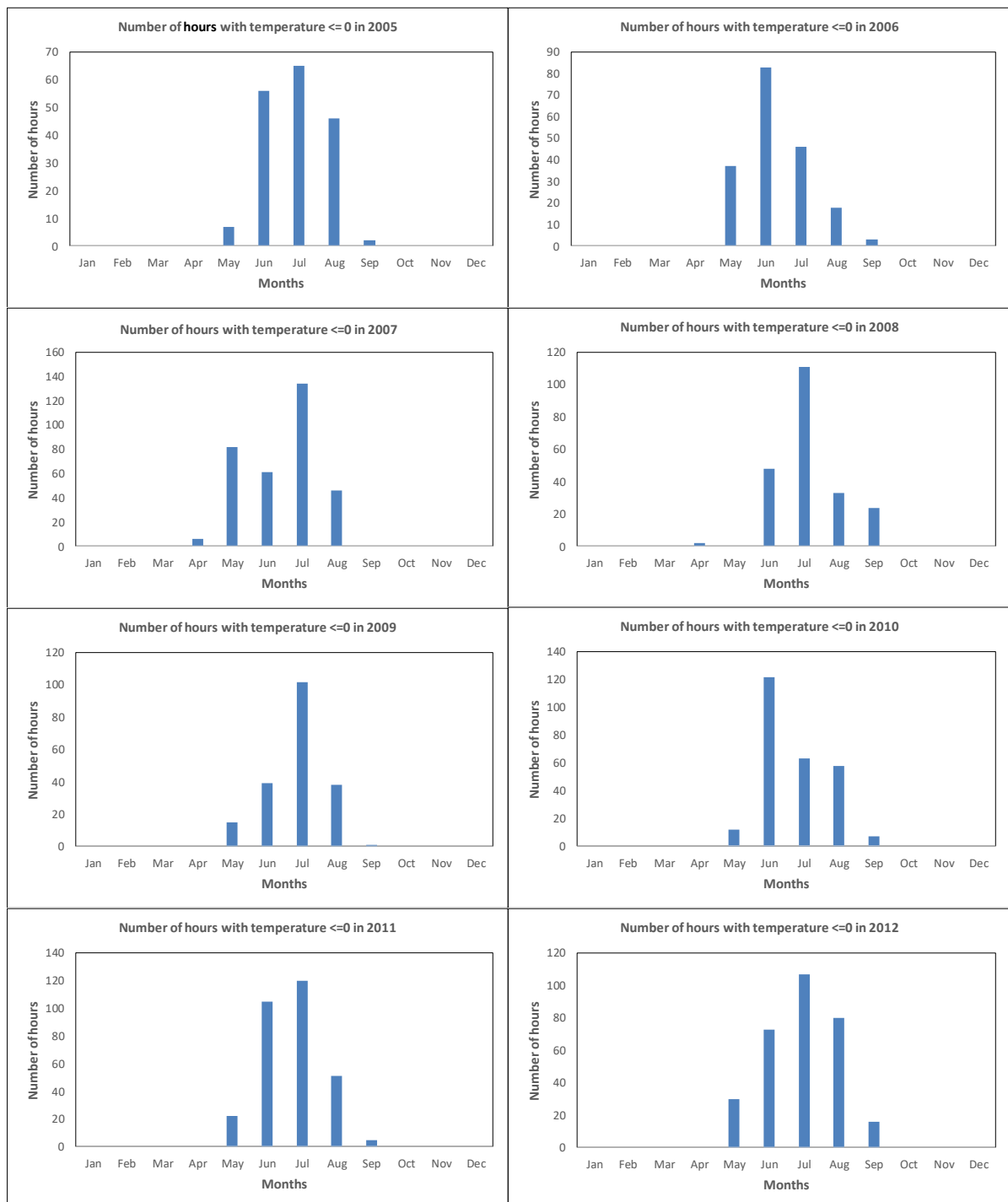


Appendix 3.27: Trend on the onset of rainfall in Wolmaranstad (1981-2019)

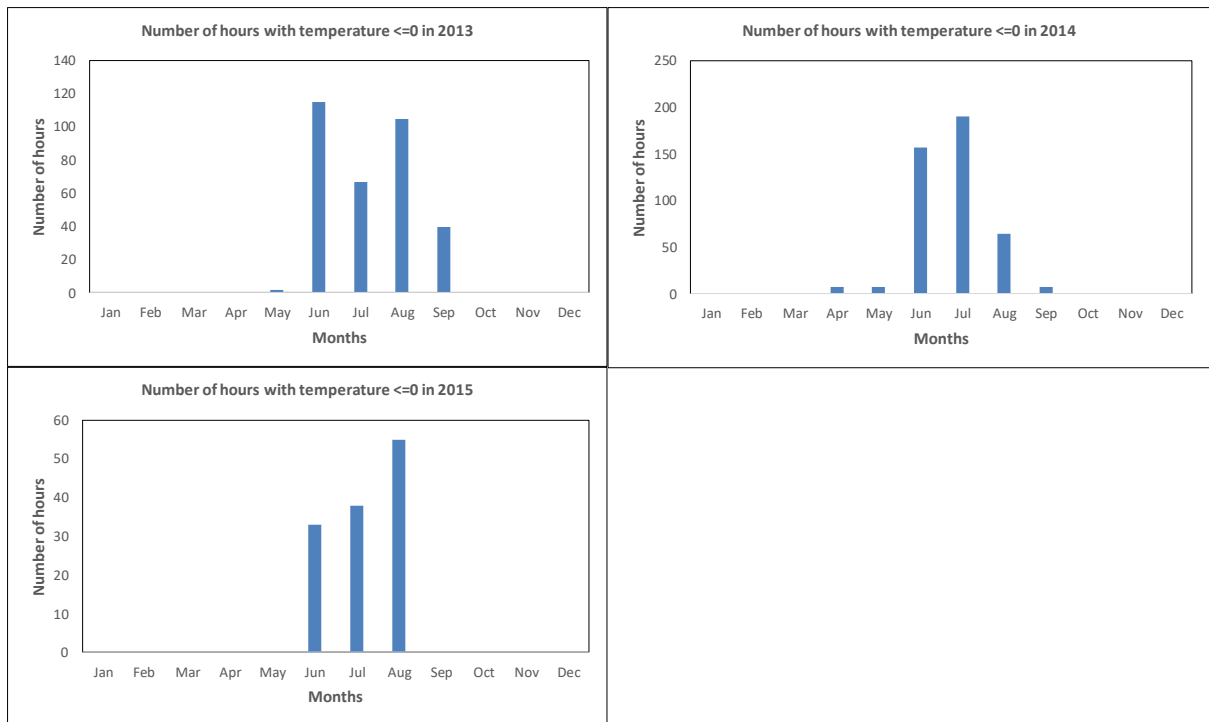


## Appendix 3.28: Total number of frost hours per month

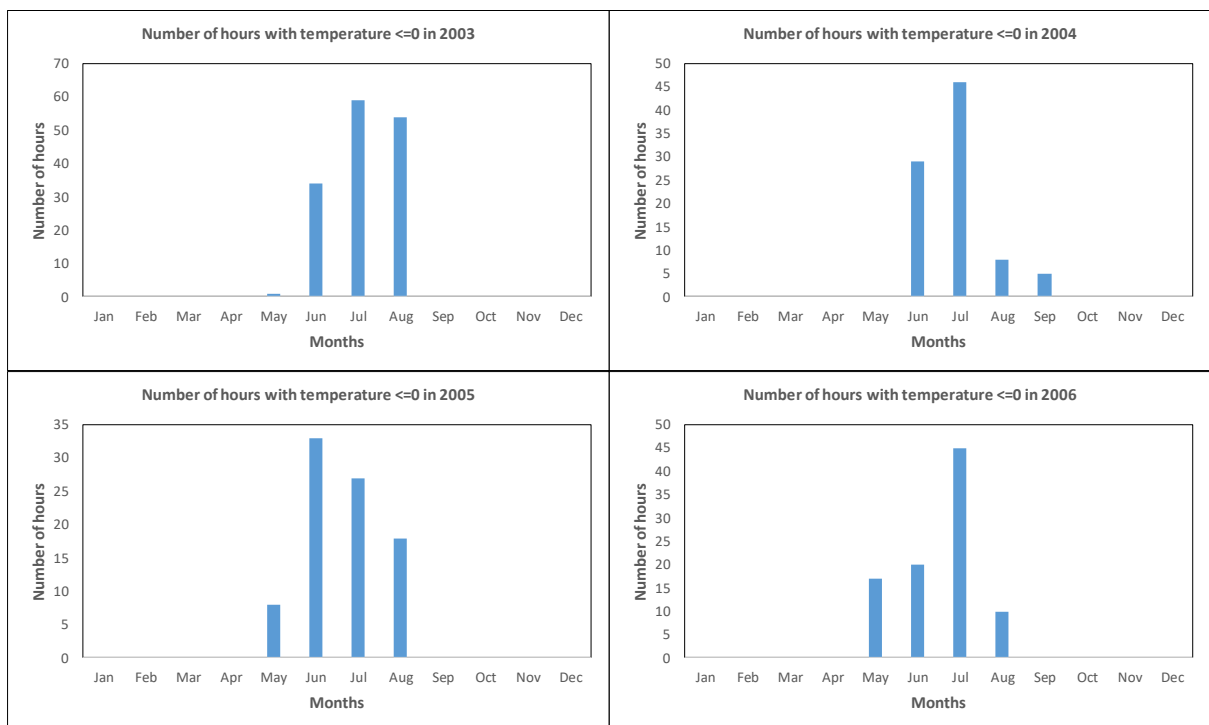
### *Bultfontein station*

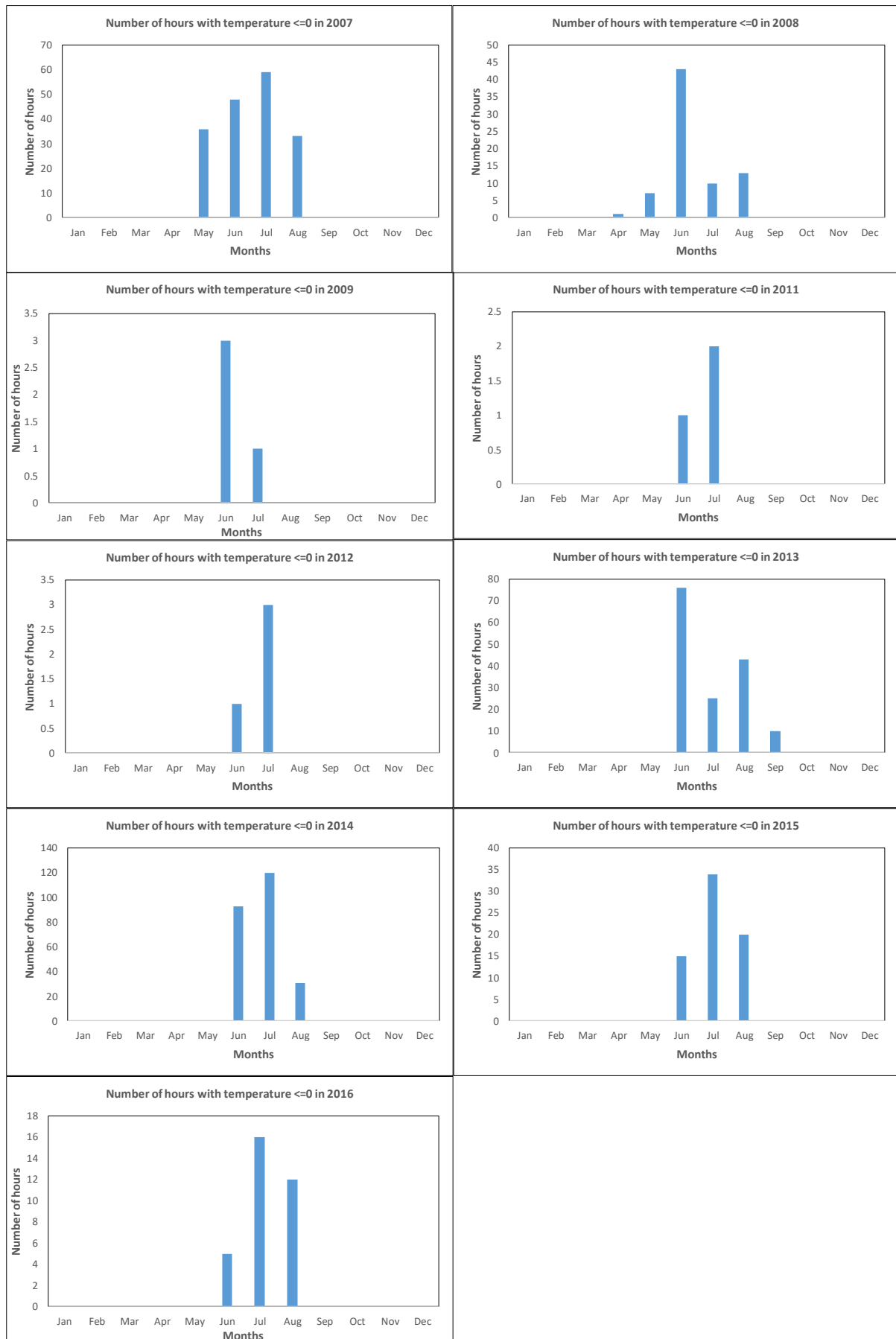




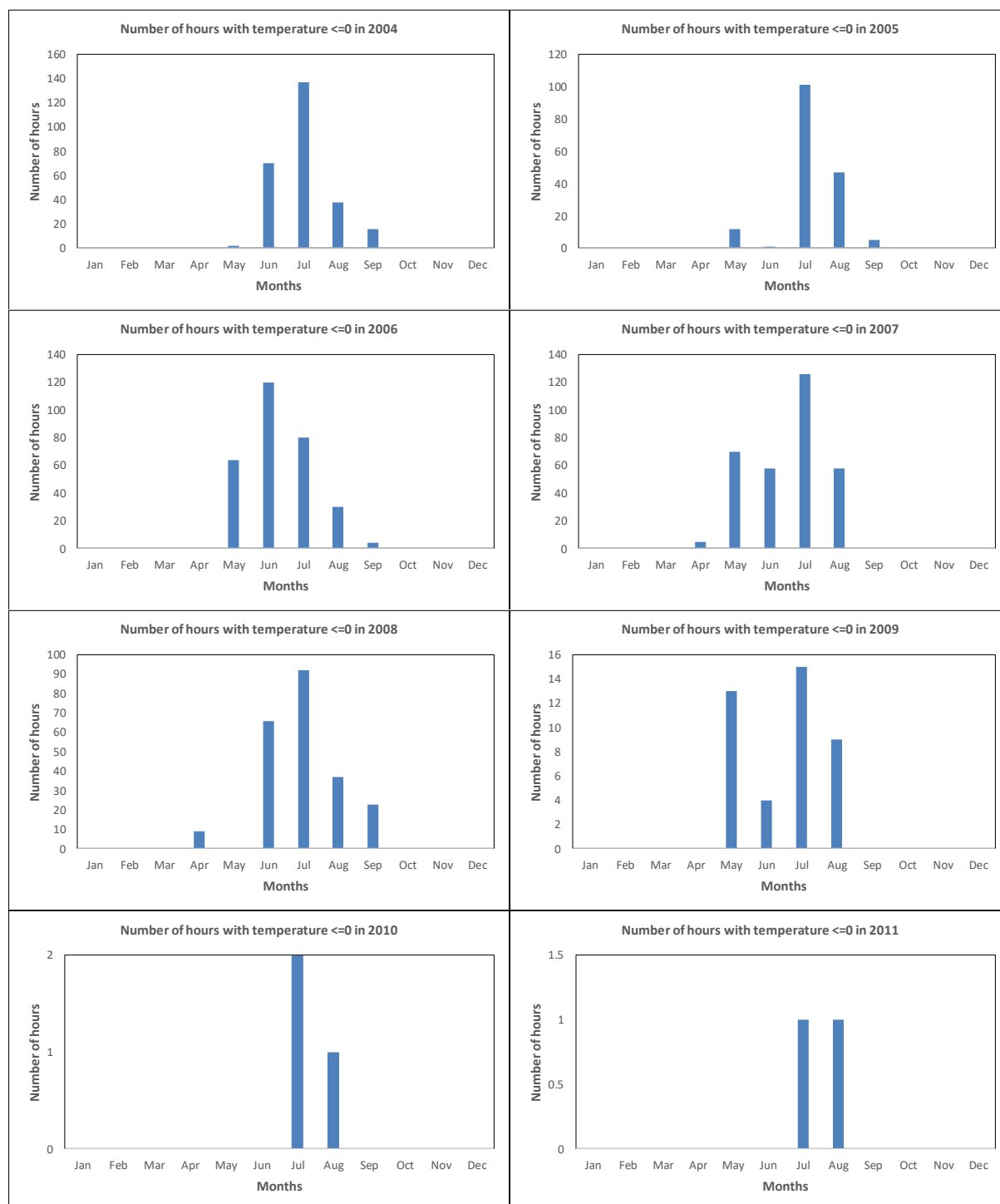


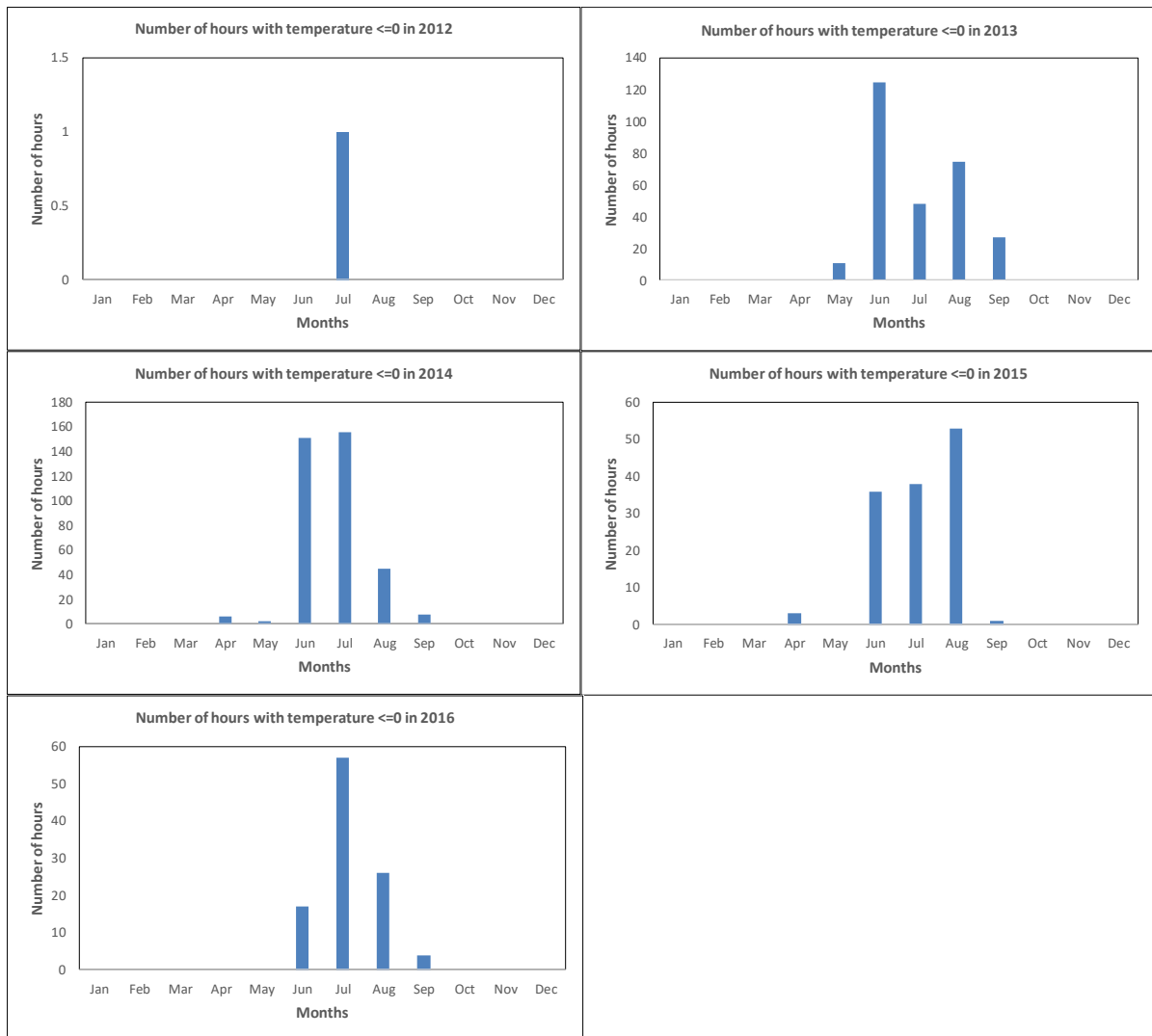
### *Hoopstad station*



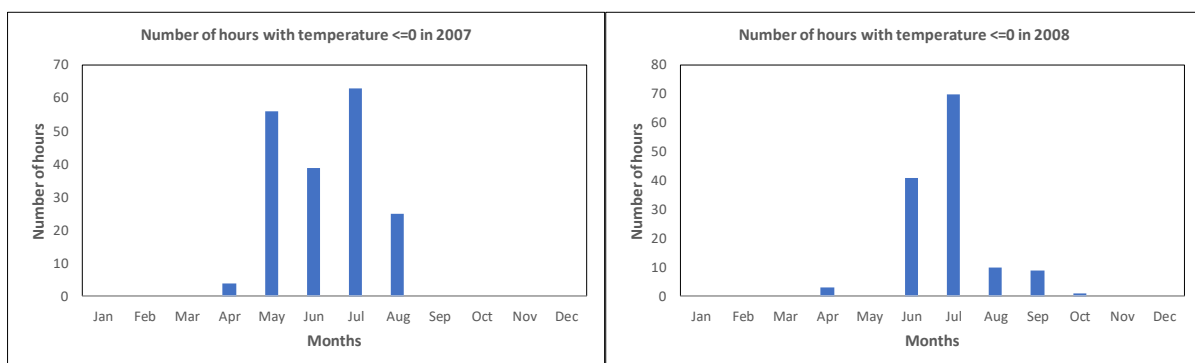


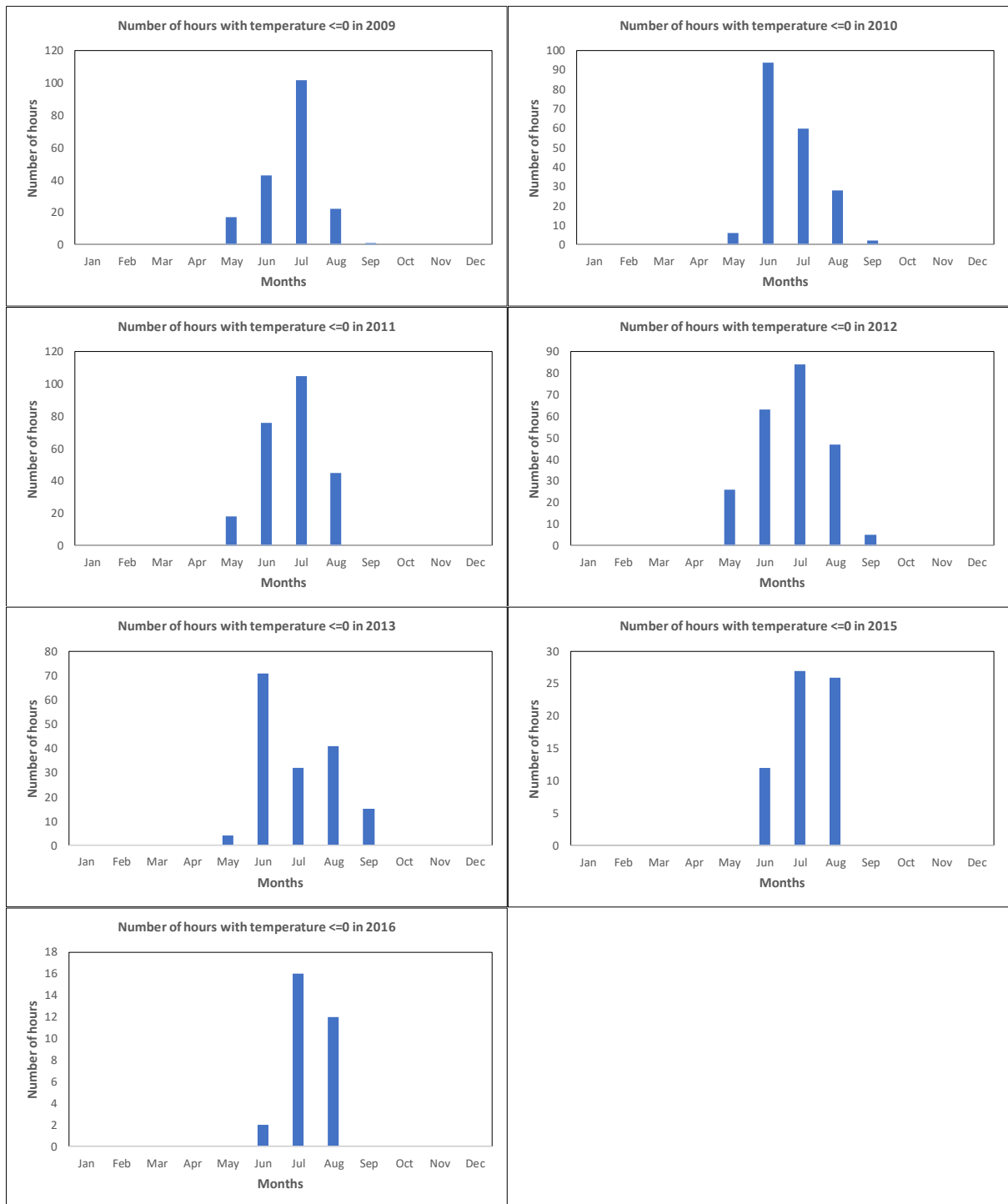
## Wesselsbron station



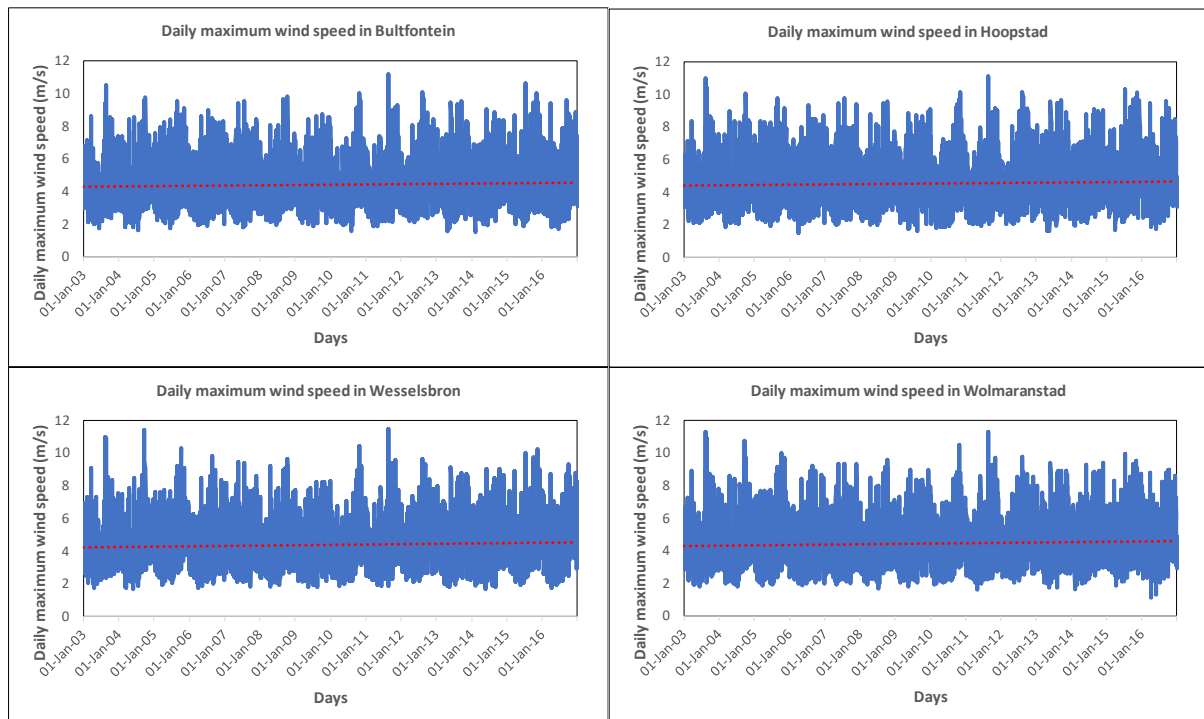


### *Wolmaranstad station*

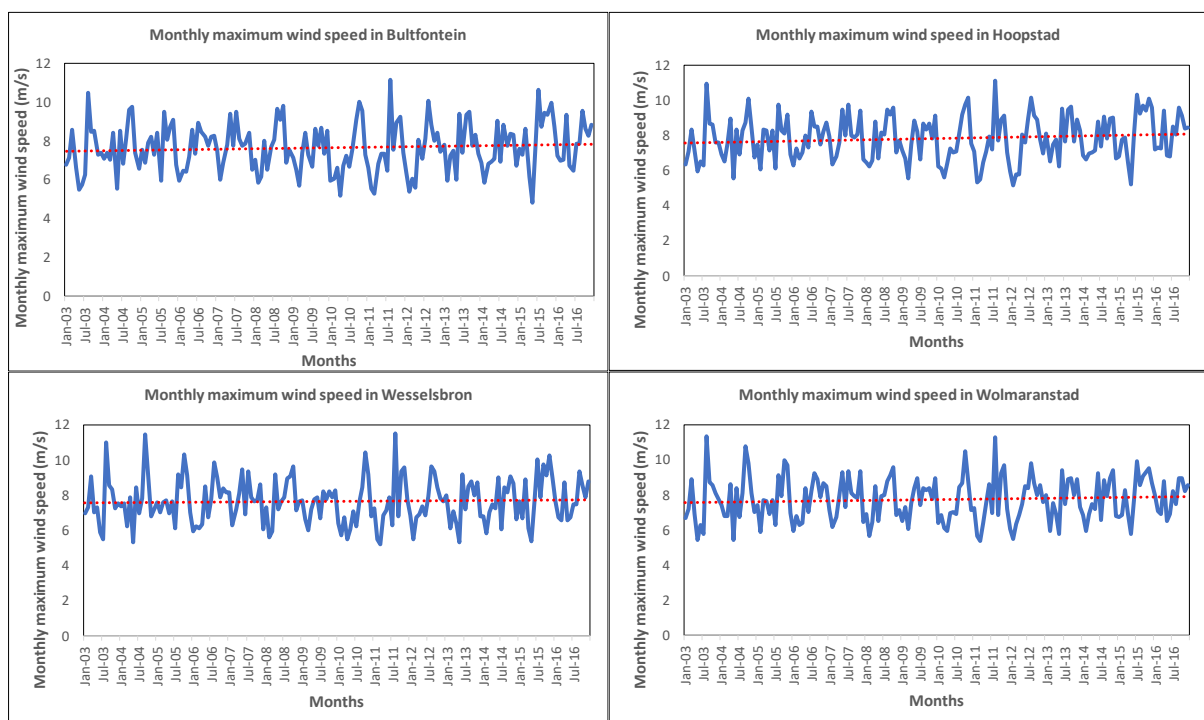




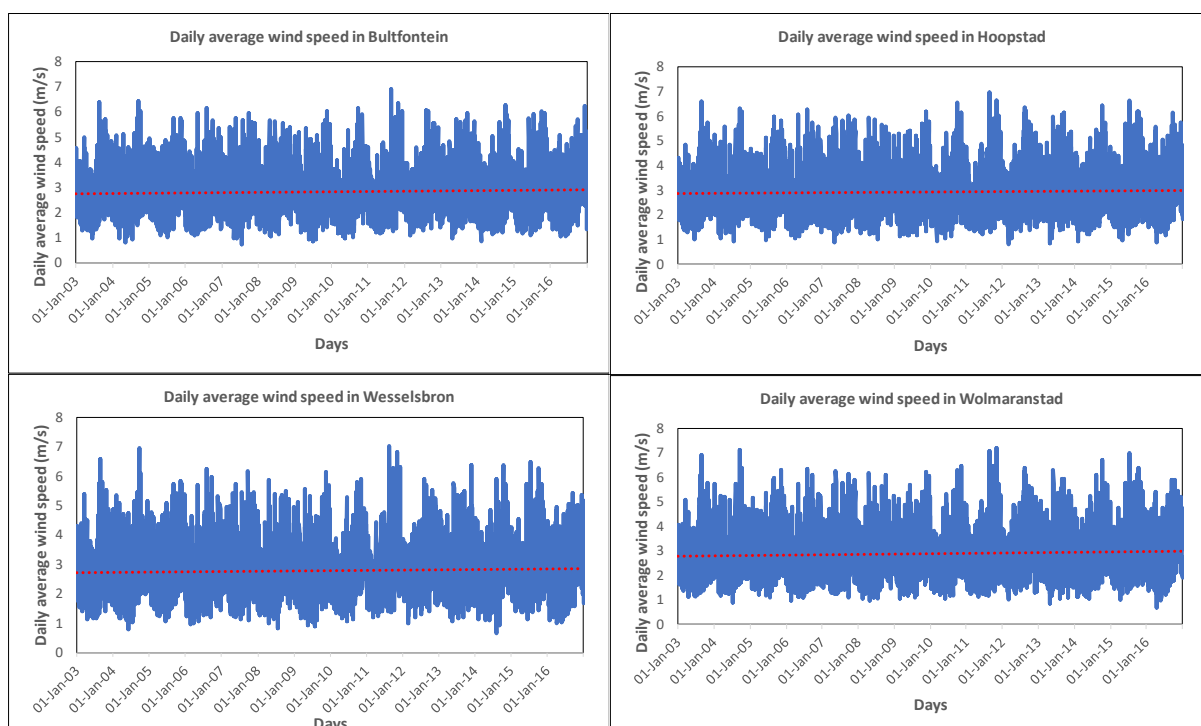
### Appendix 3.29: ERA5 daily maximum wind speed in a series of four weather stations in Free State, South Africa



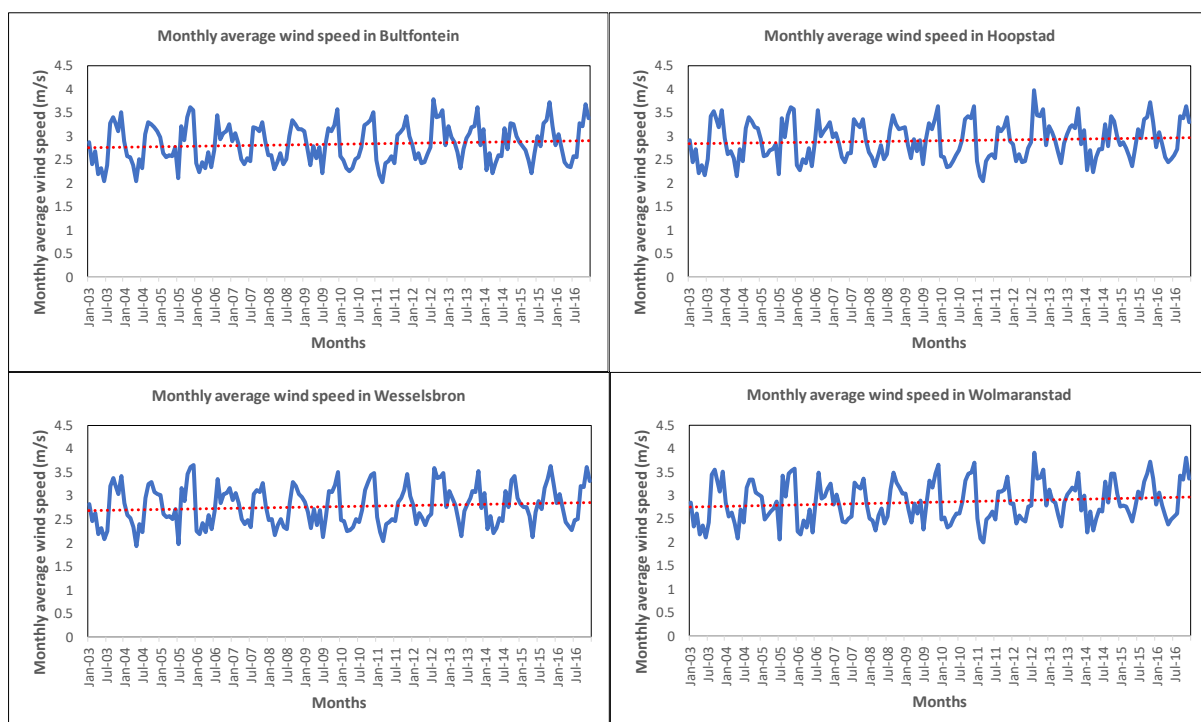
### Appendix 3.30: ERA5 monthly maximum wind speed in a series of four weather stations in Free State, South Africa



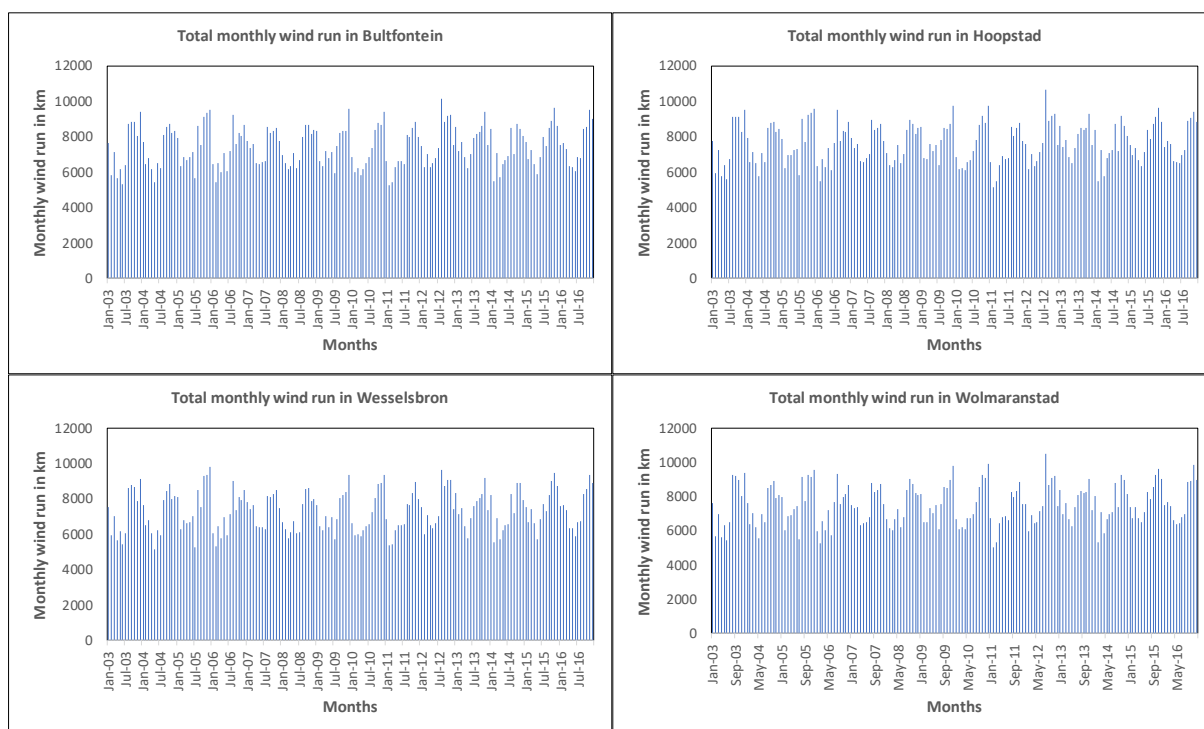
### Appendix 3.31: ERA5 daily average wind speed in a series of four weather stations in Free State, South Africa



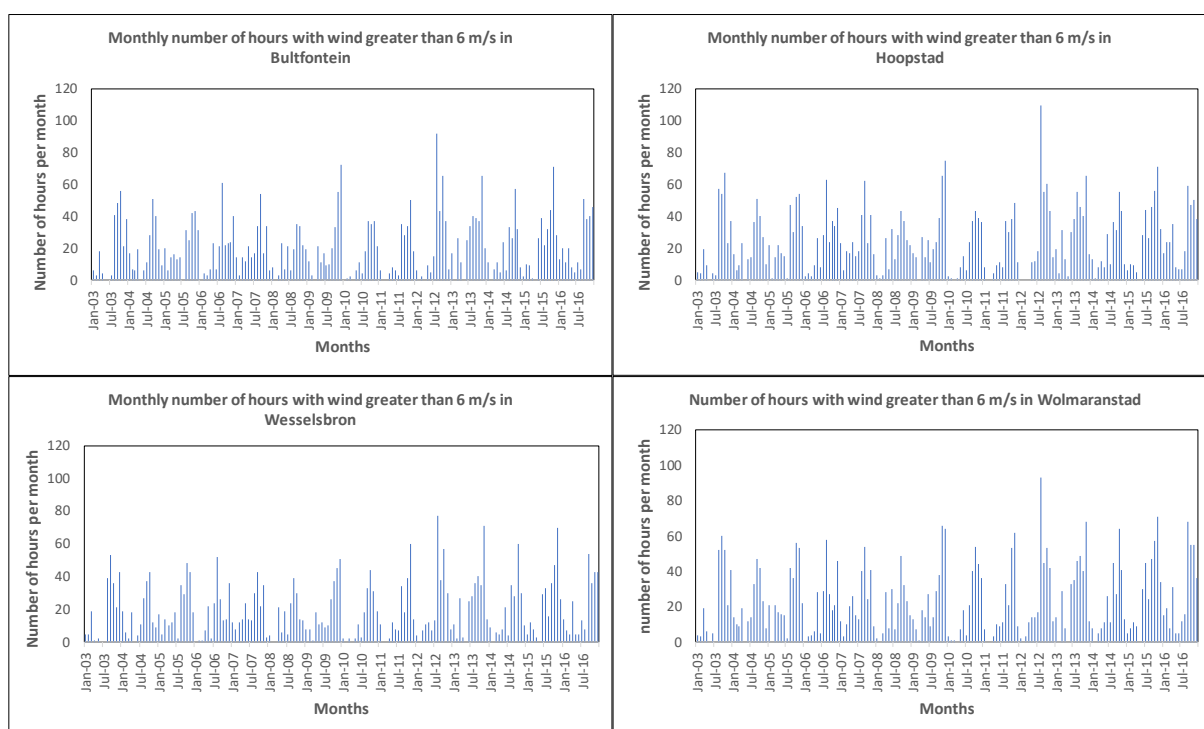
### Appendix 3.32: ERA5 monthly average wind speed in a series of four weather stations in Free State, South Africa



### Appendix 3.33: ERA5 total monthly wind run in a series of four weather stations in Free State, South Africa

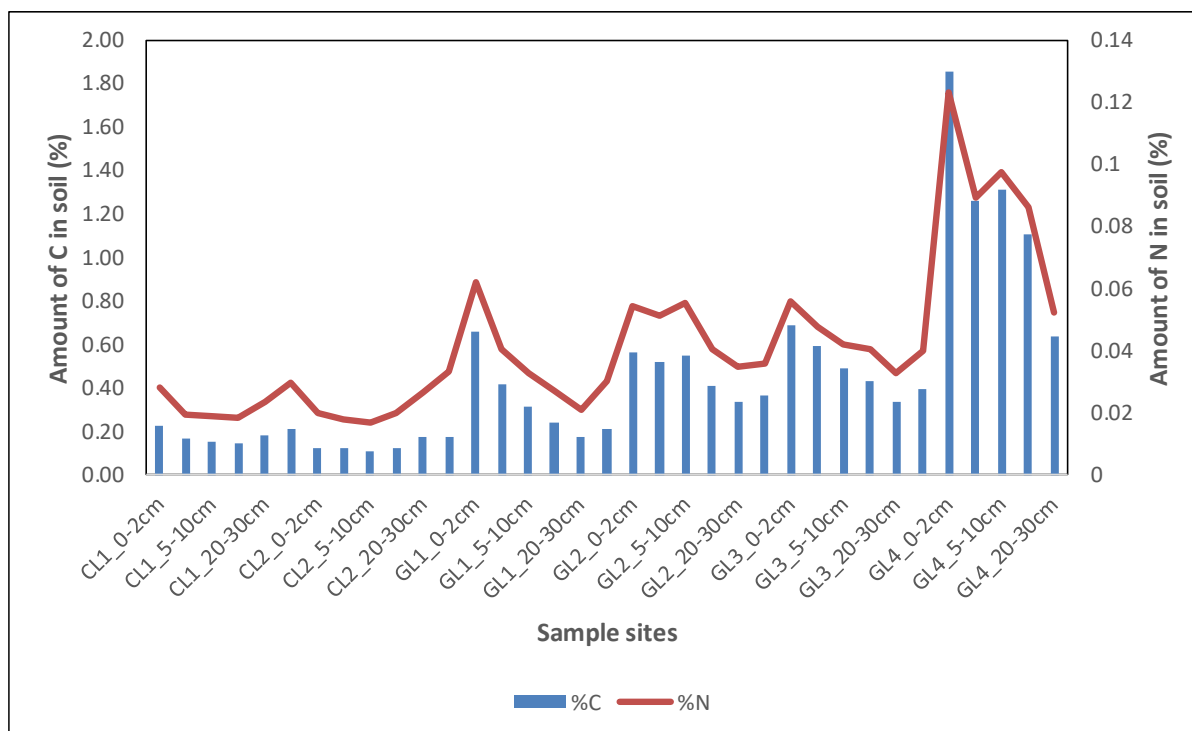


### Appendix 3.34: ERA5 monthly number of hours with wind greater than 6 m/s from a series of four weather stations in Free State, South Africa





# Appendix 4.1: Carbon and nitrogen stored in cultivated land and grassland sites with different soil types



## Appendix 4.2: Schedule files

### 1. Cultivated land with herbivory

2000 Starting year

2019 Last year

bultfontein.100 Site file name

0 Labeling type

-1 Labeling year

-1.00 Microcosm

-1 CO2 Systems

-1 pH Effect

-1 Soil Warming

0 N input scalar option

0 OMAD scalar option

-1 Climate scalar option

1 Initial system

C2 Initial crop #perennial grasses

TMDF Initial tree #temperate deciduous trees

Year Month Option

1 Block #Bultfontein herbivory only.

Graze\_low\_intensity\_\_moderate\_\_(linear)\_effect\_on\_production;\_Graze\_low\_intensity\_\_no\_effect\_on\_production\_. Note weather file (2005-2019) is exact match

2019 Last year

5 Repeats # years

2000 Output starting year

6 Output month

1.00 Output interval

F Weather choice

bultfontein\_2012.wth

1 1 CROP C6

1 1 CULT N

1 1 FERT N10.9

1 122 LAST

1 145 HARV G

1 153 HARV G  
1 253 SENM  
1 288 OMAD C  
1 306 FRST  
1 307 CULT N  
1 307 FERT N10.9  
2 122 LAST  
2 145 HARV G  
2 153 HARV G  
2 253 SENM  
2 288 OMAD C  
2 306 FRST  
2 307 CULT N  
2 307 FERT N10.9  
3 122 LAST  
3 145 HARV G  
3 153 HARV G  
3 253 SENM  
3 288 OMAD C  
3 306 FRST  
3 307 CULT N  
3 307 FERT N10.9  
4 122 LAST  
4 145 HARV G  
4 153 HARV G  
4 253 SENM  
4 288 OMAD C  
4 306 FRST  
4 307 CULT N  
4 307 FERT N10.9  
5 122 LAST  
5 145 HARV G  
5 153 HARV G

5 253 SENM

5 288 OMAD C

5 306 FRST

5 307 CULT N

5 307 FERT N10.9

-999 -999 X

## 2. Grassland with herbivory

2000 Starting year

2019 Last year

bultfontein.100 Site file name

0 Labeling type

-1 Labeling year

-1.00 Microcosm

-1 CO2 Systems

-1 pH Effect

-1 Soil Warming

0 N input scalar option

0 OMAD scalar option

-1 Climate scalar option

1 Initial system

KNZ Initial crop #perennial grasses

T MDF Initial tree #temperate deciduous trees

Year Month Option

1 Block #Bultfontein herbivory only.

Graze\_low\_intensity\_\_moderate\_(linear)\_effect\_on\_production;\_Graze\_low\_intensity\_\_no\_effect\_on\_production\_. Note weather file (2005-2019) is exact match

2019 Last year

5 Repeats # years

2000 Output starting year

6 Output month

1.00 Output interval

F Weather choice

bultfontein\_2012.wth

1 1 CROP KNZ  
1 1 GRAZ GM\_K  
1 37 GRAZ GM\_K  
1 73 GRAZ GM\_K  
1 109 GRAZ GL\_K  
1 122 LAST  
1 145 GRAZ W  
1 153 SENM  
1 155 OMAD C  
1 181 GRAZ W  
1 217 GRAZ W  
1 253 GRAZ W  
1 288 GRAZ W  
1 306 FRST  
1 324 GRAZ GL\_K  
1 360 GRAZ GL\_K  
2 1 GRAZ GM\_K  
2 37 GRAZ GM\_K  
2 73 GRAZ GM\_K  
2 109 GRAZ GL\_K  
2 122 LAST  
2 145 GRAZ W  
2 153 SENM  
2 155 OMAD C  
2 181 GRAZ W  
2 217 GRAZ W  
2 253 GRAZ W  
2 288 GRAZ W  
2 306 FRST  
2 324 GRAZ GL\_K  
2 360 GRAZ GL\_K  
3 1 GRAZ GM\_K

3 37 GRAZ GM\_K  
3 73 GRAZ GM\_K  
3 109 GRAZ GL\_K  
3 122 LAST  
3 145 GRAZ W  
3 153 SENM  
3 155 OMAD C  
3 181 GRAZ W  
3 217 GRAZ W  
3 253 GRAZ W  
3 288 GRAZ W  
3 306 FRST  
3 324 GRAZ GL\_K  
3 360 GRAZ GL\_K  
4 1 GRAZ GM\_K  
4 37 GRAZ GM\_K  
4 73 GRAZ GM\_K  
4 109 GRAZ GL\_K  
4 122 LAST  
4 145 GRAZ W  
4 153 SENM  
4 155 OMAD C  
4 181 GRAZ W  
4 217 GRAZ W  
4 253 GRAZ W  
4 288 GRAZ W  
4 306 FRST  
4 324 GRAZ GL\_K  
4 360 GRAZ GL\_K  
5 1 GRAZ GM\_K  
5 37 GRAZ GM\_K  
5 73 GRAZ GM\_K  
5 109 GRAZ GL\_K

5 122 LAST

5 145 GRAZ W

5 153 SENM

5 155 OMAD C

5 181 GRAZ W

5 217 GRAZ W

5 253 GRAZ GL

5 288 GRAZ GL

5 306 FRST

5 324 GRAZ GL\_K

5 360 GRAZ GL\_K

-999 -999 X

### 3. Grassland with no herbivory

2000 Starting year

2019 Last year

bultfontein.100 Site file name

0 Labeling type

-1 Labeling year

-1.00 Microcosm

-1 CO2 Systems

-1 pH Effect

-1 Soil Warming

0 N input scalar option

0 OMAD scalar option

-1 Climate scalar option

1 Initial system

KNZ Initial crop #perennial grasses

T MDF Initial tree #temperate deciduous trees

Year Month Option

1 Block #Nkuhlu Long-Term Herbivore Exclosure and Burn Trial yr2002-present, NO HERBIVORY except <5kg mammals (GRAZ=GL\_K), 5 year fire return in 4 years (2002, 2007, 2012, 2017). Note weather file (2002-2014) is exact match

2019      Last year  
5          Repeats # years  
2000      Output starting year  
6          Output month  
1.00      Output interval  
F          Weather choice

bultfontein\_2012.wth

1   1 CROP KNZ  
1   1 TREE TMDF  
1   1 GRAZ GL\_K  
1   37 GRAZ GL\_K  
1   73 GRAZ GL\_K  
1   109 GRAZ GL\_K  
1   122 LAST  
1   145 GRAZ GL\_K  
1   153 SENM  
1   181 GRAZ GL\_K  
1   183 TLST  
1   217 GRAZ GL\_K  
1   245 TFST  
1   253 GRAZ GL\_K  
1   288 GRAZ GL\_K  
1   306 FRST  
1   324 GRAZ GL\_K  
1   360 GRAZ GL\_K  
2   1 GRAZ GL\_K  
2   37 GRAZ GL\_K  
2   73 GRAZ GL\_K  
2   109 GRAZ GL\_K  
2   122 LAST  
2   145 GRAZ GL\_K  
2   153 SENM  
2   181 GRAZ GL\_K



2 183 TLST

2 217 GRAZ GL\_K

2 245 TFST

2 253 GRAZ GL\_K

2 288 GRAZ GL\_K

2 306 FRST

2 324 GRAZ GL\_K

2 360 GRAZ GL\_K

3 1 GRAZ GL\_K

3 37 GRAZ GL\_K

3 73 GRAZ GL\_K

3 109 GRAZ GL\_K

3 122 LAST

3 145 GRAZ GL\_K

3 153 SENM

3 181 GRAZ GL\_K

3 183 TLST

3 217 GRAZ GL\_K

3 245 TFST

3 253 GRAZ GL\_K

3 288 GRAZ GL\_K

3 306 FRST

3 324 GRAZ GL\_K

3 360 GRAZ GL\_K

4 1 GRAZ GL\_K

4 37 GRAZ GL\_K

4 73 GRAZ GL\_K

4 109 GRAZ GL\_K

4 122 LAST

4 145 GRAZ GL\_K

4 153 SENM

4 181 GRAZ GL\_K

4 183 TLST

4 217 GRAZ GL\_K  
4 245 TFST  
4 253 GRAZ GL\_K  
4 288 GRAZ GL\_K  
4 306 FRST  
4 324 GRAZ GL\_K  
4 360 GRAZ GL\_K  
5 1 GRAZ GL\_K  
5 37 GRAZ GL\_K  
5 73 GRAZ GL\_K  
5 109 GRAZ GL\_K  
5 122 LAST  
5 145 GRAZ GL\_K  
5 153 SENM  
5 181 GRAZ GL\_K  
5 183 TLST  
5 217 GRAZ GL\_K  
5 245 TFST  
5 253 GRAZ GL\_K  
5 288 GRAZ GL\_K  
5 306 FRST  
5 324 GRAZ GL\_K  
5 360 GRAZ GL\_K  
-999 -999 X