Wind Erosion and Soil Susceptibility in the Free State Province, South Africa

Pululu Sexton Mahasa

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Supervisors: Dr Charles Barker

Dr Geofrey Mukwada

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Abstract

Wind erosion is identified as one of the most problematic environmental and social-economic problems in the Free State province. The development and intensification of soil wind erosion are influenced by the factors ~~of~~ such as climate, terrain, soil and vegetation characteristics, etc. In this study of the Free State province, Geographical Information Systems GIS was utilised to determine vulnerability of soils to wind erosion using comparative and quantitative methods. The results showed that the western part of the region is highly susceptible to wind erosion. The central part is moderately affected while the eastern part is least affected by wind erosion. Wind erosion is further enhanced by sandy soil types, soil particle size, sparsely distributed vegetation and low soil moisture content in this part of the study area. The present situation of soil and wind erosion is the result of concurrent effects of climate, vegetation cover and surface soil properties. Wind erosion could be manageable with appropriate farming practices.

Key words: erodibility, farming practices, Free State province, GIS, land degradation, wind erosion.

Abstrak

Wind erosie word geïdefiseerd as die een van die mees problematiese omgewings en sosiale-ekonomiese problem in die Vrystaat provisie. Die ontwikkeling, vordering en intensivisëring van grond en wind erosie word beïnvloed deur faktore soos klimaat, terrein, grond en plantegroei eienskappe ens. Vir die studie in die Vrystaat provinsie sal Geografiese Inligtings stelsels gebruik word om die blootstelling van grond tot wind erosie te bepaal met behulp van vergelykende en kwantitatiewe metodes. Die resultate bewys dat die westelike gedeeeltes van die streek hoogs vatbaar is vir wind erosie. Die sentrale gedeeltes is slegs matig vatbaar, terwyl die oostelike gedeelte die minste vatbaar is vir wind erosie. In die studie area word wind erosie ook bevorder deur sanderige grondtipes, grootte van die grond deeltjies, skaars verspreiding van plantegroei en lae grond vog inhoud. Die huidige situasie van grond en wind erosie is die resultaat van voortdurende klimaatsomstandighede, plantegroei en oppervlakte grond eienskappe. Wind erosie kan bestuur word deur toepaslike boerdery praktyke.

Steutel woorde: erodeerbaarheid, boerdery praktyke, Vrystaatse provinsie, GIS, grondagteruitgang, wind erosie.

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Dedication

This work is dedicated to my wife Limpho Patricia ‘Maphole, my children - Mofuli Kish, Thato Augustina, Relebohile Priscilla, Morareli Gabriel, Phole Simon, Lesedi, Karabo, Tshepang Yvonne, the Mahasa Family, relatives and friends.

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Acronyms

AUSLEM	Australian Land Erodibility Model
CEMSYS	The Computational Environmental Management System model
DEAT	Department of Environmental Affairs and Tourism
FV	Factor Value
GIS	Geographic Information Systems
IWEMS	Integrated Wind Erosion Modelling System
KAP	Knowledge, Attitudes and Practices
RS	Remote Sensing
RWEQ	Revised Wind Erosion Equation
TEAM	Texas Tech Erosion Analysis Model
WEELS	Wind Erosion on European Light Soils
WEPS	Wind Erosion Prediction System
WEQ	Wind Erosion Equation
WERU	Wind Erosion Research Unit

CHAPTER 1

INTRODUCTION, AIM AND RATIONALE

1.1 Introduction

Primarily land degradation a is result of human activities. This process is particularly dominant in arid and semi-arid but can also occur in dry sub-humid areas. Generally wind erosion leads to land degradation which eventually enhances susceptibility of the land to desertification, if it persists unabated. In many cases it is mentioned that climatic variations, soil properties and vegetation account for land degradation. (D'Odorico *et al.* 2013, Meshesha *et al.* 2012). It occurs predominantly, but not exclusively, in semi-arid areas. Major impacts of desertification, among others, may include loss of biodiversity and loss of productive capacity of land. It is also associated with a change of vegetation e.g. from perennial grasses to one dominated by shrubs (Ravi *et al.* 2010). Overgrazing, over cultivation, deforestation, overdraft of groundwater and global climate change are the primary causes of desertification, while drought is a contributing factor (Mekasha *et al.* 2014, Biazin and Sterk 2013), the main causes are related to human overexploitation of the environment (Barman *et al.* 2013).

In dry environments, desertification is normally associated with widespread wind erosion. In dry environments like the western Free State of South Africa, land degradation by wind action is significant (Wiggs and Holmes 2011). According to Ighodaro *et al.* (2013), wind erosion refers to the detachment, transport and deposition of loose sediment material together with organic matter and winds happen to be very effective when vegetation is sparse. The effects of wind erosion include fertility depletion in agricultural fields, leading to a reduction in crop harvest (Sharratt *et al.* 2012) and desertification in the long run (Dawelbait and Morari 2012, Vanmaercke *et al.* 2011). The off-site effects of wind erosion include the accumulation of sand and dust on the fields, drainage ditches, farm machinery, surface water, infrastructure such as roads, railways, buildings etc. In global extent, wind erosion accounts for about 46 % of the area affected by land degradation.

It is an important environmental problem to recognise wind action in erosion, transportation and subsequent deposition of fine particles. Coarse and finer soil particles enter the atmosphere through various mechanisms, affecting a large number of physical and chemical processes and, consequently, the natural environment. This is a major environmental issue in drier regions of the world. Wind action is not only limited to erosion and deposition of soil particles, but also contributes to concerntration of the atmospheric dust that causes environmental pollution. The concentration of dust in the atmosphere influences climate.

The short term effect of high dust concentrations in the atmosphere is reduction of visibility. This is especially the case during dust storms (Giri *et al.* 2012). Where pesticides are used in agricultural fields, dust storms can be harmful to the surrounding areas (Fox *et al.* 2012). The long-term effects result from the transportation of finer dust particles that may carry organic matter, heavy metals, pesticides and fertilizers over long distances. The effects of fine airborne particles on environmental pollution have been a subject of study, in the field of both wind and water pollution. It is reported that various aspects of human health are adeversely affected by fine atmospheric dust (Lee *et al.* 2012, Man *et al.* 2011, Munson *et al.* 2011, Sharratt 2011). In addition, it cannot be underestimated how these fine dust particles in the atmosphere affect climate change (Pasqui *et al.* 2013, Wiggs and Holmes 2011).
Dust research has stimulated the integration of disciplines, including geomorphology, soil physics, meteorology, fluid dynamics, air chemistry and ocean biology. It has also involved diverse methodologies, ranging from field campaigns, Geographical Information System (GIS) analyses, Remote Sensing (RS), numerical modelling, data assimilation as well as field and laboratory experiments. In wind erosion, soil particles undergo a process of wind-forced movement which can be demonstrated to comprise of initiation, transport and deposition (Hu and Flanagan 2013). According to O'Loingsigh

et al. (2014), atmospheric conditions like wind, temperature and precipitation make wind erosion a very complex process. It is further mentioned that intrinsic soil properties, namely, soil texture, aggregation and composition contribute further to the complexity. Other elements of paramount importance to the process include land-surface characteristics (e.g. aerodynamic roughness length, moisture, non-erodible elements, topography and vegetation) and inappropriate land-use practices (e.g. farming, grazing and mining) (O'Loingsigh *et al.* 2014). These parameters are also noted by Leenders *et al.* (2011). Eroded surface can significantly modified as a result of wind-erosion owing to the interaction of these factors (O'Loingsigh *et al.* 2014).
There are several methods of assessing wind erosion. Traditional approaches are centered on quantifying wind erosion from experimental plots. Experimental plots provide the most accurate wind erosion and soil loss data. However, they have practical disadvantages that limit their application. Not only are traditional approaches expensive but they can be time consuming and generate point-based data, which in a strict sense may be valid for only the plot location (O'Loingsigh *et al.* 2014, Wiggs and Holmes 2011).

These deficiencies in erosion assessment are rectified in erosion models (Chung *et al.* 2013). Quantitative data can be produced from soil modelling in a Geographic Information Systems (GIS) and that makes GIS effective predictive tools of soil loss. Since the development of the GIS, spatial modelling has increasingly been used to estimate soil loss in many parts of the world (Shiferaw 2011). GIS is a useful tool for understanding erosion processes and their interaction. GIS models are particularly useful in evaluating land use leading to soil loss (Maurer and Gerke 2011). Several studies (Ahmad 2013, Abodeely *et al.* 2012, Amin and Fazal 2012, Imhof *et al.* 2012, Tilligkeit 2012, Arekhi *et al.* 2011, Funabashi 2011, Nanyan *et al.* 2011, Sang *et al.* 2011, Zhu *et al.* 2011) have shown that GIS is an excellent tool in wind erosion modelling and makes it easier in a computer-based environment. GIS techniques allow predictions to be made either at local or regional levels. According to Nontananandh and Changnoi (2012) and Usali and Ismail (2010), remote sensing, complemented by field ground truthing and GIS, provides the best methodological tools that can be used to investigate wind erosion.

Not only do GIS techniques make it easier to assess the impact of wind erosion as a result of human actions, but they can be used to conceptualise and interpret complex systems as they allow for easy viewing of different scenarios by decision-makers. In the GIS models, most of the data used (i.e. climatic, vegetation, relief, soil etc.) can be processed and used as first stage input to identify and map degraded lands (O'Loingsigh *et al.* 2014). This study is therefore, aimed at investigating the susceptibility of different parts of the Free State to wind erosion, using GIS techniques.

1.2 Problem statement

Wind erosion is a global environmental concern. It is predominant in the western Free State (Holmes *et al.* 2008, Holmes and Barker 2006) but its effects are felt across the whole province and other areas as well. The western area is under commercial dry land agriculture of "maize (*Zea mays*), wheat (*Triticum aestivum*) and sunflowers (*Helianthus annuus*) (Holmes *et al.* 2012: 603, Wiggs and Holmes 2011: 827)" while the eastern half is largely under mixed farming. Research conducted hitherto indicates that wind erosion in part of the Free State province has reached alarming levels, especially when the fields are fallow (Hensley *et al.* 2006, Thomas *et al.* 2005). World-over, the conversion of grasslands to shrublands is occurring rapidly in such regions (Okin *et al.* 2006), a phenomenon that has been reported in the western Free State (Wiggs and Holmes 2011, Holmes 2007, Hensley *et al.* 2006, Thomas *et al.* 2005). The factors that contribute most to this problem have been identified as inappropriate land use and agricultural practices. A manifestation of this degradation is the increase of dust storms in the area, indicating the worsening of wind erosion. Recently, there has been a change in land use patterns as a result of increased wind erosion. What remain unidentified are the main causes of wind erosion in the area

(Wiggs and Holmes 2011, Holmes *et al.* 2008). This has prompted this investigation which focuses on the erodibility of the Free State soils by wind.

1.3 Aim

The aim is to use GIS to determine how the susceptibility of soil to wind erosion varies spatially across the Free State and to assess farmers' perceptions and determine if they reflect that variability.

1.4 Research objectives

The main aim of the research is to determine erodibility of Free State soils by wind.

There are secondary objectives as well, namely:

- To assess the erodibility or susceptibility of soils to wind and how it varies spatially across the Free State.
- To identify areas that are susceptible to wind erosion.
- To assess farmers' perceptions about wind erosion and determine how these perceptions shape the decisions they make in land management across the Free State.

1.5 Research questions

The specific aim in examining the problem is to seek answers to the following set of questions:

- Do different land uses have different effects on soil erodibility or susceptibility to wind erosion?
- Which parameters can best predict soil erodibility in GIS models?
- Which land uses have the highest and lowest estimates of soil loss?

1.6 Brief Overview of Study

The study is organised as follows:

Chapter 1: Introduction, Aim and Rationale of study

This chapter provides the introduction, aim, research objectives, research questions, research hypotheses and the brief overview of the study.

Chapter 2: Literature Review

This chapter, providing the literature review relevant to the study, gives an overview of wind erosion processes, factors that determine soil erodibility, wind erosion modelling and applicable land management practices that could be adapted to address the erodibility of soils in the Free State. It also examines the management practices which farmers use to minimise the problem. The chapter addresses some different scenarios that are likely to occur in the area so as to advise farmers about land degradation in the area.

Chapter 3: Datasets and Methods

Chapter 3 presents the research methods, techniques and materials used to investigate erodibility of soils in the study area.

Chapter 4: Results

The focus of this chapter is on analysis and presentation of the research results from the collected questionnaire data, field surveys and map overlays produced from employing the ArcView 10.2.

Chapter 5: Discussion of Results

Chapter 5 presents the discussion of findings.

Chapter 6: Conclusions and Recommendations

The chapter provides the conclusions and recommendations of the study.

1.7 Summary

This chapter has addressed the entire envisaged route that the study was follow. The next chapter reviewed available literature on factors that influence erodibility of soils, land management issues in semi-arid to arid areas and some modelling of certain anticipated scenarios will also be presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter addresses wind erosion and the various expectations and challenges in the management of wind erosion. It also addresses progress made in wind erosion studies. The spatial variability of wind erosion in the study area is subsequently discussed with the main points of concern being its effects on human life, agriculture and riparian vegetation. In addition, the chapter examines aeolian geomorphology and wind erosion management practices in past and current scenario. In conclusion, the chapter focuses on what could be done in modelling wind erosion in the Free State province of South Africa, on the basis of available research.

2.2 Land Degradation

There are several definitions of land degradation, but all try to comment on the negative quality of land/soil due to natural occurrence and mainly to mismanagement by man. Land degradation can be related to both natural and human-induced changes (Huffman *et al.* 2012, Medugu *et al.* 2011, Saad *et al.* 2011). These researchers define soil degradation as an outcome of human activities and their interaction with the natural environment as shown in the conceptual diagram in Figure 2.1. These researchers also distinguished three types of soil / land degradation *viz* biological, chemical and physical. Degradation of soil structure, crusting, compaction and erosion results in physical land degradation (Haile and Fetene 2012). Chemical degradation includes acidification, salinization and nutrient and fertility depletion, whereas biological degradation includes the reduction of soil carbon and soil biodiversity processes. Accelerated land degradation is a biophysical process, which can be caused by political and socio-economic conditions (Oghenero 2012). Soil degradation is not a result of high population density but is related to what people do to the land determine the extent of degradation (Vanmaercke *et al.* 2011).

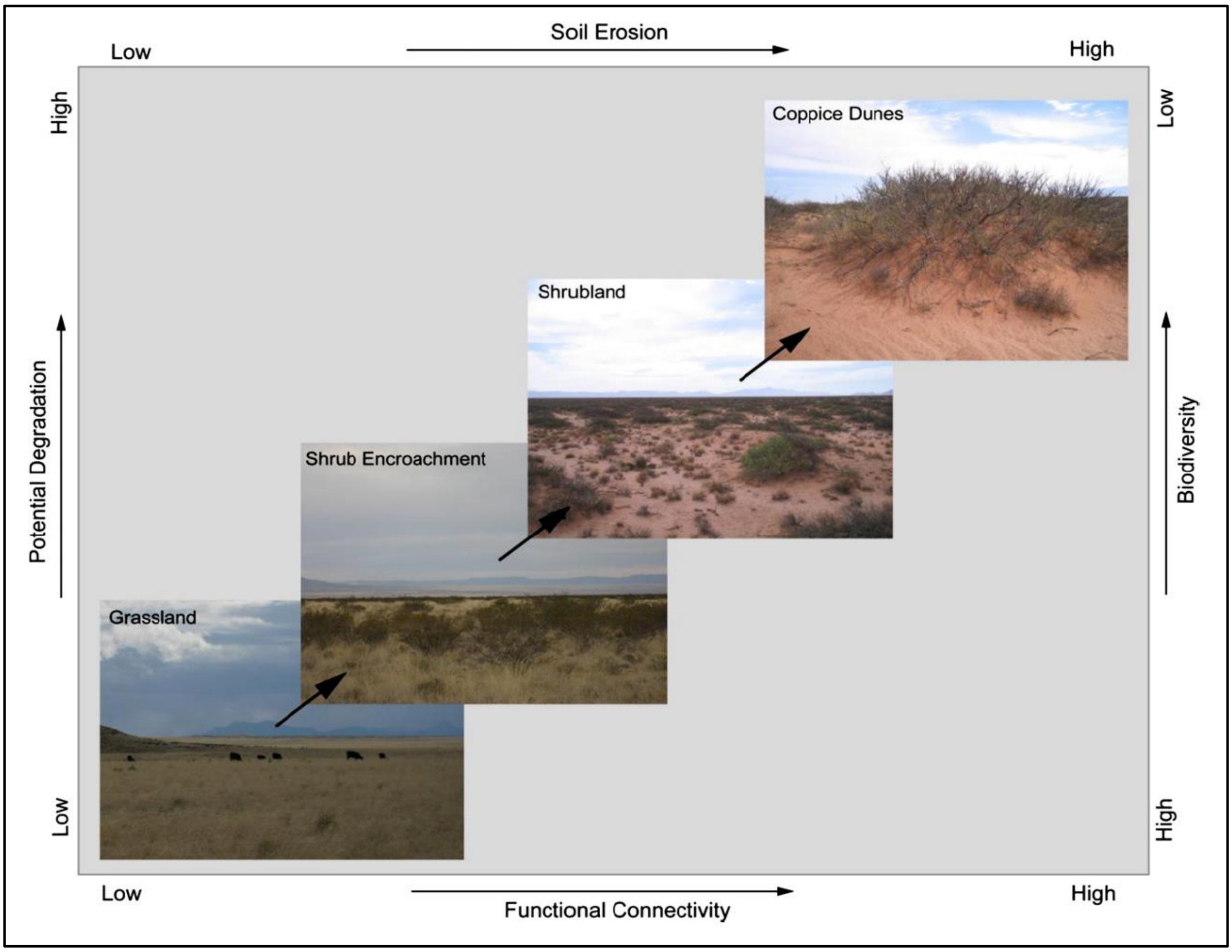

Figure 2.1: Conceptual diagram showing the different stages of grassland degradation in the desert along with changes in biodiversity, functional connectivity and soil erosion rates (Ravi *et al.* 2010: 243).

2.3 Wind erosion

Land degradation due to wind erosion is a serious threat to the quality of the soil, land and water resources upon which man depends for sustenance (Lafond *et al.* 2011, Medugu *et al.* 2011). Mitiku *et al.* (2006), similar to Fox *et al.* (2012) and Youssef *et al.* (2012), generally describes wind erosion as the detachment and transportation of the soil from land surface by wind. According to Blanco and Lal (2008), particles are transported may deposited at some distance downwind because of the abrupt change ability of wind to carry them. Detachment, transport, and deposition are the three dominant processes of wind erosion as in the case of erosion by water (Fig. 2.2). The movement modes and mechanics of soil particle are complex (see Sankey *et al.* 2011). Suspended particles are deposited uniquely depending on their size and follow Stoke's Law (Blanco and Lal 2008). According to this law, the larger the particle the faster it settles leaving small particles as dust (Wang and Lai 2014). Similar observations to these were also made by among others Pasqui *et al.* (2013) and Ku and Park (2011).

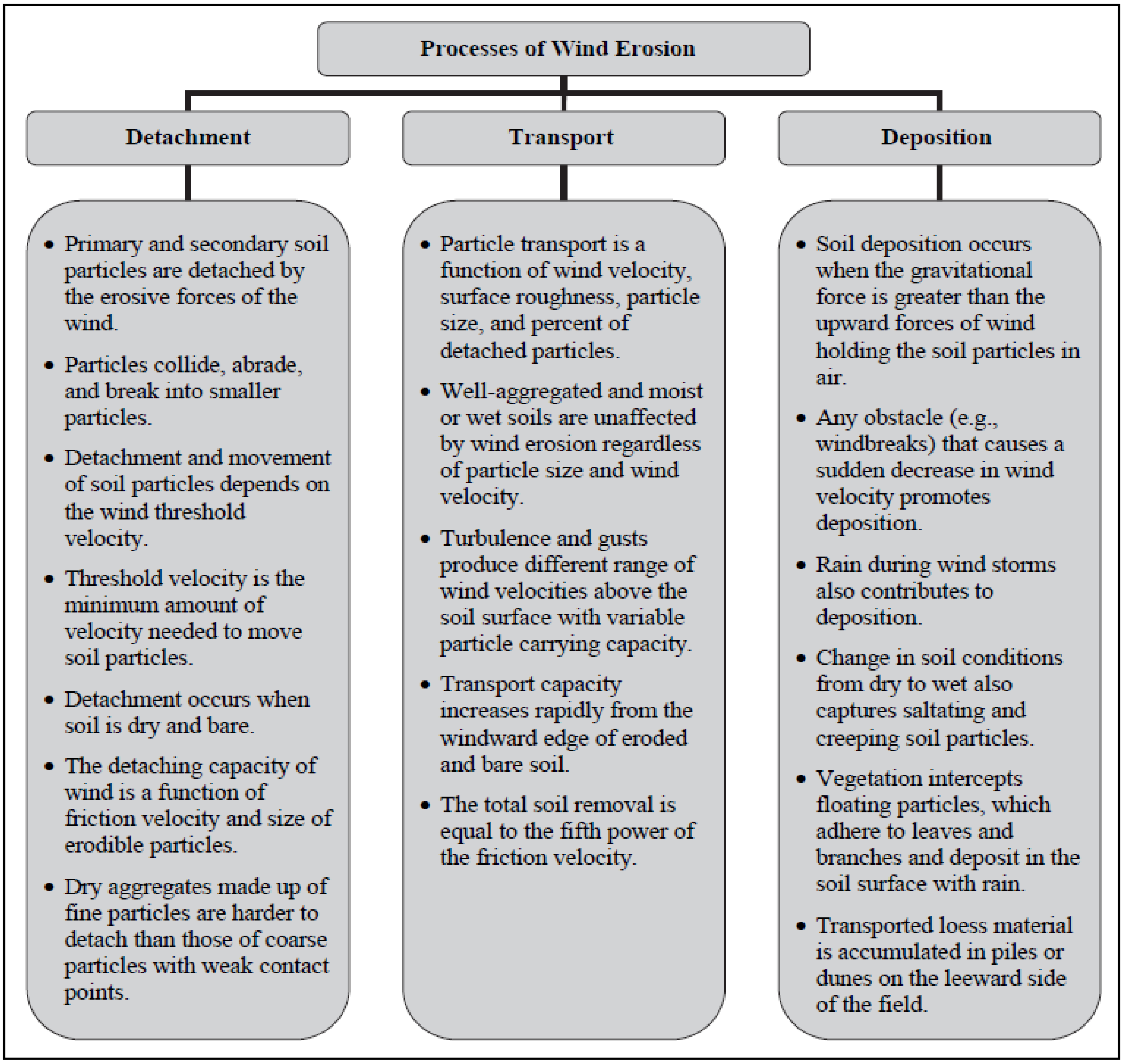

Figure 2.2: Three main processes of wind erosion (Blanco and Lal 2008: 56).

Transport of soil particles follows three pathways: saltation, surface creep and suspension (Baxter *et al.* 2013, Li *et al.* 2013b, Hagen *et al.* 2010) (Fig. 2.3). The size of soil particle exhibits distinctive characteristics when being transported during wind erosion. Particles that are small (< 0.1 mm) are transported selectively in suspension. These are usually from pulverised soils. Particles that are of medium size (0.1 - 0.5 mm) are transported in saltation and particles that are large (0.5 - 2 mm) by surface creeping. Creeping and saltating particles may break into smaller particles by abrasion, rebounding, and rebouncing effects and finally may be carried in suspension. Saltation, surface creep and suspension can occur together but are interactive (Fig. 2.4). In wind transportation, the size of moving particles within the wind decreases as height increases above the soil surface as influenced by wind velocity profile (Fig. 2.5) and on bare soil (Figure 2.6).

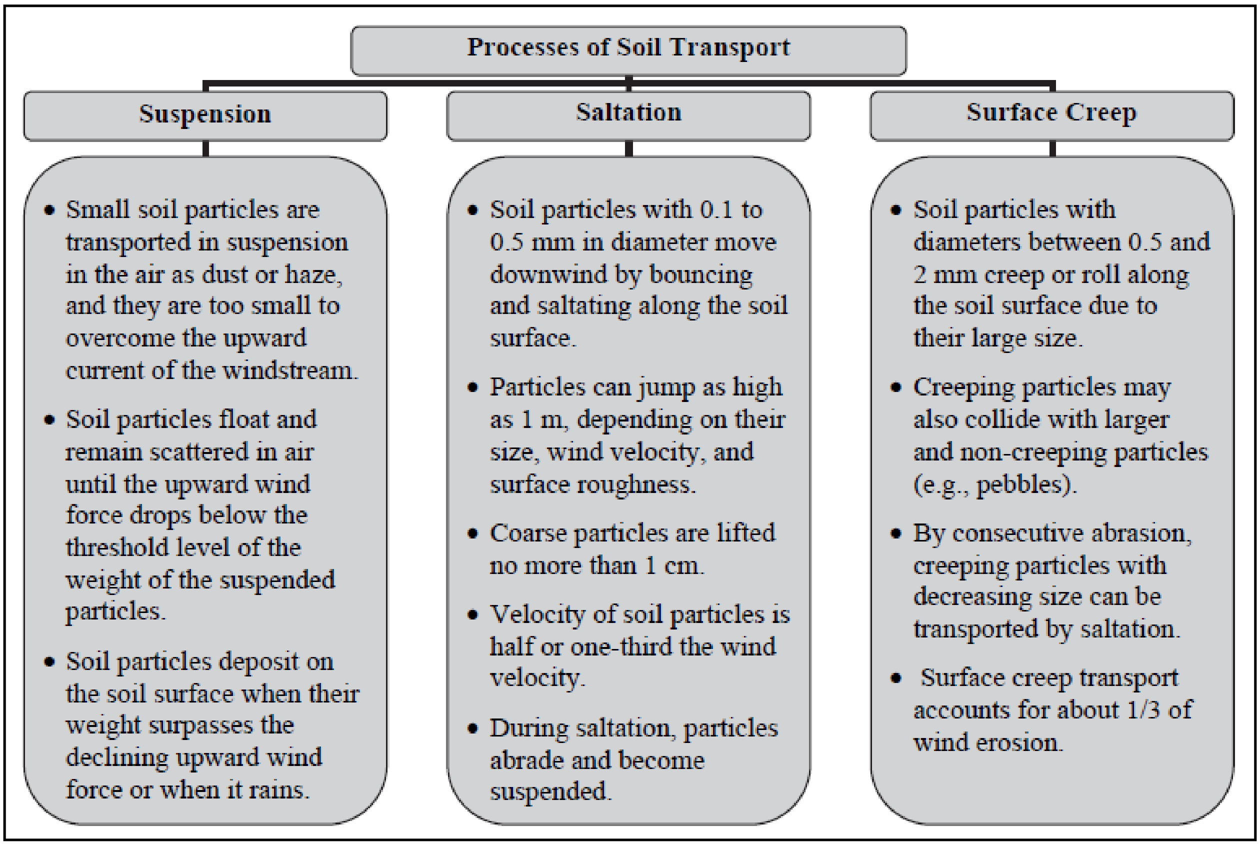

Figure 2.3: Transport processes of during wind erosion (Blanco and Lal, 2008: 57).

Saltation may account for 50 - 70% of total wind erosion (Dupont *et al.* 2013b). Suspension may account for 30 - 40% while surface creep could be about 5 - 25% (Grotzinger *et al.* 2013, Yurk *et al.* 2013). Saltating particles consist of fine inorganic and organic particles. The particles carried in suspension travel the longer distances than those in saltation and creep (Fig. 2.4). When there is an increase in both the area of a bare field and wind velocity, these results in more particles transported by suspension. Intensive wind erosion creates distinct features. Sedimentary rocks get polished or weathered, giving rise to rock outcrops when affected by wind erosion. Wind streams that exist in large concentrations along depressions carve channels and pits, leading to deflation hollows. With the prolonged blowing away of small particles by wind, paved landscapes usually result in arid regions. These comprise of stones and exposed pebbles.

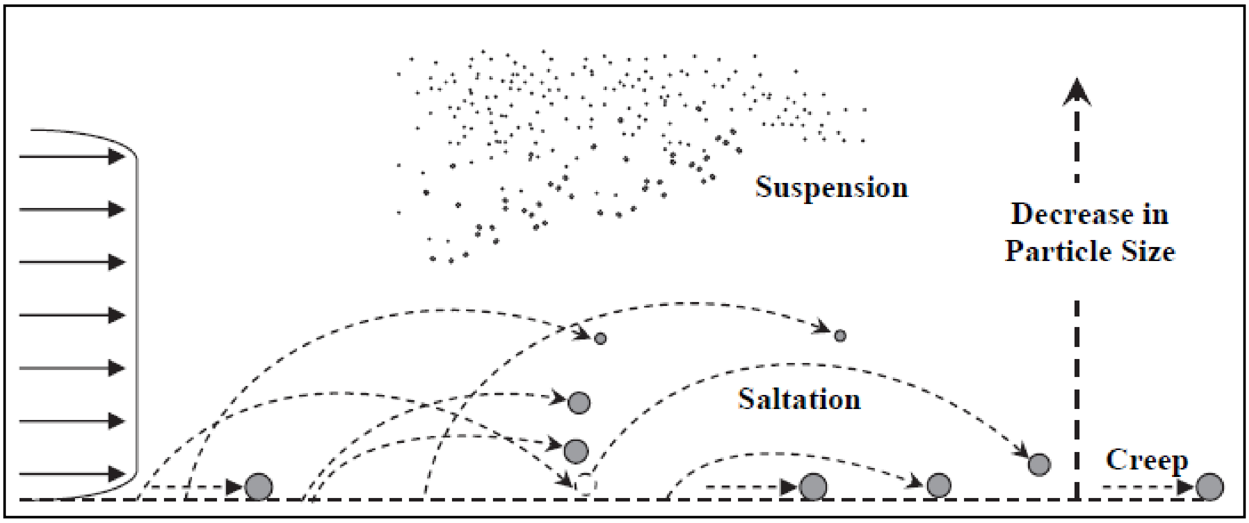

Figure 2.4: Modes of soil particle transport during wind erosion (Blanco and Lal 2008: 57).

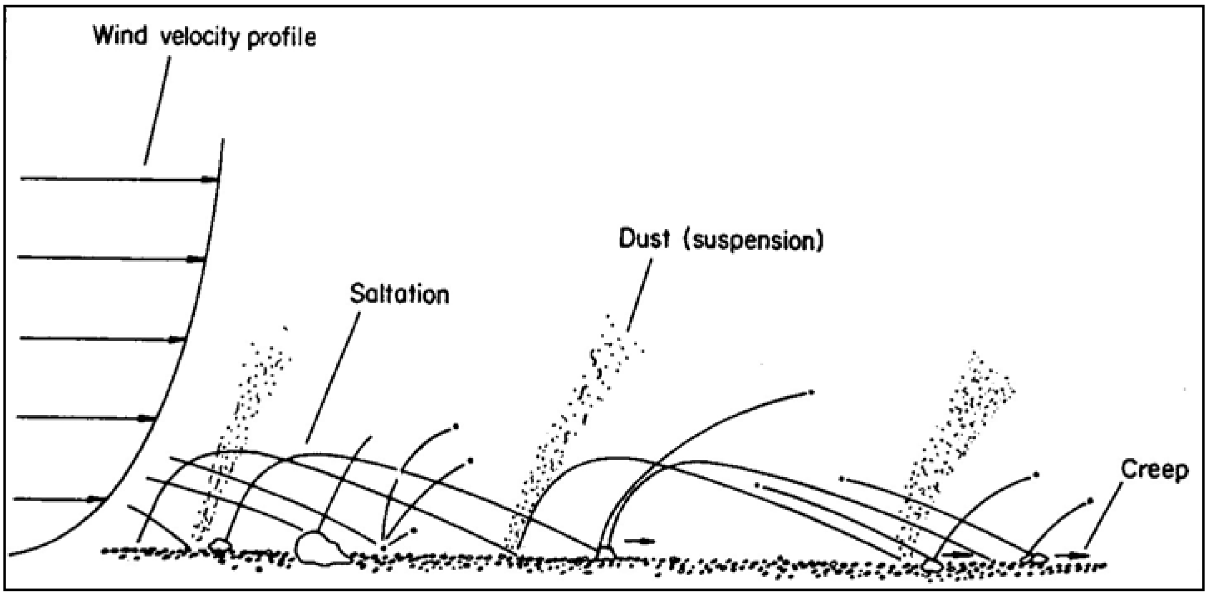

Figure 2.5: General wind velocity profile and related dust transport modes (McTainsh and Boughton 1993: 10).

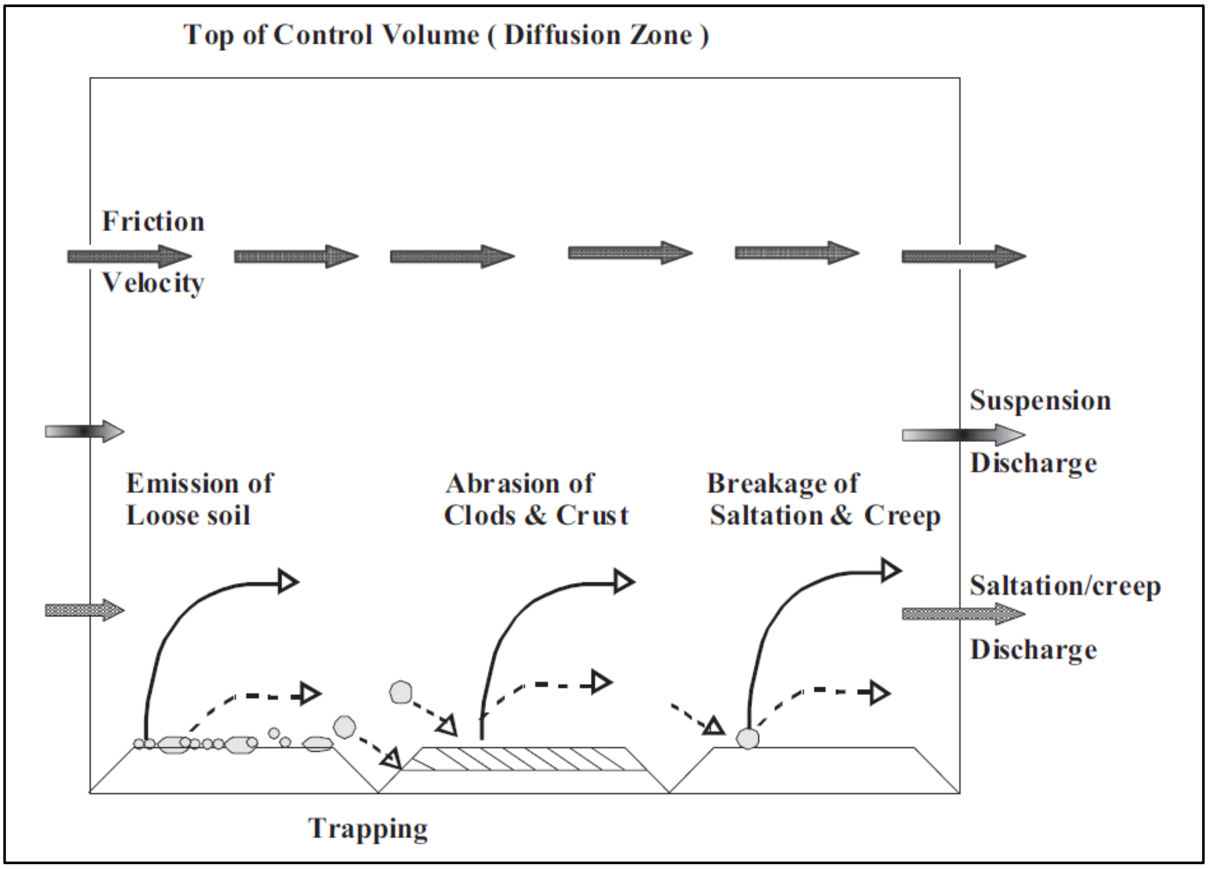

Figure 2.6: Schematic of control volume illustrating major wind erosion processes on bare soil (Hagen 2010: 2).

2.4 Factors affecting wind erosion

Wind erosion rate and magnitude are controlled by a number of factors which include the erodibility of the soil, climate, soil surface roughness, vegetation cover and unsheltered distance.

2.4.1 Erodibility of Soil

The ability of soils to be detached and transported by erosive agents of water or wind is defined as soil erodibility (Webb and Strong 2011, Zhou *et al.* 2010). However, it is important to note that erodibility is complicated to determine even at field level (Miller *et al.* 2012). Miller *et al.* (2012) and Shinoda *et al.* (2011) noted that the assessment of erodibility is very complicated because it depends on many variables. Wang *et al.* (2014) noted that erodibility not a static characteristic but rather time varying one. Soil erodibility is also a factor of soil cohesion, which in turn can be influenced by moisture content as well as the adsorptive and electromagnetic forces that bind soil particles together, especially in clays and silt (He *et al.* 2013, Nourzadeh *et al.* 2013, Saha *et al.* 2012, Khalit *et al.* 2012). The traditional methods of assessing soil erodibility are invariably very expensive (Wiggs and Holmes 2011). As an alternative to the expensive and time consuming traditional methods, simple field surveys have been developed to estimate erodibility (Youssef *et al.* 2012).

2.4.2 Soil Surface Roughness

This is the resultant micro-variation in soil elevations across a field due to tillage practices and soil erosion. It is one of the major factors that determine wind erosion and as well as one of the primary inputs in many wind erosion models (Zhao *et al.* 2013). Little resistance to the wind is given by soil surfaces that are not ridged or rough (Polymenakou 2012, Zheng *et al.* 2012 and Moreno *et al.* 2010). Ridges can be filled with time and abrasion may make produce smoothen the surface making it vulnerable to the wind. Excess tillage may result in the breakdown of soil structure and increased rate of erosion (Chen *et al.* 2011).

2.4.3 Climate

All factors relating to climate play vital roles in wind erosion. Meteorological observations indicate that dust emission can be suppressed by rainfall (Ho *et al.* 2014 Nield *et al.* 2014, O'Loingsigh *et al.* 2014). It is also observed that wind speed and duration directly influence wind erosion (Baxter *et al.* 2013, Xue *et al.* 2013, Singh and Kaur 2012). Although soil moisture may be a highly variable parameter, spatio-temporally due to the heterogeneous nature of soil properties, evapotranspiration, land cover, topography and precipitation but it can also influence wind erosion (Al-Shrafany *et al.* 2013). Low levels of soil moisture during droughts or at the surface of excessively drained soils may release particles to wind erosion (Bettis 2012, Bruins 2012). Freeze – drying in the surface is produced by this effect during winter months (Rohrmann *et al.* 2013).

2.4.4 Unsheltered Distance

Lack of windbreaks can lengthen unsheltered distance thus promoting wind erosion. Windbreaks can be made up of vegetation, residue, etc. This allows soil particles to be blown over longer distances, and by so doing increasing abrasion and wind erosion. Exposed soils result in ridges and knolls, making these ridges and knolls to suffer mostly under wind erosion (Li *et al.* 2013b).

2.4.5 Vegetative Cover

Extensive erosion by wind results when there is lack of permanent vegetation cover in certain locations (McTainsh *et al.* 2011). While bare soil that is loose and dry, is the most vulnerable to wind erosion, crops residue may provide enough resistance. Also, in severe cases even crops that yield a lot of residue may not shield the soil. The most effective vegetative cover in terms of soil protection should include a combination of living windbreaks networked adequately with crop selection, good tillage and residue management (Bargout 2012). Vegetation seasonality as suggested by Hély and Lézine (2014), Dupont *et al.* (2013a) and Abella *et al.* (2012) also has a tremendous influence on wind erosion.

2.4.6 Bioturbation

Bioturbation refers to the burrowing of soil by fauna that live in it resulting with improved soil aeration (Armas-Herrera *et al.* 2013). This term bioturbation is frequently used to describe how living organisms affect the substratum in (or on) which they live (Kristensen *et al.* 2012, Ngo *et al.* 2012). According to Leveque *et al.* (2014) and Kristensen *et al.* (2012), in sediment environments these bioturbating organisms modify microbially driven biogeochemical activity and loosen the soil. It is further mentioned that biogeochemical reactions can be affected by bioturbation and change the physical structure of the soil, the availability of resources for microbes or abiotic conditions that affect microbial reaction rates (e.g. redox and temperature). When these organisms have increased burrowing and continued ventilation activities that results in substantially affecting the sedimentary and biogeochemical processes and properties, translating into both negative and positive effects (Kristensen *et al.* 2012, Schiffers *et al.* 2011).

2.5 Dynamics of erodibility

In any potentially erodible area, erodibility is influenced by the distribution and density of vegetation cover and other roughness elements that protect the soil surface (e.g. rocks and soil clods) (Webb and Strong 2011). Intrinsic properties of soils also control soil erodibility leading to variation of soil aggregate size distribution (Wang *et al.* 2014), and the combined influence of temporal soil properties of moisture, surface crusting, aggregation, (Rodríguez-Caballero *et al.* 2012) and the availability of loose erodible material (LEM) (Figure 2.7 and 2.8). By intrinsic properties of soils, one refers to texture, mineralogy, chemistry and organic matter content, all of which influence soil particle sizes and weight. These in turn influence the soils' ability to retain moisture and form bonds (Webb and Strong 2011, Namikas *et al.* 2010). Some important requirements in the formation of soil aggregates and physical and biological crusts are enough soil moisture and inter-particle bonding (Webb and Strong 2011). As indicated by Burri *et al.* (2013) that these make the the stability of soil aggregates critical for their resistance to disruption by abrasion.

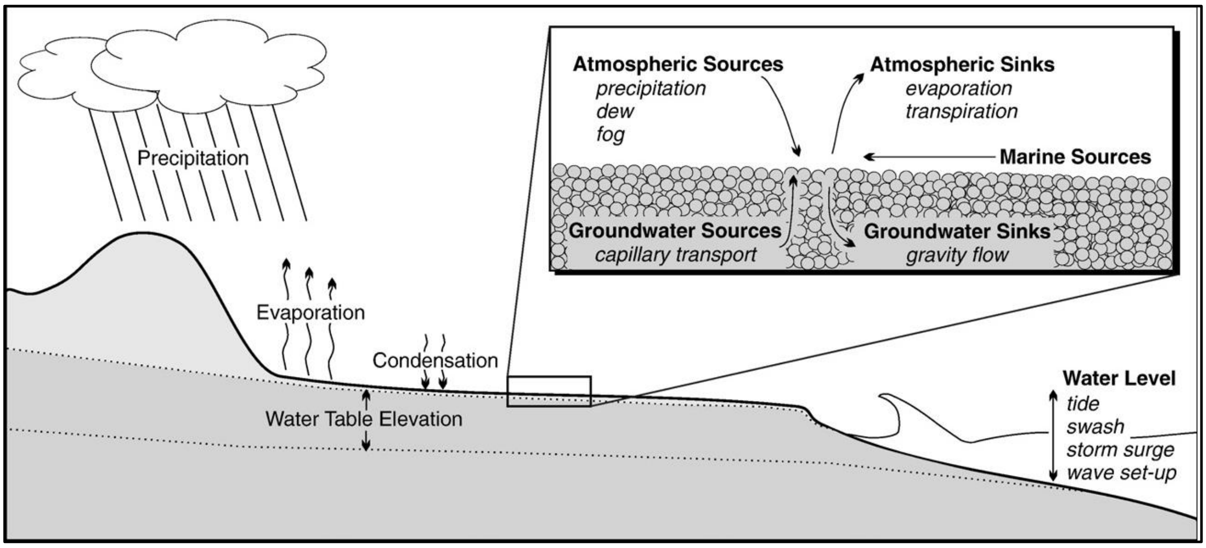

Figure 2.7: Processes influencing surface moisture content (Namikas *et al.* 2010: 304).

Because these intrinsic properties of soil vary through space and time in their degree of influence on erodibility (Webb and Strong 2011, Zhou *et al.* 2010), they are also known to control the availability of loose erodible material (LEM), the roughness of the soil surface, and the wind shear force (u_*) required for detaching and transporting soil grains. Webb and Strong (2011) mention that spatio-temporally, there is a state of soils to move from minimum to maximum erodibility continuum. For any erodible soil, spatial variations in intrinsic soil properties, the condition of temporal soil properties, and their responses to climate variability and land management determine this position in the continuum (Webb and Strong 2011).

The long-term annual soil loss per unit area (E) is given by

$$E = ICKLV \qquad \text{..} 1$$

where the factors are soil wind erodibility (I), climate (C), surface roughness (K), field length (L), and vegetation (V) (Hagen 2010).

In wind erosion models, it becomes very complicated and challenging to represent different factors that control soil erodibility in different environments together with identifying key drivers (see Muth and Bryden 2013). This is because these factors vary in their degree of influence through space and time (Zhou *et al.* 2010). "The representation of soil erodibility in wind erosion models has been further complicated by: differences in the metrics used to measure and represent erodibility in field studies, which tend to capture only components of the total erodibility of soils; the practicalities of monitoring multiple temporal soil properties to resolve drivers of soil erodibility change, which tends to be prohibitively expensive and time-consuming; and difficulties in combining the multiple available metrics into a measure of erodibility that aligns with our concept of soils existing within a single erodibility continuum" (Webb and Strong 2011:166).

In a study undertaken by Webb and McGowan (2009) to review approaches taken to represent the erodibility of landscapes in wind erosion models, it was observed that there was need to improve model representations of soil erodibility. It is of paramount importance to have inherent understanding of soils as a requirement in order to study wind erosion and dust emission models. This knowledge should address the understanding of soil erodibility dynamics, identifying key processes and mechanisms that need to be investigated and eavaluated. The evaluation should also measure soil erodibility at different spatio-temporal scales, and determine how the complexity of multi-temporal erodibility assessments can be simplified leading to the improvement of wind erosion models using new methods (Webb and Strong 2011).

2.6 Erodibility concepts, models and environmental controls

The presence of non-erodible roughness elements that affect the wind erosivity control how vulnerable any landscape could be to wind erosion, and the erodibility of its soils (Figure 2.8a) (Sankey *et al.* 2010, Webb and Strong 2011). Furieri *et al.* (2014) observed that the presence of non-erodible particles strongly attenuate soil wind erosion and may ultimately lead to the pavement effect. It is further noted in Webb and Strong (2011: 167 - 168) that the influence of these non-erodible roughness elements could be by: "(1) their interactions with the air stream, as a portion of the total shear stress exerted by the wind on the land surface becomes absorbed by non-erodible roughness elements; and (2) the physical protection and sheltering of the soil surface. The degree to which a surface is sheltered by roughness elements and the effect of these elements on the wind shear velocity (u_*) is dependent on the size, shape and distribution of roughness elements, and the direction from which the wind blows over a surface at any given time."

It follows from this that both the area of soil surface covered by a roughness element and an area immediately downstream are protected from the wind erosion (Figure 2.8b). It could also arise that there is a mutual sheltering effect where elements are sufficiently close to one another, with upwind elements protecting not only the intervening space, but also part (or all) of the downstream elements, resulting in skimming flow over the land surface (see Furieri *et al.* 2014). The protective nature or sheltering rendered by roughness elements therefore determines an important characteristic – the potentially erodible area of a land surface (Figure 2.8c), that is, the area of exposed soil surface that is subject to erosive winds. In size, this erodible area may lead to changes in roughness elements, for example through changes in vegetation cover prompting reaction to growth, senescence or harvesting, and changes in wind strength and direction (Chappell *et al.* 2011). The erodible area of a landscape therefore varies through both space and time (Webb and Strong 2011).

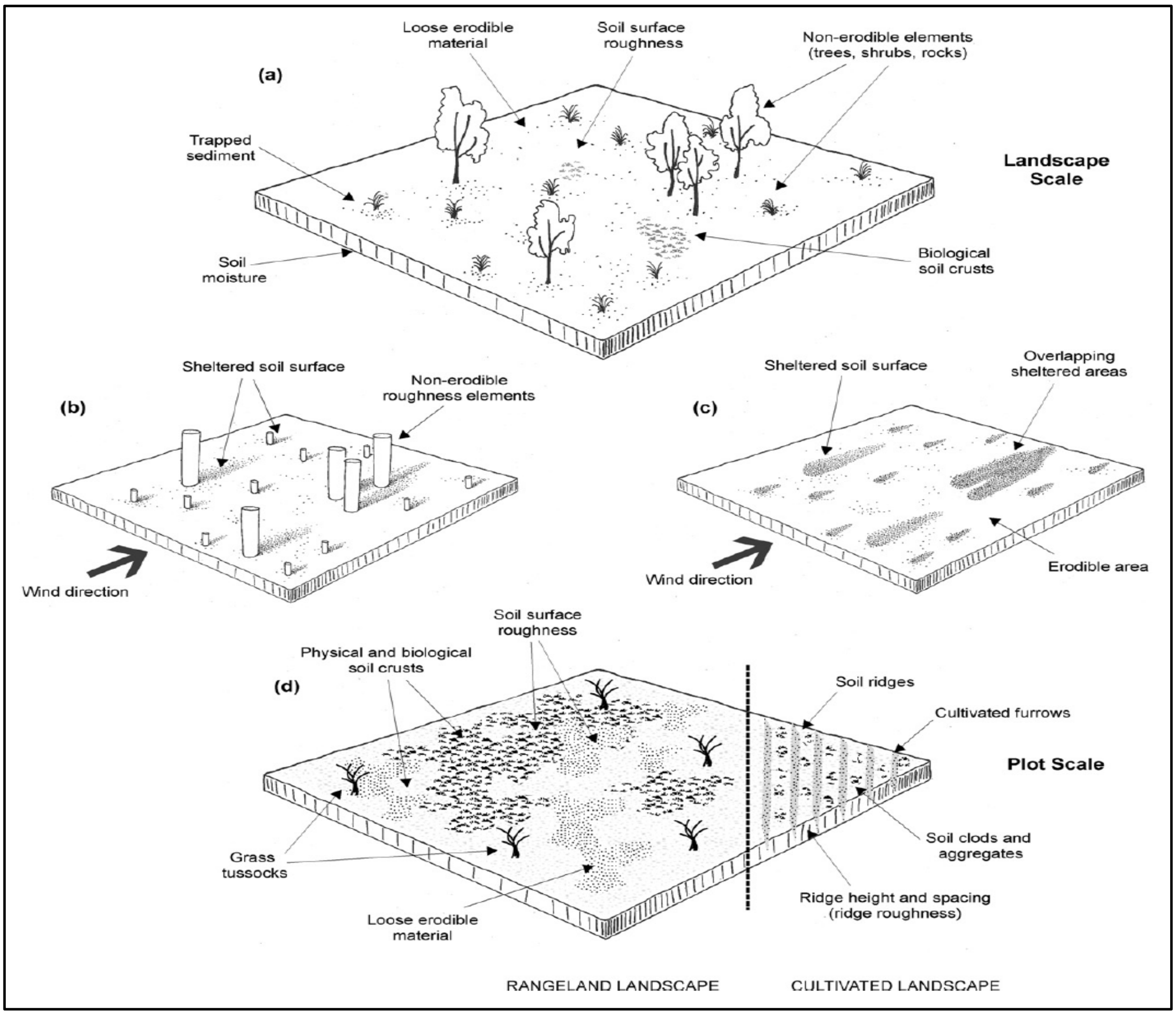

Figure 2.8: Diagrams illustrating controls on the vulnerability of a land area to wind erosion at the landscape (a), and plot scales (d). The landscape scale view (a) shows the effects of non-erodible roughness elements and soil properties influencing land erodibility. The effect of roughness elements on the erodible area of a soil surface is dependent on element size, shape, density and distribution (b), and the wind speed and direction. Together these influence the erodible area of the soil surface (c). At the plot scale (d), the erodibility of the potentially erodible area of a landscape (c) is determined by soil crusting and aggregation, soil ridge height and spacing (in cultivated lands), soil surface roughness, and the availability of loose erodible material (LEM) (Webb and Strong 2011: 167).

According to Webb and Strong (2011), it remains apparent that the erodibility of soils within the erodible area of a landscape becomes complicated and changes from time to time (Figure 2.8d) and that the controls on this erodibility vary spatially across different scales as determined by wind erosion processes. Properties such as soil particle size (texture), soil moisture content, mineralogy, electrostatic forces, soil chemistry, and the presence of micro-biota control variations in soil erodibility at the smallest spatial scales (e.g. grain, <10^{-2} m) (Figure 2.9). When these factors act together, then the magnitude of grain (aggregate) weight, inter-particle cohesion forces and drag, and the threshold friction velocity (u_{*t}) for grain mobilisation by wind may be determined. Similarly the relationships established herein can influence erodibility at the plot scale (10 meter length) through wind-driven processes of particle saltation, emission and deposition, which abrade soil aggregates and crusts, and generate and redistribute loose erodible material (LEM). An insight could be the contribution made by Algayer *et al.* (2014), who assessed the relationship in heterogeneity of aggregate stability for an underlying material (sub-crust) and crusted soil and also investigated how they influence standard soil properties.

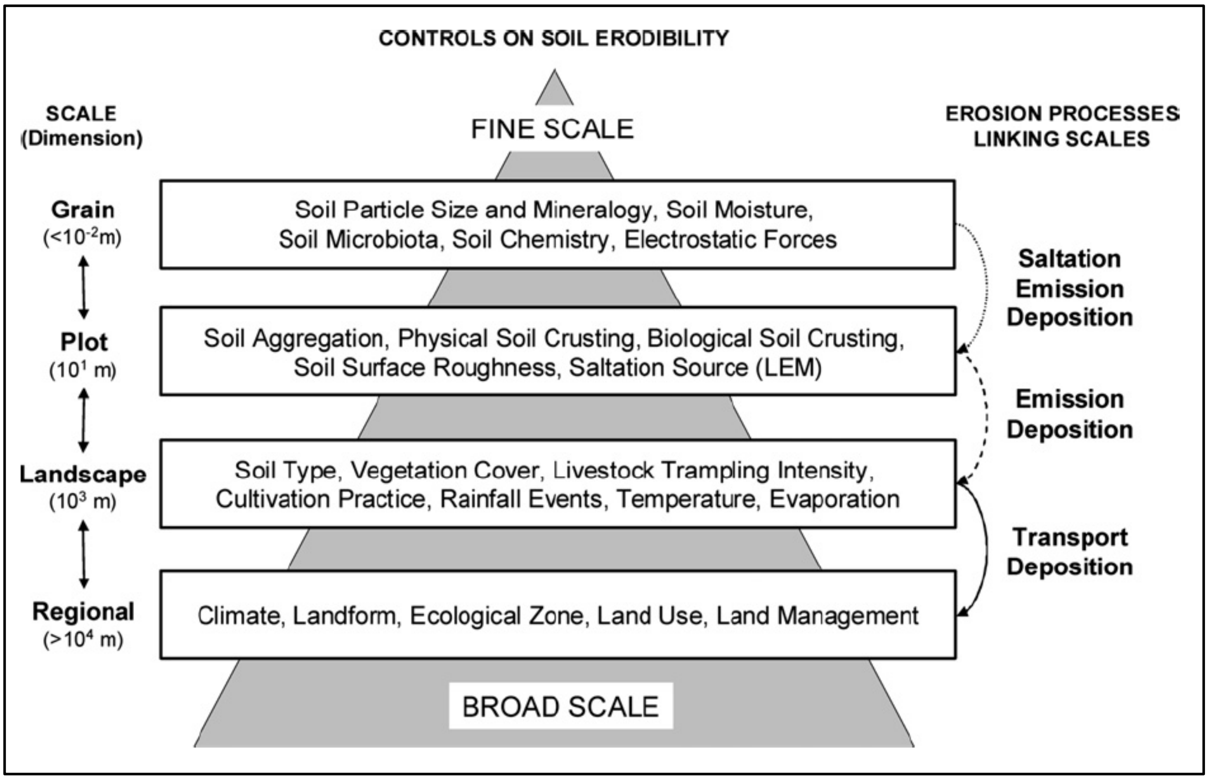

Fig. 2.9: Diagram illustrating controls on soil erodibility at different spatial scales, including within and between the soil grain (<10^{-2} m), plot (10 meter length), landscape (1000 meter length) and regional (10 000 meter length) scales. Arrows down the right-hand side of the figure show the erosion processes that functionally connect the scale domains (Webb and Strong 2011: 168).

At a coarser scale, erodibility through soil aggregation and crusting, and the availability of LEM is determined by the grain-scale conditions of soil texture, moisture content and inter-particle bonding. It should be noted that properties of LEM are physically different in aggregation and crusting but both can influence the shear stress imparted by the wind on the surface grains, surface sheltering at a small scale, and the supply of saltation material. While factors influencing erodibility at finer scales are important, erodibility at landscape scale (1km length) is largely dependent on soil surface roughness, u_{*t}, and the availability of LEM alone because areas that are in-between vegetation arrangements become more prone to wind erosion. This ceates bare areas of deflation between linear vegetation establishmets which can lead to crop mortality either by emission of soil particles or by burial (Sankey *et al.* 2012, Webb and Strong 2011).

As mentioned in Webb and Strong (2011: 168), at the landscape and regional (>10km length) scales (Figure 2.9), "environmental conditions of soil type, landform, climate and ecological zone; and land use and land management practices influence soil erodibility". Collectively, these conditions determine the relative effects of temporal soil properties of moisture content, aggregation and crusting on soil surface conditions, and the nature of plot-scale spatio-temporal patterns of soil erodibility dynamics. Dust transport and deposition processes influence climate, ecological zones and land use. Dust transport and deposition processes in turn influence landscape and finer-scale patterns of erodibility controls (Webb and Strong 2011).

In dust emission and wind erosion models, the erodibility of soils is represented through the effects of soil texture and moisture content on u_{*t} (Wang *et al.* 2014). This modelling approach expresses the effects of these conditions through scaling factors that are necessary for calibration and used to adjust (increase) u_{*t} irrespective of whether the soil is dry, bare and in a loose condition. Determination of soil textural effects is done relative to soil particle size, while soil moisture tension is obtained as a result of the effects of soil moisture (Webb and Strong 2011). Also mentioned in Chen *et* *al.* (2014) is that additional scaling factors in determining the source area may be applied to account for the effects of soil salts and crusting, yet in the absence of robust scaling functions these may be typically set to a value of 1 (i.e. no effect). This means soil erodibility modelling is mainly accomplished best at the smallest spatial scale (Figure 2.9) best, indicating that representation of temporal variations in soil erodibility controls at the plot, landscape or regional scales are not accommodated in the models. The dominant drivers of soil erodibility variations that influence wind erosion through space and time are not accounted for in wind erosion models such that determining key factors in controlling erodibility, and how they vary between environments, would be of paramount importance in representing soil erodibility in wind erosion models (Webb and Strong 2011).

2.6.1 Erodibility of croplands

Agricultural landscapes tend to be technically and intensively cultivated in terms of farming operations and management because according to Houyou *et al.* (2014) and Mulale *et al.* (2014), they are strongly affected by land use. That is both in terms of the size of the erodible area and that area's erodibility. Aspects of climate, namely soil moisture availability and growing temperatures determine optimum times for the sowing and harvesting of crops (Webb and Strong 2011). This means, in response to crop cycles and residue management practices (e.g. retention, burning, etc.), that the area of exposed soil surface will change at seasonal to annual time-scales. When natural vegetated areas are converted to croplands, the result is such that only purely annual vegetation grows, which is only able to protect the soil for a given period of time each year. Another notable aspect is that since cultivation often relies on tillage, this may produce smaller aggregates with lower stability, thereby aggravating the soil's susceptibility to wind erosion (Houyou *et al.* 2014). Sometimes when fields or paddocks are adjacent, management practices in one area can increase or decrease the fetch, resulting in either a decrease or increase in wind erosion of the neighbouring fields (Lal *et al.* 2011, Webb and Strong 2011, Delgado-Fernandez *et al.* 2010).

Erodibility of croplands can also be explained with particular reference to the water balance equation:

$$\mathbf{R = P - ET - IG - \Delta S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{2}$$

where:

R = Runoff

P = Precipitation

ET = Evapotranspiration

IG = Deep/inactive groundwater

ΔS = Change in soil storage

Generally inter-relationships between components for any given piece of cropland all parameters in the water balance equation are related and complement each other. The amount of runoff generated over croplands will only occur when sufficient precipitation has been experienced beyond the needs of both field capacity and evapotranspiration have been exceeded. Usually more runoff will result if the change in storage is depicted as a positive value indicating that there is water that could be lost and contribute towards runoff. The variations of all these components or factors in the water balance equation bear particular consideration of soil condition (i.e. soil texture and structure, infiltration capacity, clay content, physical characteristics like the ability to seal at the surface, etc.), vegetation or crop cover and type, antecedent conditions and land practices.

In humid climates, the water stored by the soil is sufficient to ensure satisfactory growth in rainfed agriculture. Instead, in climates with extended dry periods, irrigation is necessary to compensate for the evaporation deficit due to insufficient precipitation. Net irrigation water requirements in irrigation are defined as the volume of water needed to compensate for the deficit between potential crop evaporation and effective precipitation over the growing period of the crop. It varies considerably with climatic conditions, seasons, crops and soil types. The extent to which erodibility can increase for soils with high silt and clay content is thus dependent on the nature, severity and timing of disturbance events (e.g. cultivation)" (Webb and

Strong 2011: 169). Similar observations are made by Lal *et al.* (2011) and Delgado-Fernandez *et al.* (2010).

2.6.2 Erodibility in rangeland settings

Landform and vegetation characteristics determine the exposed potentially erodible area of the landscape in rangelands, with land management driving vegetation structural change and the impacts of livestock on vegetation cover and soil surface condition. Utilising pasture for livestock rearing reduces surface roughness and protects the soil surface from erosive winds, and increases the differential distribution of roughness elements and the distribution of potentially erodible areas occurs in space (Webb and Strong 2011). When controls on the erodibility of rangeland soils are present, they are observed to differ markedly from cropland settings due to differences in both disturbance mechanisms and disturbance intensities. There is usually lack of the regular mechanical disturbance of the soil profile associated with cultivation practices in rangelands. As a result, physical and biological crusts are more likely to form on soils in the rangelands. Soil particle re-arrangement following wetting often leads to the formation of crusts, or the growth of micro-biota (e.g. lichens, fungi and cyanobacteria), and have their own dynamic responses (spatio-temporal patterns of change) to climate, wind erosion events and land management. Because soil crusts are widely distributed and have the ability to consolidate soil grains, they play a important role over aggregation in determining the erodibility of soils in rangelands (Kidron *et al.* 2012, Kidron and Tal 2012, Yu *et al.* 2012, Root *et al.* 2011, Webb and Strong 2011).

More importantly, physical and biological soil crusts tend not to have the same effects on soil erodibility as one another (Bu *et al.* 2013, Briggs and Morgan 2012, Root and McCune 2012, Weber *et al.* 2012). Different types of crusts behave differently when subjected to rainfall and disturbance events depending on their various characteristics, be they physical, chemical or biological (Burri *et al.* 2013, Kidron *et al.* 2012, Yu *et al.* 2012, Yönter and Uysal 2012). It is therefore clear that these properties influence crust cover and strength, surface roughness and the availability of LEM. According to Webb and Strong (2011: 169), "the effects of physical and biological crusts on soil erodibility are manifested through four properties, including: (1) their ability to consolidate otherwise loose and potentially mobile sediment; (2) their surface roughness characteristics; (3) the size distribution of soil aggregates resulting from crust break-down during disturbance; and (4) their ability to trap LEM on the soil surface, which may be reactivated and work as a ready saltation source." Yu *et al.* (2012) are in support of these with similar observations.

In rangeland management, spatio-temporal changes influencing erodibility are heavily reliant on climate variability influences land managers adopt their actions and practices to changes in moisture availability and pasture growth. However, in rangelands it may not necessarily mean the climatic controls on soil surface condition will be triggered by possible disturbance due to livestock activities or numbers (Lal *et al.* 2011, Delgado-Fernandez *et al.* 2010). At seasonal to inter-annual time scales, increased livestock numbers coupled with low rainfall amounts do not necessarily correlate with the greatest rates of change (increases) in soil erodibility to wind. Periodic livestock grazing distributions and perpetual movement to watering points may impact on soil erodibility thereby creating heterogeneous landscapes with soils in a range of conditions through the erodibility continuum (Webb and Strong 2011).

2.7 Soil–climate–management interactions as they influence changes in soil properties controlling erodibility dynamics.

Two forms of soil erodibility dynamics are:

a) Soil aggregation and erodibility dynamics
b) Soil crusting and erodibility dynamics

a) Soil aggregation and erodibility dynamics

Combined effects of climate variability and cultivation practices may have have an effect on the size distribution and stability of soil aggregates, and the availability of LEM. Observations have revealed that in fine-textured soils greatest changes in erodibility resulting from climate and management effects on aggregation are found. Cultivation and over winter freeze-thaw cycles are responsible for these changes in soil aggregation, indicating the evolution of the erodible fraction of soils in response to climate and land management (Webb and Strong 2011).

b) Soil crusting and erodibility dynamics

Soil textural characteristics, site stability and climate are the main deteminatnts in the formation of physical and biological crusts. Physical crust formation is inherently determined by the intensity and frequency of precipitation while rates of crust degradation influence biological crust growth (Rodríguez-Caballero *et al.* 2012, Yu *et al.* 2012). Amounts of incoming solar radiation and potential evaporation regulate precipitation, crust cover and strength. "Crust formation may be triggered by precipitation events, crust degradation may occur as a result of: drying and desiccation; photo-degradation; fire; structural breakdown in self-mulching soils; and mechanical disturbance, including trampling by livestock and abrasion during erosion events." (Webb and Strong 2011: 171). Briggs and Morgan (2012), Root and McCune (2012), Mager and Thomas (2011), Root *et al.* (2011) have equally noted this properties.

Several information gaps exist in the soil; climate and management factors on the erodibility of soils (i.e. dry aggregate size distribution, erodible fraction and soil surface roughness). It remains apparent that further research needs to conducted in order to understand soil aggregation and crust responses to climate and management and their evolution through time to support the development of approaches for representing soil erodibility in wind erosion models (Webb and Strong 2011). Several shortcomings identified have prompted the establishment of the soil erodibility continuum, which is a new conceptual model of erodibility change between the states of minimum and maximum erodibility (Figure 2.10).

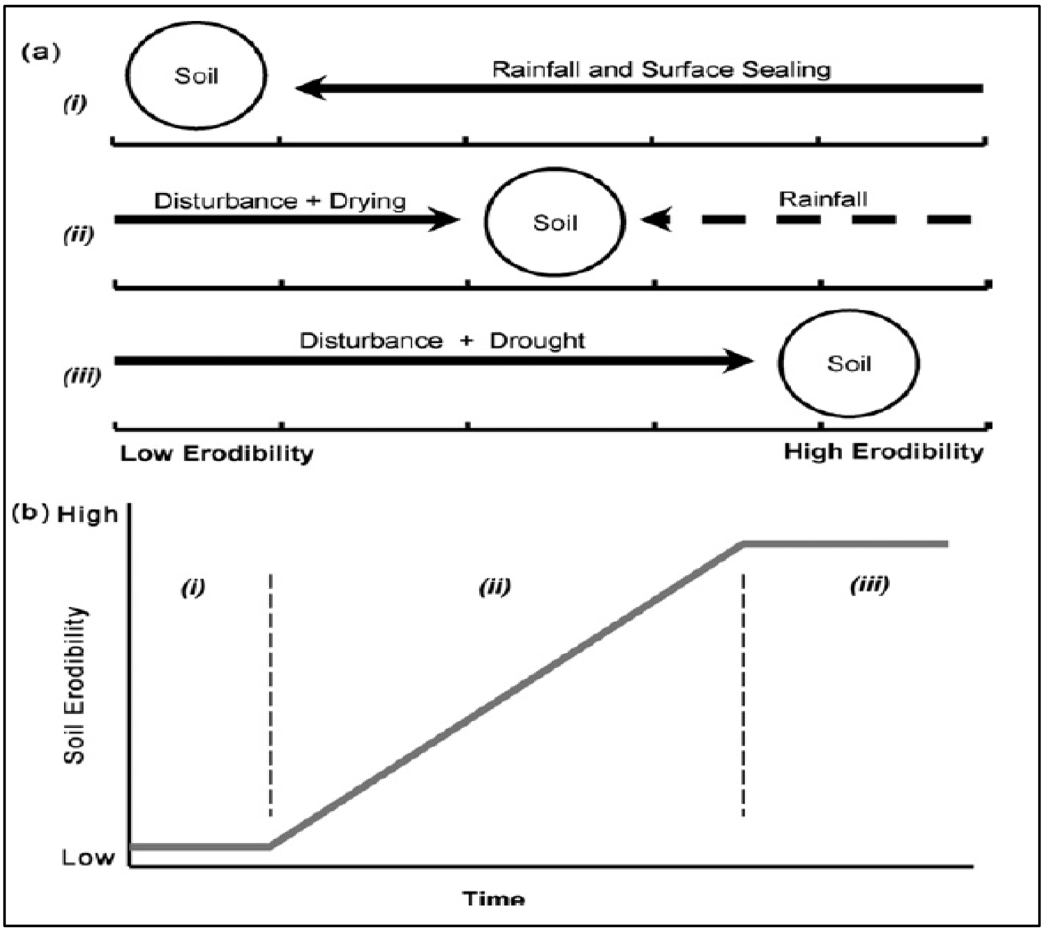

Figure 2.10: Conceptual diagrams (a) and (b) of the movement of a soil through the erodibility continuum, from minimum to maximum erodibility. The diagrams illustrate three phases of movement: (i) a condition of minimum erodibility; (ii) a transition phase of increasing erodibility; and (iii) a condition of maximum erodibility. The period of time that a soil remains in each phase is determined by its physical, chemical and biological properties, climate and land management conditions (Webb and Strong 2011: 171).

The first phase (i) of the soil erodibility continuum defines a condition of minimum erodibility. When rainfal amounts are enough to promote overall surface sealing, this will promote the breakdown of dry aggregates and the consolidation of surface material in a saturated matrix. Soil moisture takes charge of controlling erodibility once rainfall stops, allowing the soil to be at the position of minimum erodibility. This condition will hold so until wind shear forces can dominate because the moisture content decreases to a level at which the water tension between soil particles is low enough. During phase (i), erodibility will remain constant for soils that seal and form physical or biological crusts but for sandy soils an increase in erodibility will occur during this phase.

The second phase (ii) is the transition, from a condition of minimum erodibility to maximum erodibility of a soil through the continuum. This phase is charecterised by complex interactions between soil surface drying/desiccation, cultivation, or trampling by livestock, which induce a breakdown of surface crusts and aggregates increase in erodibility. Small rainfall events during this phase may temporarily increase the soil moisture content and aggregation, and decrease erodibility. Most soils in rangelands are observed to remain under phases (i) and (ii), unless disturbance levels affecting them are extreme (e.g. under high stocking rates during extended drought).

Maximum erodibilityis defined by phase (iii). For this condition to be reached by a particular soil, the should be minimum conditions of moisture content (antecedent rainfall) and maximum conditions of disturbance to the soil surface. Loose, dry soils, that have an effective grain diameter of 80 – 120 µm, that also require a minimum wind shear velocity to initiate particle mobilisation are said to be under maximum erodibility scenario.

Figure 2.11 shows three hypothetical soil erodibility frequency distributions. These could represent the same soil under three levels of disturbance intensity, for example under low (a), moderate (b) or high (c) stocking rates; or the responses of three different soils, for example a clay (a), a loam (b) and a sand (c) to a similar level of disturbance.

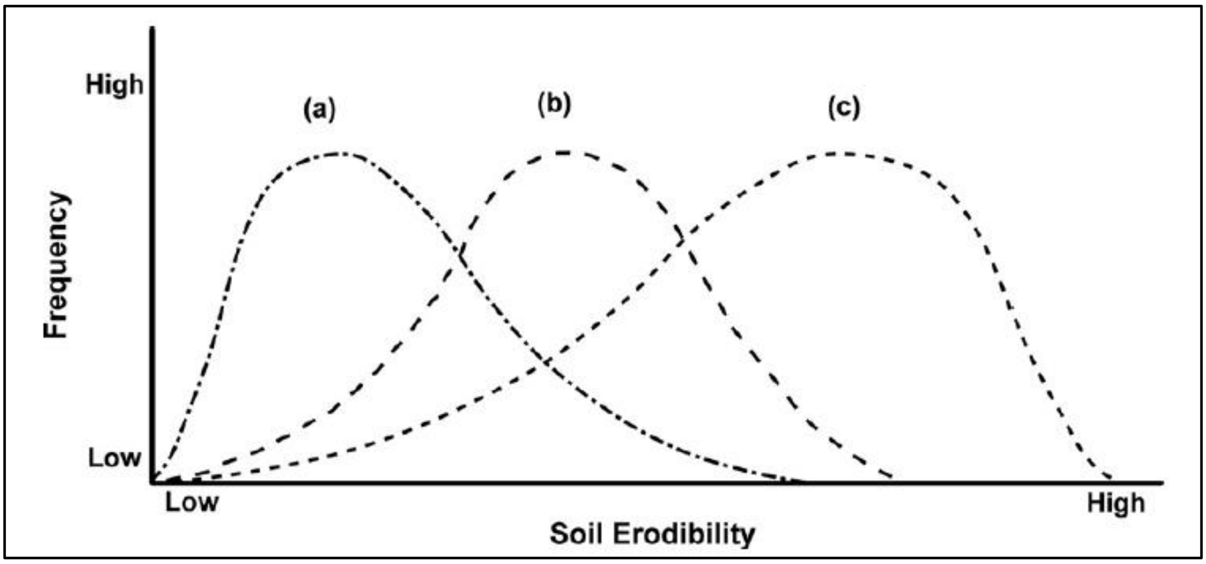

Figure 2.11: Conceptual diagram showing the frequency distributions of three soils in the erodibility continuum. These could represent the same soil type under three levels of disturbance intensity, for example under low (a), moderate (b) or high (c) stocking rates; or the responses of three different soils, for example a clay (a), a loam (b) and a sand (c) to a similar level of disturbance (Webb and Strong 2011: 173).

2.8 Impacts of wind erosion

The effect of wind erosion can be on-site as well as off-site. The on-site effects are loss of topsoil and plant nutrients, which have a direct impact on crop growth. Soils become less productive because they contain less nutrients and less capacity to retain water. A field experiment conducted on the effect of wind erosion in inner Mongolia showed that it could result in significant soil coarseness, infertility and dryness (Zhao *et al.* 2011). Abrasion caused by flying soil particles does considerable damage to crops and to young plants in particular. In addition to this, evaporation from plant leaves is accelerated by wind, restricting wheat growth.

Sand cover on fertile agricultural areas is considered as an example of the off-site effects. This affects crop growth and leading to decrease of harvest eventually. In a number of situations there will be soil textural changes resulting in decrease of clay particles and reduction in the ability of soil to conserve water. In a study on the effect of wind erosion on soil properties in China, similar results were reported: decrease of clay content and nutrient reduction in the soil e.g. decreases of organic matter, nitrogen and phosphorus contents (Li *et al.* 2012). Also, infrastructure can be covered by over-blown sand which will be a nuisance. In extreme cases, the thick sand cover may make the land baren. Suspended fine dust in the atmosphere will have environmental problem causing health hazard to human beings (Goudie 2014).

2.9 Methods of wind erosion assessment

Assessment of wind erosion is done by direct modelling and field measurements (Yue *et al.* 2015, Fox *et al.* 2012). According to Hong *et al.* (2014), the most well-known model to predict soil erosion by wind is the WEQ (wind erosion equation) empirically developed in 1960s. Based on the WEQ, revised or new models, such as RWEQ (revised wind erosion equation, and WEPS (wind erosion prediction system), have been suggested. The later models have supplemented various physical processes of soil erosion because the wind erosions predicted by models do not show significant level of agreement with measured in situ under certain situations due to varied, non-uniform and changing climate and soil conditions.

WEQ-based studies have been conducted through field measurement and numerical simulation targeting mostly large areas over long time frames using yearly or monthly units, and daily units in the particular case of the WEPS (Arekhi *et al.* 2011, Ram and Davari 2010, Webb and McGowan, 2009). These long-term approaches give good predictions by reducing various factors that fluctuating from moment to moment, but this approach may decrease the accuracy and efficiency of predictions of temporal variation in soil erodibility caused by changes in wind conditions. For example, where wind breaks are installed to prevent wind erosion, the number, location, arrangement and direction of the breaks needs investigation at a suitable scale to develop methods that will efficiently prevent the soil erosion over the wider field.

According to Fister *et al.* (2012), laboratory-based wind tunnels have been used to analyse the links between soil erodibility and various physical factors to derive a numerical relationship between them. Wind tunnels provide a controlled environment protecting against variable field conditions in order to investigate the effects of several particular factors on soil erosion behaviour. Wind factors, such as vertical profiles of wind speed and turbulence quantities can be artificially controlled in the wind tunnel and soil factors including soil texture, grain size, water content, surface roughness, soil compactness, etc. can be manually adjusted to be similar to field conditions. However, while each of the soil properties can be independently varied it is possible to vary them beyond field conditions. If the properties of the soil samples used for testing are not realistic, the test results may produce errors and uncertainty despite the advantages of using a wind tunnel (Hong *et al.* 2014).

The use of a portable wind tunnel is an alternative method to overcome the uncertainty of using artificial soil samples. Portable wind tunnels have been used by installing them on the ground of test site thus removing the requirement for preparing soil samples to investigate soil erosion. The strength of this approach is that erosion behaviour can be investigated on real soil whilst retaining the ability to control wind speed. Because the erosion area for testing is limited by the test area of the portable wind tunnel, which is typically a few square metres, very low soil losses through wind erosion, less than 1 gm^{-2} 10 min^{-1}, have been observed (Hong *et al.* 2014, Lee *et al.* 2012).

2.10 Wind erosion modelling

Global interest in climate change, desertification and land degradation has increased attention towards the modelling of wind erosion and dust emission processes in cropland and rangeland environments (Hoffman *et al.* 2013, Pasqui *et al.* 2013 and Fox *et al.* 2012). Several wind erosion studies from Chepil (1941) down to Mezõsi *et al.* (2015) have always had an element of modelling incorporated in them but the process still needs further refinement (Shinoda *et al.* 2011). A requirement for broad-scale assessments of soil erosion to inform land management activities lead to the development of wind erosion models; and to improve our understanding of dust transport processes and their effects on biogeochemical cycles, air quality and climate. Central to the development of wind erosion modelling systems is an

understanding of how the mechanisms driving wind erosion interact and change through space and time. High temporal resolution wind data is fundamentally important for precise wind erosion modelling (Guo 2013).
In particular, the wind erosion susceptibility of a land surface is highly sensitive to changes in the erodibility of its soils. It is therefore important that the factors that determine soil erodibility are understood and represented in wind erosion models. Identification of key challenges in modelling wind erosion, relating to the representation of land surface processes in models is, necessary (Guo 2013). These challenges are associated with: (1) quality land surface representations; (2) up-scaling to meet unresolved spatio-temporal heterogeneity; (3) the availability of spatial data; and (4) large-scale parameter estimation. Representing soil erodibility dynamics is relevant to each of these challenges and can be regarded as a priority in the on-going development of wind erosion models (Webb and Strong 2011).

A model is a simplified representation of a complex system or reality (Shinoda *et al.* 2011). The amount of sediment transported by the wind is central in modelling sediment transport (Leenders *et al.* 2011). Modelling aeolian transport presents challenges because of non-ideal conditions found in natural environments, such as variability of the surface slope and of the wind field. Furthermore, the models assume a homogeneous transport field, however, significant transport variability has been documented (e.g. de Vries *et al.* 2014, Barrineau and Ellis 2013). One of the difficulties with modelling transport is slope; the aspect and angle of the surface over which sediment is transported greatly affects transportation and deposition. For example, it takes more energy to transport grains up a windward slope than down the knoll. Another factor affecting model accuracy is surface roughness, or any element (e.g., plant or sand fence) that disrupts the wind flow. Vegetation typically reduces wind velocity and alters the roughness length encountered by the flow.

From the earliest empirical studies to the most recent experiments by Burri *et al.* (2011), nearly all observations have shown a negative relationship between vegetation density and sediment transport. For example, it was found that an 8% vegetation cover corresponds with a reduction in transport in excess of 50%. Further observation showed a 90% reduction in sand transport with a 12% vegetation cover compared to bare sand. The variability of natural vegetation covers presents difficulties in both measuring and predicting sediment transport. Many previous studies investigating the impact of vegetation on transport were performed in arid environments or in laboratory-based wind tunnels.

The core of the study similarly noted as in De Vries *et al.* (2014) that a model for aeolian transport in supply limited situations is presented to calculate aeolian sediment transport rates by applying the model to three test cases it is concluded that:

- The model is able to reproduce aeolian sediment transport rates which are dependent on wind speed and supply where both variables can govern total sediment transports. When supply is limited, wind driven equilibrium transports do not occur and supply governs the transport. When supply is abundant, wind driven equilibrium transports occur and wind governs transport.
- In supply limited systems, the length of increase in sediment transport rates in the direction of the wind, often ascribed to the fetch effect, can be explained by supply magnitude. The conventional fetch effect concept suggests a generic principle where the fetch distance versus critical fetch distance is an important parameter governing total transport. However, the critical fetch distance can be governed by the temporal and spatial variability of the supply instead. Therefore, determining critical fetch distances generically is very difficult if not impossible without quantifying supply magnitudes.
- Under supply limited conditions a linear model fits the simulated data best, whereas for abundant supply a cubic model fits the simulated data best. Predicted sediment transport using 3rd power models imply a large dependence on variability in wind speed. This large (3rd power) dependence on wind speed is unrealistic in supply limited situations.

Predicted sediment transport using a linear model is less dependent on variability in wind speed. As a result the linear function highlights the importance of supply rather than the importance of wind speed.

- Field data indicate that in a supply limited system sediment transport rates and wind speed are well represented using a linear relationship. This is also suggested by the model results and it could be hypothesised that when fitting a linear relationship, the resulting parameters can be used to quantify the sediment supply (and/or variability in sediment supply) when field data is available. The theory of linear relationships could be relevant to apply to several available field data sets with the aim of quantifying local supply magnitudes.

The study by De Vries *et al.* (2014) placed an emphasis that wind erosion models are for the purposes of (1) estimation of wind-erosion intensity and development of guidelines for land conservation, (2) quantification of global and regional dust cycles, and (3) investigation of wind-erosion mechanisms (Pasqui *et al.* 2013, Shinoda *et al.* 2011). Wind erosion prediction or modelling approaches are not new concepts (Webb and McGowan 2009). They are used in the investigation of fundamental processes and to guide resource management. They control soil wind erodibility and show that erosion begins when friction velocity exceeds a threshold. The also endorse that transport capacity is directly related to the cube of friction velocity for saltation/creep.

Estimates of the relative strength of dust emissions for different parts of the world are variable but in general they demonstrate the importance, firstly of the Sahara (with over half of the global total), secondly of China and Central Asia (with about 20% of the global total), thirdly of Arabia and fourthly of Australia. Southern Africa and the Americas are relatively minor sources, together accounting for less than about 5% of the total. By composition, aeolian dust is dominated by SiO_2 and Al_2O_3, but other significant components are Fe_2O_3, CaO and MgO. It may also have a large salt content, an organic content (Goudie 2014).

In order to determine soil loss, transport, and deposition, models use conservation of mass equations (Dietze *et al.* 2014, Lu *et al.* 2014, Hagen

2010). Based on the development principle, erosion models can be divided into three categories (Hagen 2010). These are stochastic, empirical and physically-based or analytical component models (Al-Shrafany *et al.* 2013 and Moody *et al.* 2013).

2.10.1 Stochastic models and Empirical models

The empirical Wind Erosion Equation (WEQ) is the most widely used model. They express existing, expected and possible erosion. The main issues in the application of empirical method are lack of data and data precision (Najm *et al.* 2013).

2.10.2 Physically-based or Analytical component models

The Wind Erosion Prediction System (WEPS) is a continuous, process-based model was developed to replace WEQ. In WEPS, surface conditions are simulated in the weather simulators on a daily basis while erosion is simulated on a sub-hourly basis. Other wind erosion models used include the Revised Wind Erosion Equation (RWEQ), Australian Land Erodibility Model (AUSLEM), the Computational Environmental Management System model (CEMSYS) formerly known as Integrated Wind Erosion Modelling System (IWEMS), Wind Erosion on European Light Soils (WEELS) and Texas Tech Erosion Analysis Model (TEAM) (Hagen 2010). Of all these models, only the use of the RWEQ could be possible in this study because others are region-specific.

The RWEQ has the ability to be scaled-up to the regional level (Guo *et al.* 2013a) such as the Free State after fulfilling certain requirements. The model input is based on four physical modules, respectively Soil, Vegetation, Roughness and Weather (Youssef *et al.* 2012). The results (Factor values) of all modules can be combined to obtain the wind erosion quantities as the average soil loss (S_L; kgm^{-2}) and the aeolian mass transport rate ($Q(x)$; $kg\ m^{-1}$) for one specific location. Each module depends on simple equations which represent the Factor value(s) for that module. As mentioned in Sharratt *et* *al.* (2012), for a complete and detailed description of all model equations see the RWEQ manual of Fryrear *et al.* (1998).

a) Soil Module = Soil Crust Factor (S_{CF}) and Erodible Factor (E_F)
   S_{CF} = *f* (Organic matter, Clay)

   E_F = *f* (Organic matter, Clay, Silt, Sand, Calcium Carbonate)

b) Vegetation Module, = Crops On Ground factor (C_{OG})
   C_{OG} = *f* (Flat cover, Standing silhouette, Canopy)

c) Roughness Module = Single soil roughness factor (K_{tot})
   K_{tot} = *f* (Random roughness, Orientated roughness)

d) Weather Module = Weather Factor W_F (kg/m)
   W_F = *f* (Wind factor, air density, gravity constant, soil wetness, etc.)

The combined module factors are used to determine the main model output equations.

Total aeolian mass transport (Q(x); kg m^{-1}) is equal to:

$$\boldsymbol{Q(x) = Q_{max} \cdot \left(1 - e^{-\left(\frac{x}{s}\right)^2}\right)} \quad \textbf{3}$$

Where x is the distance (m) from the non-erodible boundary, s is the critical field length (m) and Q_{max}; (kgm^{-1}) is the maximum transport capacity defined as:

$$\boldsymbol{Q_{max} = 109.8 \cdot (W_F \cdot E_F \cdot S_{CF} \cdot K_{tot} \cdot C_{OG})} \quad \textbf{4}$$

The Critical field Length *s* (m) is defined as the distance at which the 63% of the Q_{max} (kg/m) is reached and is calculated by:

$$\boldsymbol{S = \mu_{sa} \cdot (W_F \cdot E_F \cdot S_{CF} \cdot K_{tot} \cdot C_{OG})^{-\mu_{sb}}} \quad \textbf{5}$$

Whereby, μ_{sa} and μ_{sb} are RWEQ calibration parameters with their (μ_{sa} =150.7 and μ_{sb} = 0.3711) default values based on field experiments in the USA (Fryrear *et al.*, 1998).

Finally the average soil loss (S_L; kg m^{-2}) is calculated by:

$$S_L = \frac{2 \cdot x}{s^2} Q_{max} \cdot e^{-\left(\frac{x}{s}\right)^2} \text{.....................................} 6$$

Limitations that could lead to non-usage of RWEQ are primarily data related. Data could be unavailable and the model would rather be complex to employ for the current study.

2.11 Wind Erosion Modelling Approach using GIS

The modelling approach could follow the descriptive – normative one employing GIS (Javed *et al.* 2012). This approach could be concerned with a simplified description of reality by projecting wind erosion changes across the province from west to east. Influences of spatially adjacent places can also be incorporated in such models which suggests that vegetation types and land use can be modelled. Most processes of dryland degradation follow and are directly related, with slight exceptions in some wind erosion change paths. Summarily, on a short term basis, models can be used to determine changes in land use under an assumed process. These models are best suitable where there is no information on the driving forces and mechanisms of wind erosion changes is available (Sang *et al.* 2011).

Composite suitability analysis forms the basis for methodologies used in models using map overlays and their extension including statistical analysis. The approach in this study could be to use models in the combination and integration of maps in the determination of an optimal erodibility. Whilst there are numerous of integration models in GIS, only the Index Overlay model was selected so as to deal with only areas that have features that are known to have an influence on vulnerability of soils to wind erosion and also feasibly accessible for the study area. (see Akinluyi *et al.* 2015, Aubault *et al.* 2015). Eventually, a combination of maps were used to eliminate areas of absolute unacceptability (Akinluyi *et al.* 2015, Aubault *et al.* 2015, O'Loingsigh *et al.* 2014). A final erodibility map could be made based on the highest suitability values.

2.12 Management of wind erosion

In regions that are susceptible to wind erosion, land management activities in a particular field could lead to wind erosion processes that occur in neighbouring fields. The land management has a direct effect on the vegetation cover which tends to be the most important protective factor of soil against erosive winds (Meshesha *et al.* 2012). Generally most management practices are a desperate attempt to control wind erosion by reducing the speed of wind at the soil surface or by creating a soil-surface that is non-erodible (Liu *et al.* 2014) i.e. stabilising the agricultural surface. Since the western Free State area is relatively dry, it is mainly used for commercial dry land cultivation (maize, winter wheat and sunflowers) and to a lesser extent for supporting mixed farming (large and small stock). Large stocks graze on crop stubble. In many farms around the area, crop rotation and fallow are systematically applied. Post-harvest standing residue is used to control wind erosion by agriculturalists during the windy season on the Highveld (Wiggs and Holmes 2011).

Standing crop residues have been shown to be more effective in reducing loss of soil wind erosion processes than vegetation lying flat on the ground (Sharratt *et al.* 2012, Feng *et al.* 2011a, b). Standing vegetation is generally effective and thus controls wind erosion even when dead (Sharratt *et al.* 2012). Thus, in South Africa, standing stubble is retained on the land throughout the winter, until the threat of wind damage has passed (Wiggs and Holmes 2011). Hagen (2010) states that, unless the plant cover is destroyed by wind action, human disturbance or abrasion, it can suppress dust emissions from the surface. This suggests that wind erosion decreases with an increase in surface residue cover. The friction velocity above standing biomass is depleted by the leaves and stems to obtain the friction velocity at the surface that is used to drive erosion (Figures 2.12 and 2.13). Leaves are represented by a leaf area index and stems by a stem silhouette area index (WERU, 2004, Zender *et al.* 2003) as opposed to Figure 2.14A and B (see Harper *et al.* 2010).

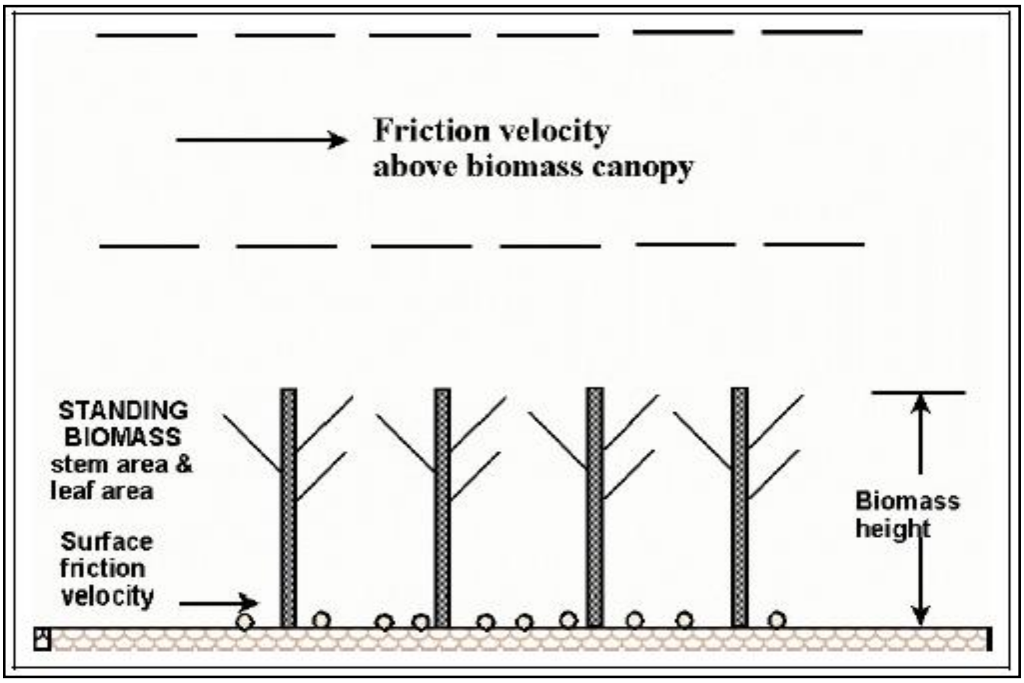

Figure 2.12: Diagram illustrating friction velocity above standing biomass that is reduced by drag of stems and leaves to the surface friction velocity below the standing biomass (Hagen 2010: 2, WERU 2004).

Despite immense research done on wind erosion and possible management practices, wind erosion still remains unabated as many farmers persist in cultivating crops where soil could be adequately protected. Sophisticated technology or great costs are not necessarily a requirement for wind management practices implementation, but rather ability of farmers to adapt (Yue *et al.* 2015) and succeed in curbing wind erosion (Gedikoglu and McCann 2012). There is an indication implementation of good practices may be effective where farm managers accepted them (Yue *et al.* 2015, Adimassu *et al.* 2013, Nordstrom and Hotta 2004).

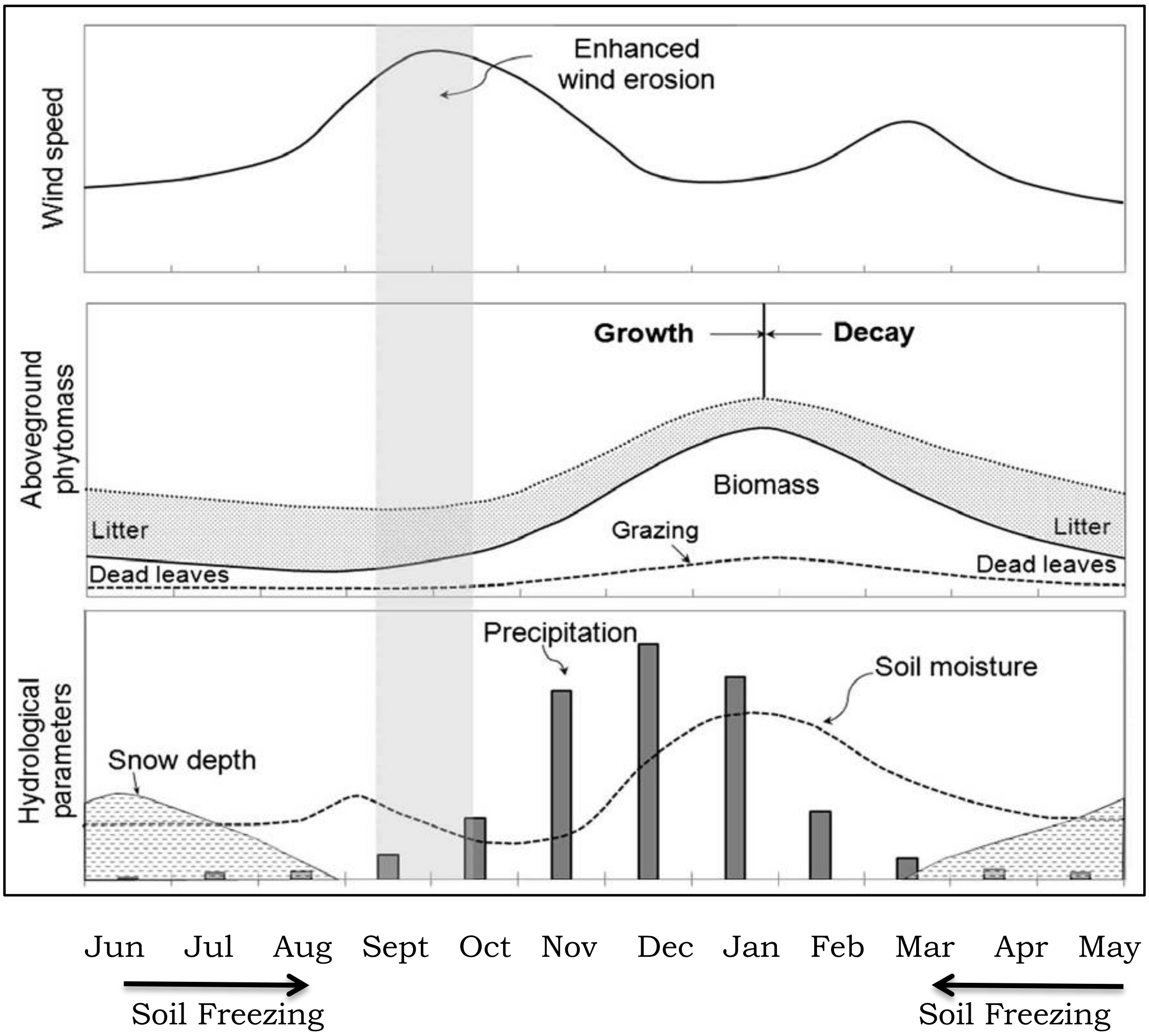

Figure 2.13: Typical seasonal changes of wind speed, aboveground biomass and hydrological parameters and their relationships with wind erosion (Shinoda *et al.* 2011: 3).

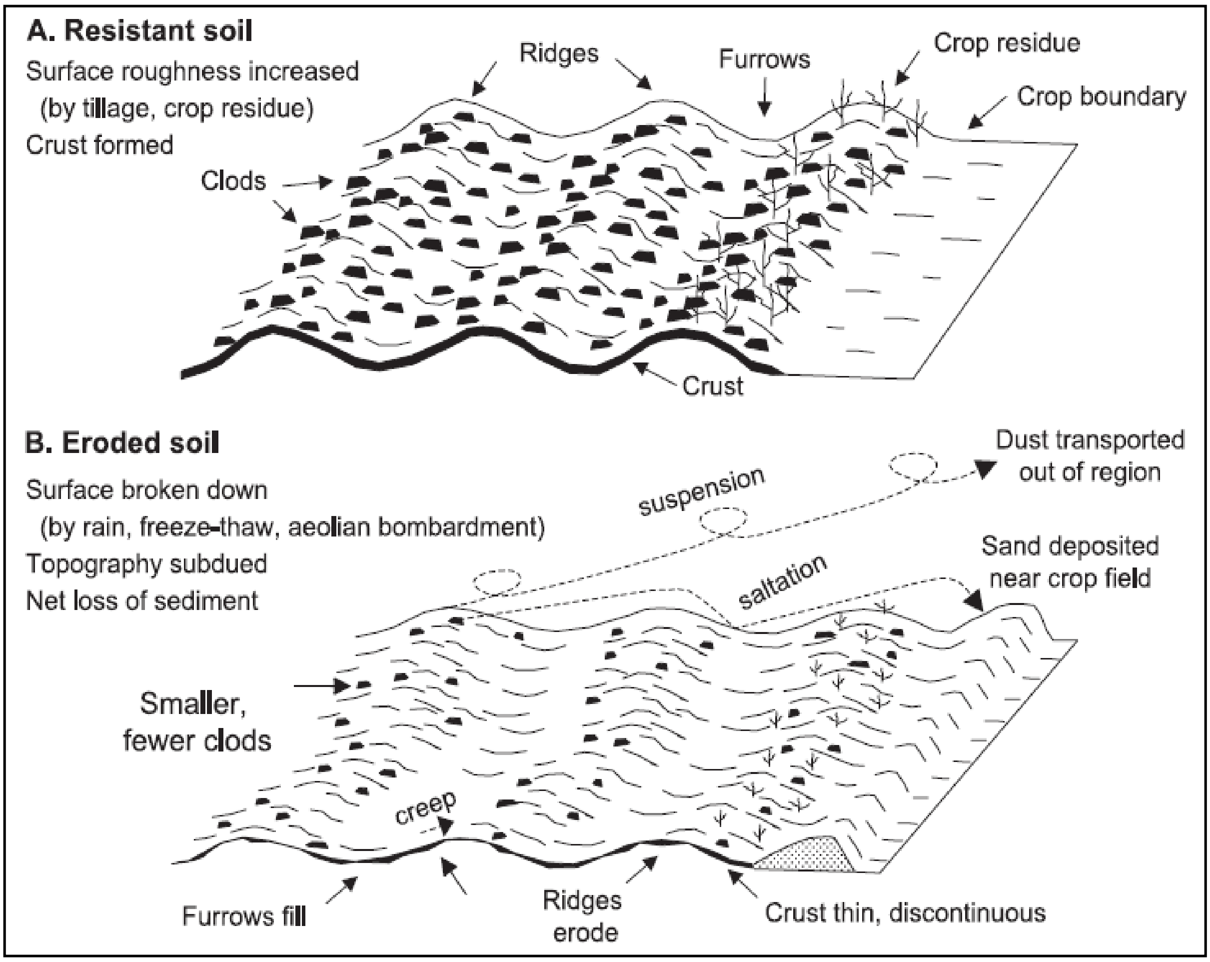

Figure 2.14: Farm fields characteristics of affecting vulnerability to wind erosion (Nordstrom and Hotta 2004: 161).

Table 2.1 below suggests some factors that affect vulnerability of agricultural lands to wind transport and management practices that could be put in place to curb the problem of wind erosion in agricultural areas.

Table 2.1: Factors affecting vulnerability of agricultural lands to wind transport (Nordstrom and Hotta 2004: 160).

Factor	**Impact on erosion Potential**	**Common action to improve/control**
Climate/weather		
Climate	determines natural controls; limits crop options	avoid marginal land; plant suitable crop
Wind speed/ direction	determines amount of surface erosion	use wind breaks; alter surface of field
Temperature/ humidity	affects air density; surface erodibility	select suitable time for farm operations
Soil properties		
Aggregate size	determines erodibility for given wind condition	use tillage to create clods
Dry aggregate stability	influences breakdown-rate to small sizes	control subsequent saltation
Clay content	produces clods that resist erosion	re-surface clay by using tillage
Bulk density	moisture potential; particle erodibility	tillage
Characteristics of surface		
Roughness (ridges, clods)	to reduce surface shear; to trap saltating grains	tillage; control subsequent saltation
Surface crust	to improve surface stability; resists erosion	initial tillage (continued tillage breaks surface)
Surface moisture	to affect surface erodibility	select appropriate crop and residue
Field width	to affect sediment source width, saltation	make use of shelterbelts; reduce size of field
Ground cover		
Crop type	affects wind, soil properties, seasonality	optimise crop silhouette, time harvested
Crop residue	to reduce wind erosion	make crop selection a priority
Windbreaks	to decrease wind speed and surface exposed	optimise their location; maintain through time
Active farm operations		
Preparation of land, cultivation, harvest	direct suspension by machines and tools	use low operating speed and personal exposure; plant less labour intensive crop
Use of access routes	direct suspension by vehicles	use surface stabilisers

2.13 Soil loss tolerance

Soil loss tolerance is when soil can economically and indefinitely still provide for high crop productivity under maximum annual soil erosion conditions (Hancock *et al.* 2015). Limits of soil loss tolerance define also the loss of soil quantities that are achievable to retain, economically and continuously, the sustainability of the soil (Montanarella and Vargas 2012, Perkins *et al.* 2011, Powlson *et al.* 2011). Within these limits, soil formation processes and wind erosion are in equilibrium. That means soil type is dependent on soil loss tolerance. On very deep soils that are also homogenous, wind erosion effects will be less pronounced than on soils that are shallow (Bhattacharyya *et al.* 2012).

2.14 Summary

Desertification, in the literature consulted, is indicated as a serious environmental problem that involves land degradation in arid and semi-arid areas and that it is caused primarily by human activities and climatic variations (Barman *et al.* 2013, Bhattachan *et al.* 2013 and Saad *et al.* 2011). According to Wiggs and Holmes (2011), desertification in the Free State is a combination of these factors that they change over time and vary by location. Wind erosion is a major environmental issue affecting land resources and socio-economic settings (Zegeye *et al.* 2014) including the Free State (Wiggs and Holmes 2011). The next chapter addresses datasets and methods used in this study.

CHAPTER 3

DATASETS AND METHODS

3.1 Introduction

This study follows a multi-disciplinary approach. It integrates two data sources, namely GIS and Land management approaches to investigate the wind erodibility of soils in the Free State. Due to the availability of tools such as the Geographic Information Systems (GIS), management of large datasets such as traditional digital maps, databases, and models, is possible (Ahmad 2013, Hendriks *et al.* 2012, Meshesha *et al.* 2012). The quantitative data handling capability offered by GIS enabled the research to overlay numerous spatial data sets and to statistically analyse these data and to develop quantitative relationships not achievable using simple map drawing or graphics display programmes (see Hong *et al.* 2014). In this study the Index Overlay model was adopted (Al-Bakri et al. 2014, Mas et al. 2014, Molinari 2014).

The central objective of this research was to discover how erodibility factors affect the vulnerability of soil to wind erosion and how that susceptibility varies across the Free State. Until now there has been very little linking of the two in the study area and elsewhere in South Africa as a whole. Though quantitative analysis sheds light on general patterns of wind erosion it has limited capacity. Such an analysis could be limited to complex factors that underpin decisions taken by farmers. Consequently, this study adopted a qualitative approach that produced information of the perceptions and complex values that could lead to decision-making about the role played by farmers themselves (see Lwin *et al.* 2013). In keeping this approach, the core of the methodology adopted in this study was the use GIS to determine the susceptibility of soils to wind erosion, simple observational field surveys and a series of structured interviews undertaken with farmers at randomly selected sampling sites along two parallel west-east transects (Fensholt *et al.*

2013) of a particular latitudinal band (Cook and Pau 2013) in the Free State province.

The justification on the approach followed in this study is that central to the development of wind erosion modelling systems is an understanding of how the mechanisms driving wind erosion interact and change through space and time. Precise wind erosion modelling requires data that has high temporal resolution (see Guo 2013) but this wind data was not available. Where such data are not available one can only simulate the susceptibility or erodibility of a site using other variables.

3.2 Characteristics of the Study Area

The primary study area is the Free State (Figure 3.1), one of the nine provinces of South Africa. The characteristics of the area are discussed below.

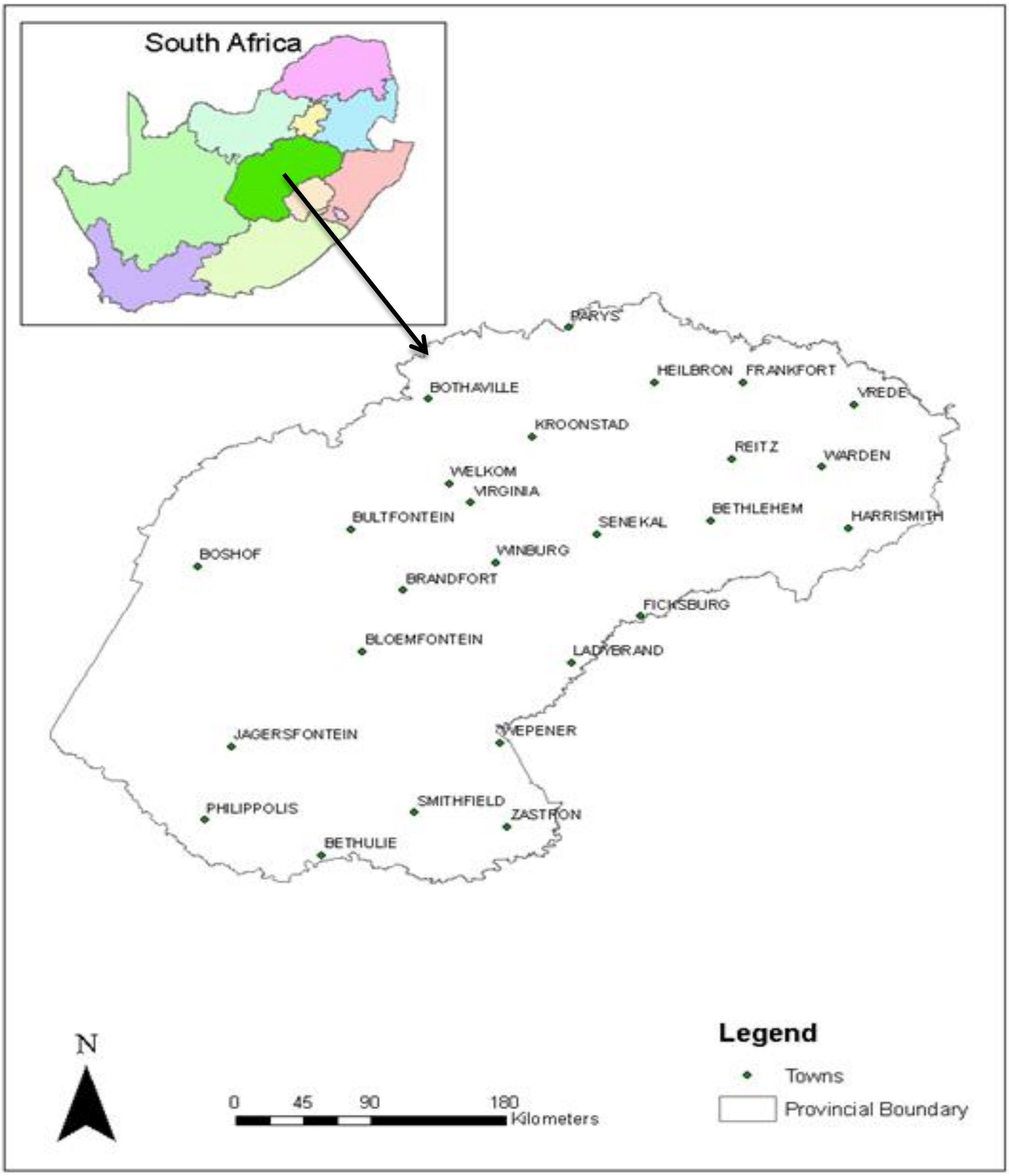

Figure 3.1: The Map of the study area (Source: DEAT 2004).

3.2.1 Vegetation

Mucina and Rutherford (2011) indicate that the Free State province is grassland and the major vegetation bioregions of the province given in Figure 3.2 and are described and generally distributed as indicated in the section to follow.

- The Dry Highveld Grassland is centrally located in the province. It comprises of the following vegetation types: Aliwal North Dry Grassland, Xhariep Karroid Grassland, Besemkaree Koppies Shrubland, Bloemfontein Dry Grassland, Central Free State Grassland, Winburg Grassy Shrubland, Bloemfontein Karroid Shrubland, Western Free State Clay Grassland, Vaal-Vet Sandy Grassland, Vredefort Dome Granite Grassland and Vaal Reefs Dolomite Sinkhole Woodland.
- The Mesic Highveld Grassland is found in the eastern to north-eastern of the province. It has the following vegetation types: Zastron Moist Grassland, Senqu Montane Shrubland, Eastern Free State Clay Grassland, Eastern Free State Sandy Grassland, Basotho Montane Shrubland, Frankfort Highveld Grassland, Northern Free State Shrubland, Soweto Highveld Grassland and Rand Highveld Grassland.
- The Central Bushveld has the Central Sandy Bushveld vegetation type.
- The Eastern Kalahari Bushveld is found to the west of the area and has the following vegetation types: Kimberley Thornveld, Vaalbos Rocky Shrubland and Schmidtsdrif Thornveld.
- The Drakensberg Grassland has the Northern Drakensberg Highland Grassland, Drakensberg-Amathole Afromontane Fynbos, uKhahlamba Basalt Grassland and Lesotho Highland Basalt Grassland.
- The Sub-Escarpment Grassland has the Low Escarpment Moist Grassland vegetation type.
- The Upper Karoo Bioregion has the Northern Upper Karoo vegetation type.

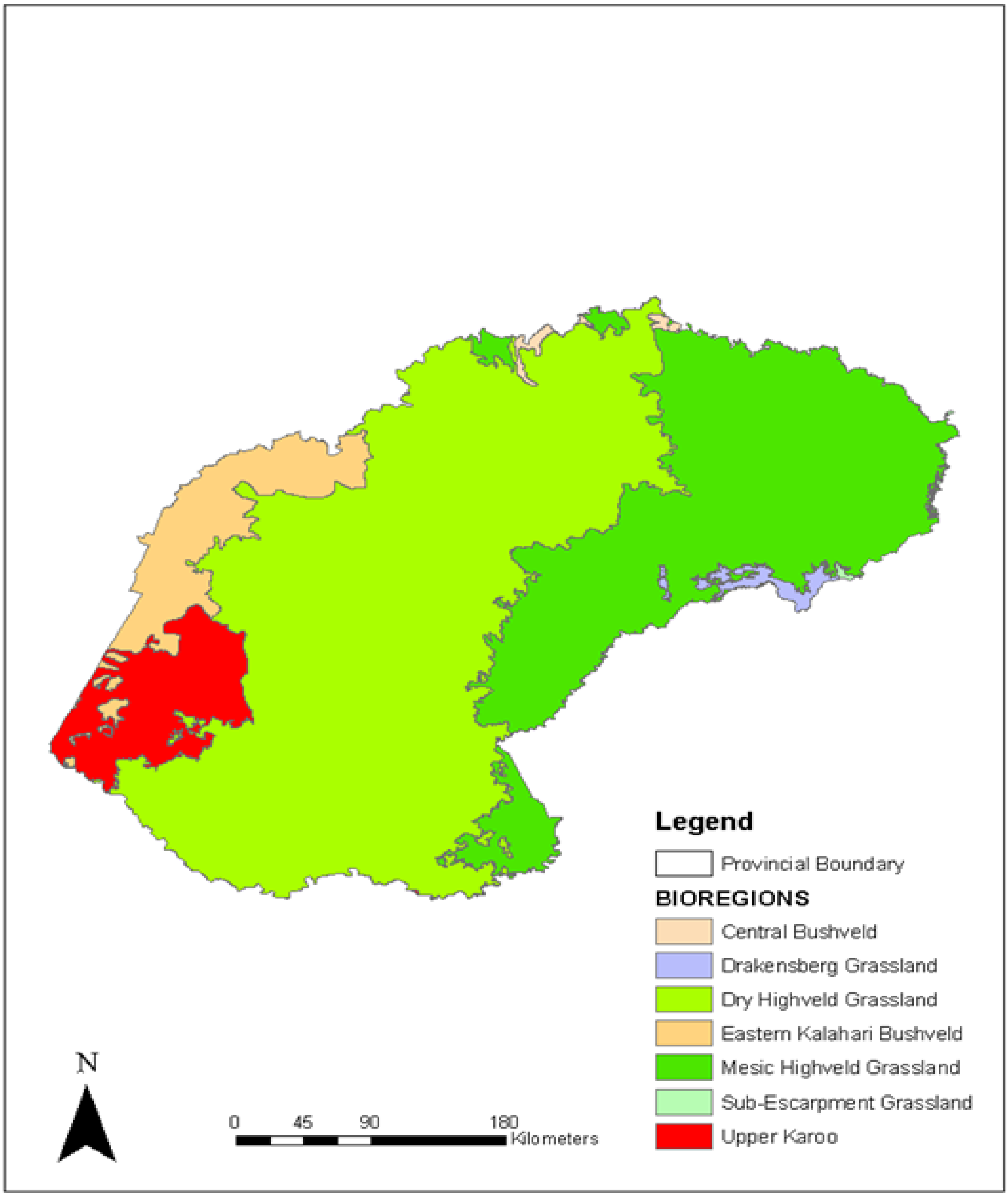

Figure 3.2: The major vegetation bioregions of the Free State province (Source: Mucina and Rutherford 2011).

3.2.2 Soils

The major soil types, relative to the clay content in the province are, given in Figure 3.3. They are divided into four functional groups: where clay content is <15%, 15 – 35%, >35%, and where no data is available.

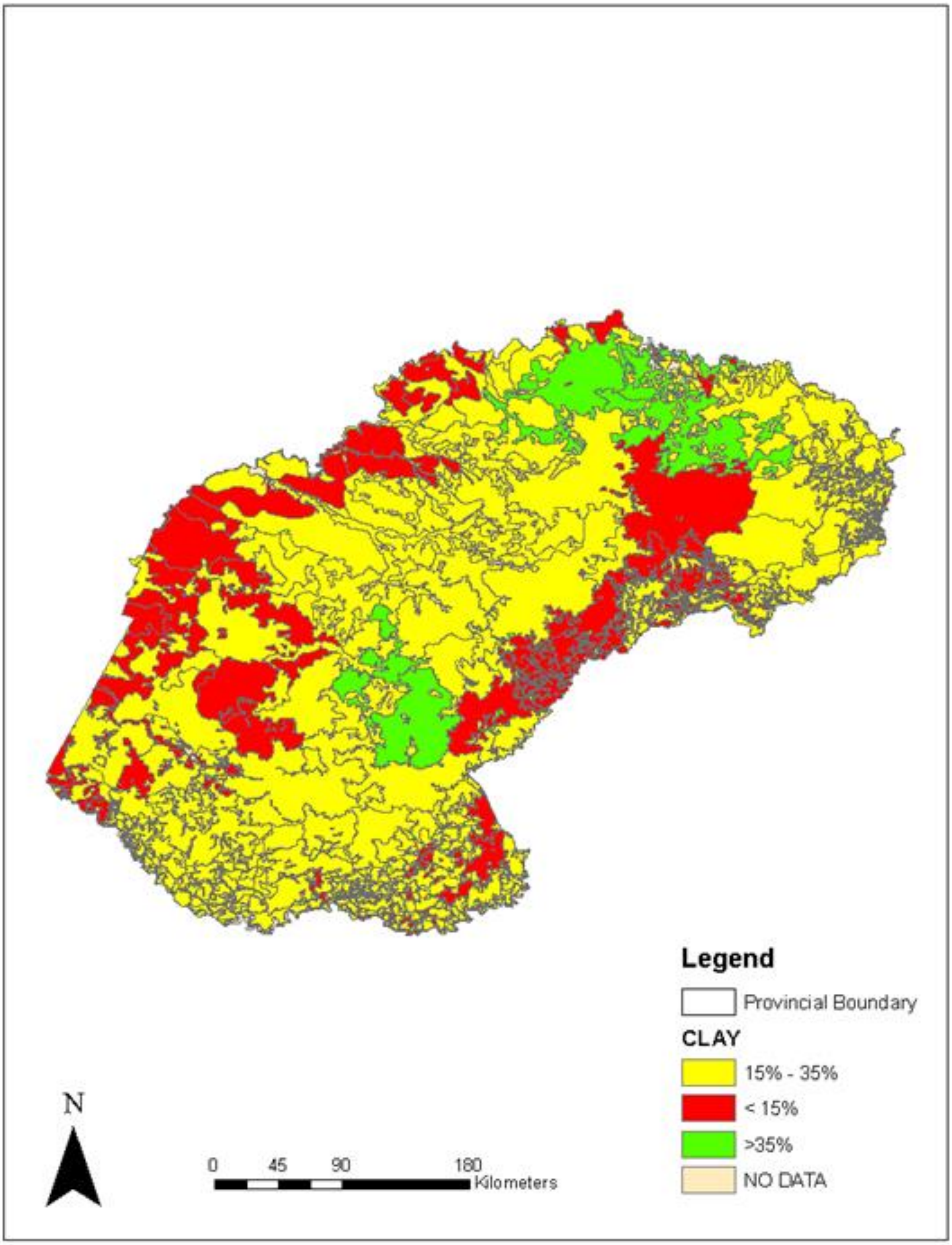

Figure 3.3: Clay content of the soils in the Free State province (Source: DEAT 2004).

3.2.3 Geology

Geologically, the province is dominated by mudstone; which accounts for approximately 50%, followed by shale at about 30% to the west of the province and arenite located in the north-west and south-east of the province makes about 10%. The remaining 10% is made up of patches of dolerite, sedimentary and basalt. Figure 3.4 gives the relative distributions of these geological formations.

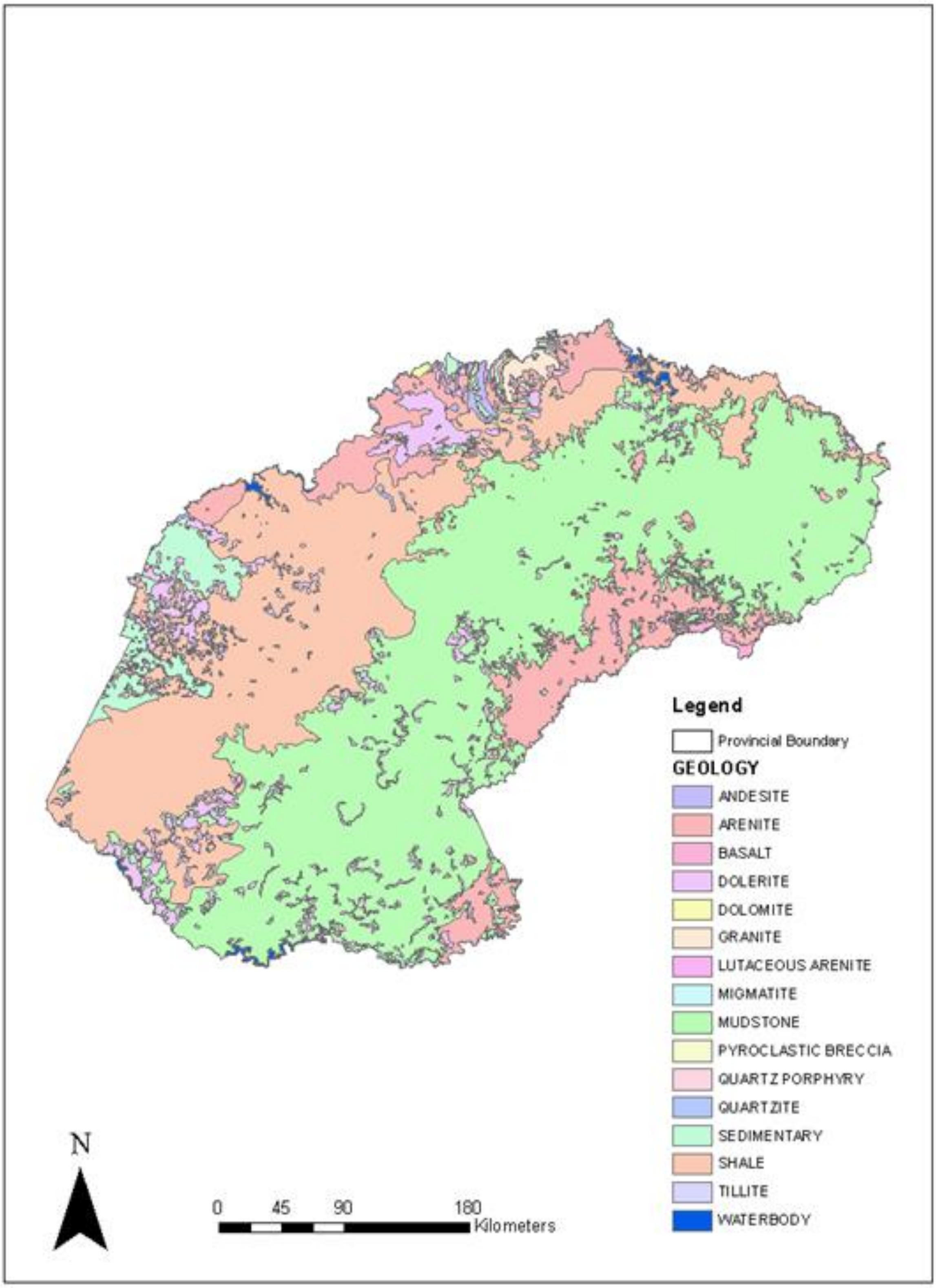

Figure 3.4: Geology map of the Free State province (Source: DEAT 2004).

3.3 Research Design

The design of the study is sub-divided into two investigations, namely, GIS modelling approaches and field surveys, as outlined in Figure 3.5.

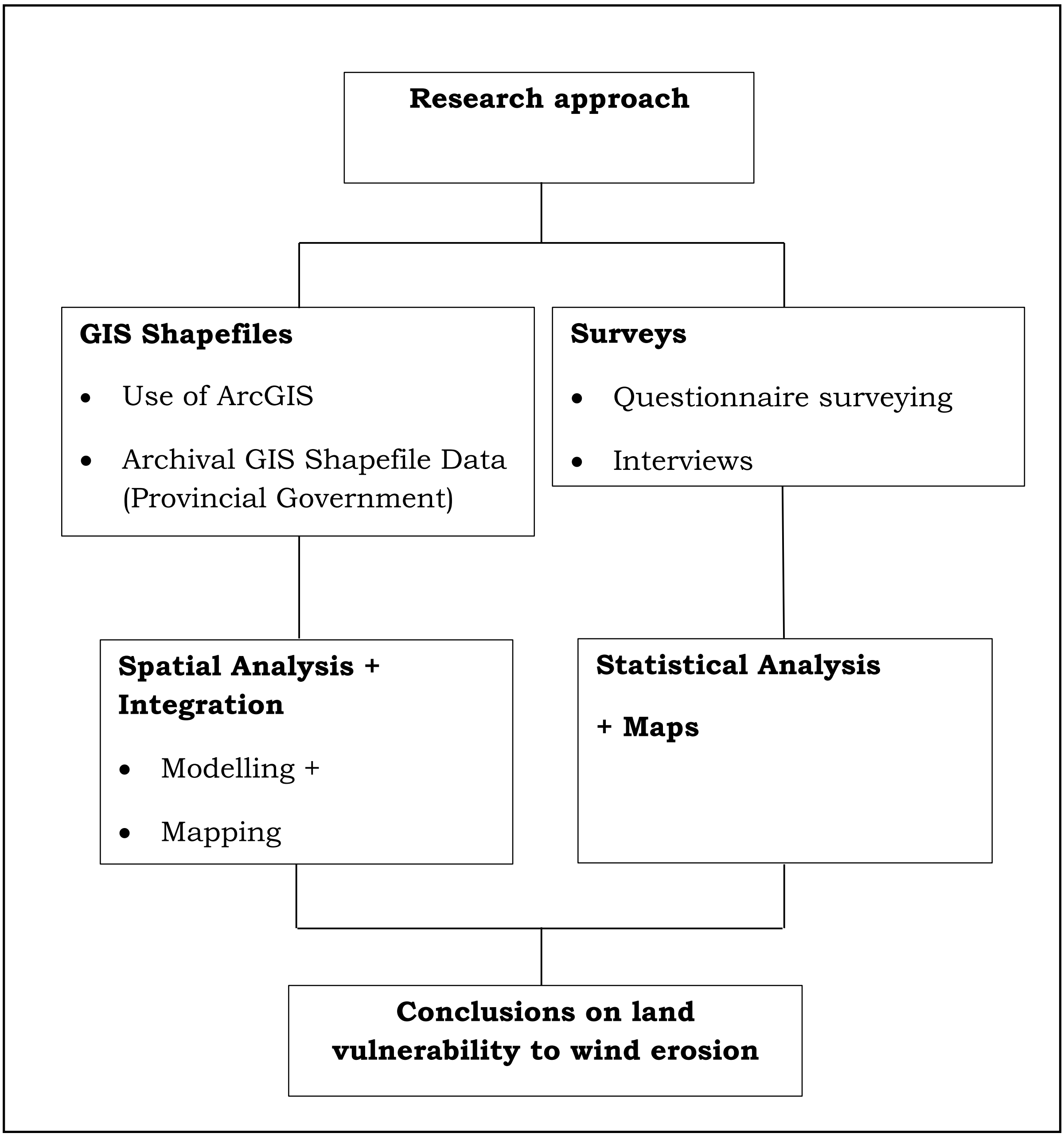

Figure 3.5: A Methodological framework of the study.

3.4 Data Collection for GIS operations

Shapefiles of the provinces soil characteristics were collected. This included shapefiles of different soils, ranged clay content, towns, roads and vegetation. The inclusion of towns and roads served as reference points for easy analysis. It was very necessary to look into characteristics of soils (i.e. different soil types, clay etc.) and vegetation because they vary extremely across the province. The inclusion of these shapefiles would allow for wind erosion modelling. All these data was made available in digital format from the Department of Environmental Affairs and Tourism (ENPAT) and was acquired from the GIS section of the University of the Free State in 2006.

3.5 Technical Approach

GIS-based analyses was done using Spatial Analyst extension in ArcGIS. After manipulating the data in this, maps highlighting "erodible" geographic areas were derived from combined maps based on established "erodible" criteria. The final step in modelling determined the final erodibility map.

3.6 Data Collection for determining farmers' management practices

Data used to assess farmers' perceptions about wind erosion and determine how these perceptions shape the decisions they make in land management across the Free State was collected by way of structured interviews. Random sampling technique was adopted two line transects (two major roads) running from west to east across the province (Figure 3.6). The choice of sampling sites was based on studies by Meusburger *et al.* (2013) and Sankey *et al.* (2013), who advocated the use of transects in a scientific investigations. The lower transect (N8) was along the Kimberley – Bloemfontein - Ladybrand road. The exercise was resumed on the upper transect (R64/R73 - N5) running along the Kimberly – Boshof – Brandfort - Winburg - Senekal - Bethlehem - Harrismith road (Figure 3.6). The interviews were largely directed at decision-making processes and narratives around wind erosion management practices on sampling sites or farms (see Farauta *et al.* 2011). Interviews were divided into three sections comprising 80 questions in all. The first section was on general demographic information. Section two was on direct causes of land degradation and interventions by farmers about wind erosion management. It covered basic facts of the problem of wind erosion and its management. Section three focused on indirect causes of land degradation and these relate to the socio-economic factors which are often crucial in order to understand why land degradation occurs.

The criteria used for classifying land management practices included items such as: provision of training and/or advices to farmers; allocation of enough budgets for the management of land operations; availability of enough farm assistants and time-management. The interviews were designed in such a way as to enable respondents to indicate land management methods. The questionnaire was structured to generate data on the causes of land degradation.

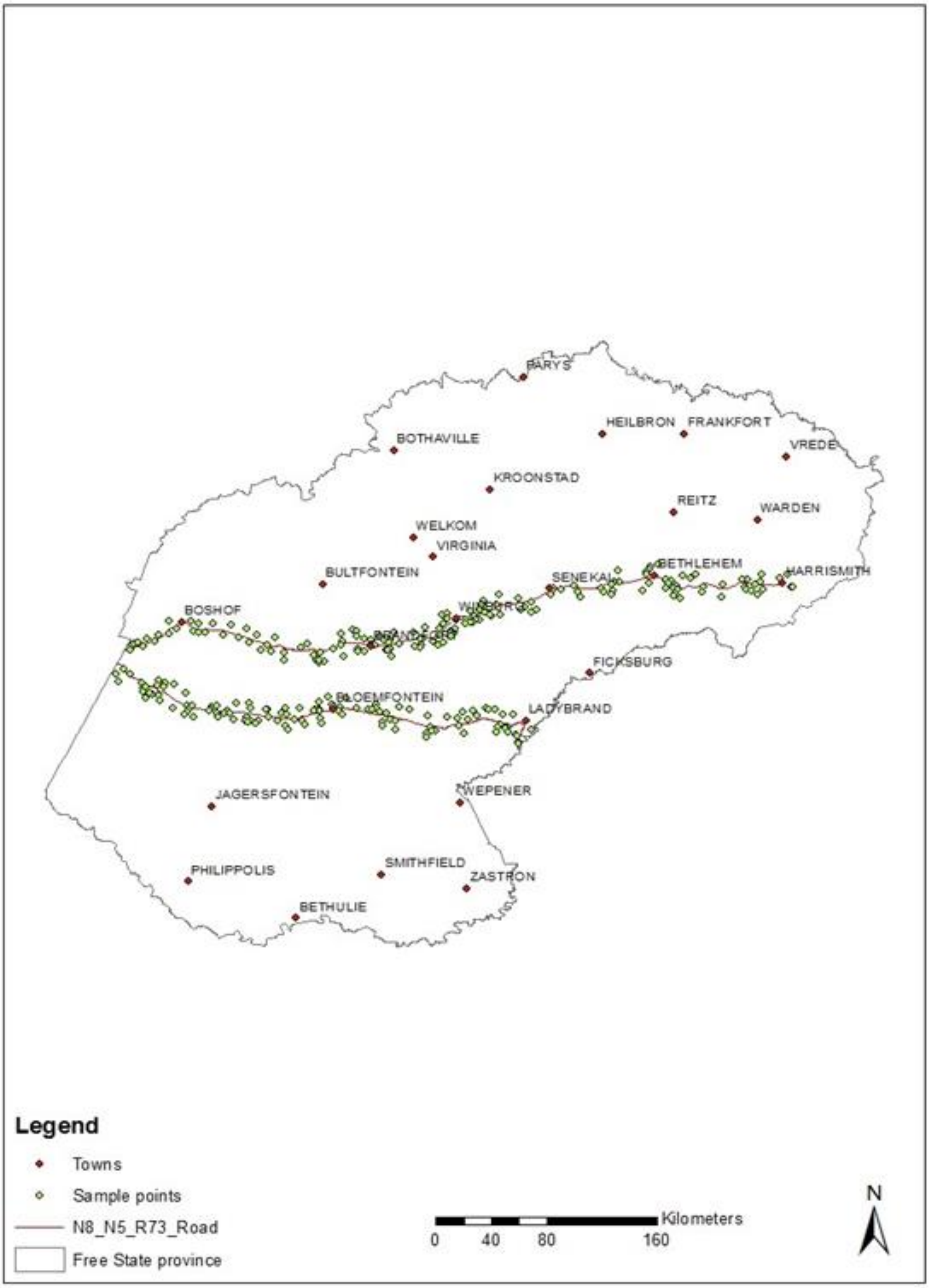

Figure 3.6: Map showing the location of sampling sites visited on the line transects used in the study (Source: DEAT 2004).

Justification for inclusion of shapefiles for roads and towns was on the basis for determining how erosion varied across the province by establishing west – east transects. Data on the current state of operational procedures with regard to the land management practices was obtained from official reports of the Free State Agriculture, Bloemfontein.

3.7 Unit of Analysis

A unit of analysis selected was each individual farm irrespective of the size. This was done irrespective of whether a particular farm was either commercial or communal (Adimassu *et al.* 2013, Barman *et al.* 2013).

3.7.1 Specification of Variables

Specification of variables (Table 3.1) depends on all aspects that lead to land management practices. Land management practices depend on several factors including the size of farm, location etc.

3.8 Validity

A pilot study of 5 draft interviews was earlier administered to eliminate ambiguities after which a validated, reliable questionnaire was used including 80 questions about the respondents' knowledge, attitudes and practices (KAP) and personal and professional variables addressing similar issues to those by (see Barman *et al.* 2013).

3.9 Ethical Considerations

This study was based on data collected through questionnaires, observations and documentary sources already in the current public domain. The four fundamental ethical principles were observed at all times were:

- Autonomy (respect for the person - a notion of human dignity): the principle of respect for autonomy which gave the researcher an obligation to respect the decisions made by the farmers concerning their farms.

Table 3.1 Interview Variables (scale = ordinal)

List of Variables
Demographic
Farm Owner Characteristics
The size of farm
Farming Operations
Economic
Road access
Presence of economic structures (projects, credit, inputs)
Accessibility of national markets
Accessibility of international markets
Price changes
Increased opportunities for diversifying off-farm jobs
Agro-technical
Overgrazing
Land / Soil degradation
Ploughing
Increase in use of fertilisers
Presence of water and soil management practices
Irrigation systems
Lack of labour force
Unavailability of Land
Institutional
Presence of environmental policies
Presence of agricultural policies or land tenure
Absence of agricultural policies or land tenure
Climatic
Availability and distribution of rainfall
Fires

(Source: van Vliet *et al.* 2013: 5)

- Beneficence (benefit to the research participant): the principle of beneficence which obliged the researcher to give a positive feedback when doing observations and conducting the research. All participants in the project were informed about the intentions of the research.

- Non-maleficence (absence of harm to the research participant): the principle of non-maleficence obliged the researcher to take positive steps and prevent harm while conducting the research. The designs of the embedded tasks in the observation schedule were sensitive to the potential for harm to participants. To this end, both pilot surveys and piloting of the schedules were conducted long before the actual data collection to ensure that no harm whatsoever befell any of the participants.
- Justice (notably distributive justice - equal distribution of risks and benefits between communities): the principle of justice obliged the researcher to provide details of the study to all those who had a direct interest either in the study itself, or in the study area or in the security of participants.

3.10 Choice of Model Used

One model was considered for use in this study, Wind Erosion Equation (WEQ) (see Tatarko *et al.* 2013) and according to Hong *et al.* (2014), it is the most well-known model to predict soil erosion. Several reasons discussed herein indicate reasons that led to the final model.

3.11 WEQ

Due to the ease of application and readily available data, the use of WEQ was feasible (see Guo 2013, Mezõsi *et al.* 2013 and Wang *et al.* 2013 and compare with Varga *et al.* 2013).

3.12 Model Flow Chart

The model flow chart in the study was carried as shown in Figure 3.7. The model was run to produce a map overlay as shown in Figure 3.8.

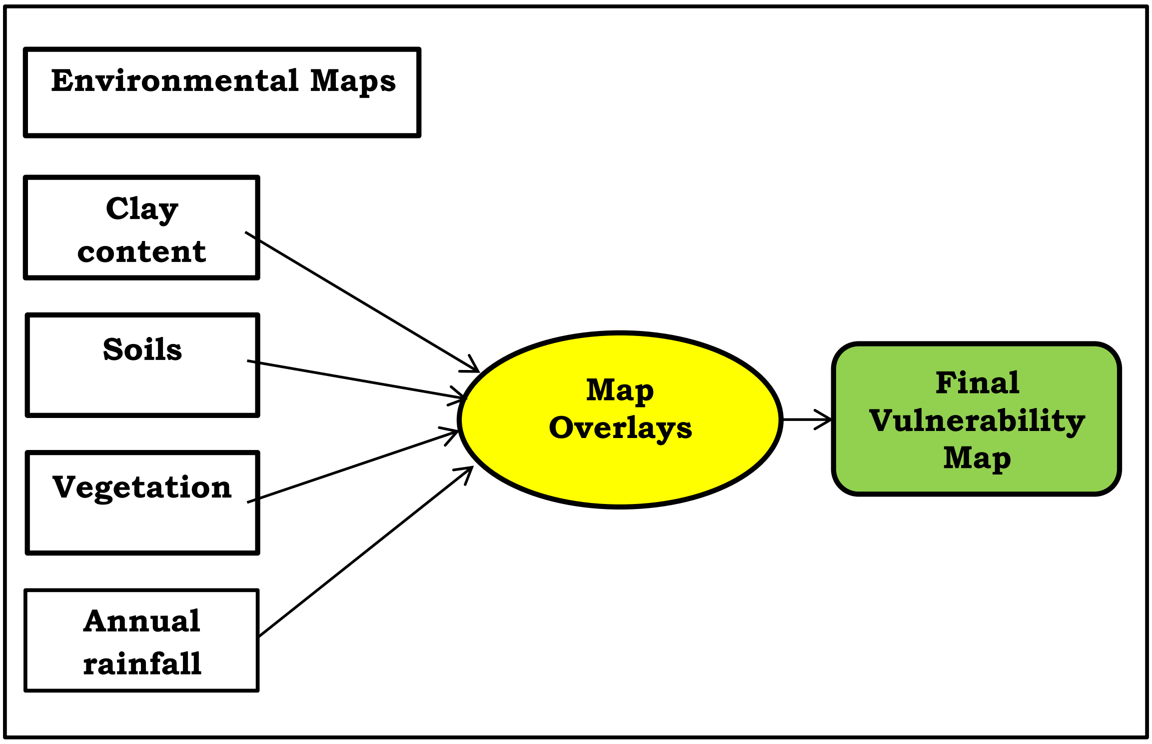

Figure 3.7: Model Flow Chart

The research was intended to map areas in the Free State that are susceptible to wind erosion but also to find out what farmers do on the ground to manage impacts of this.

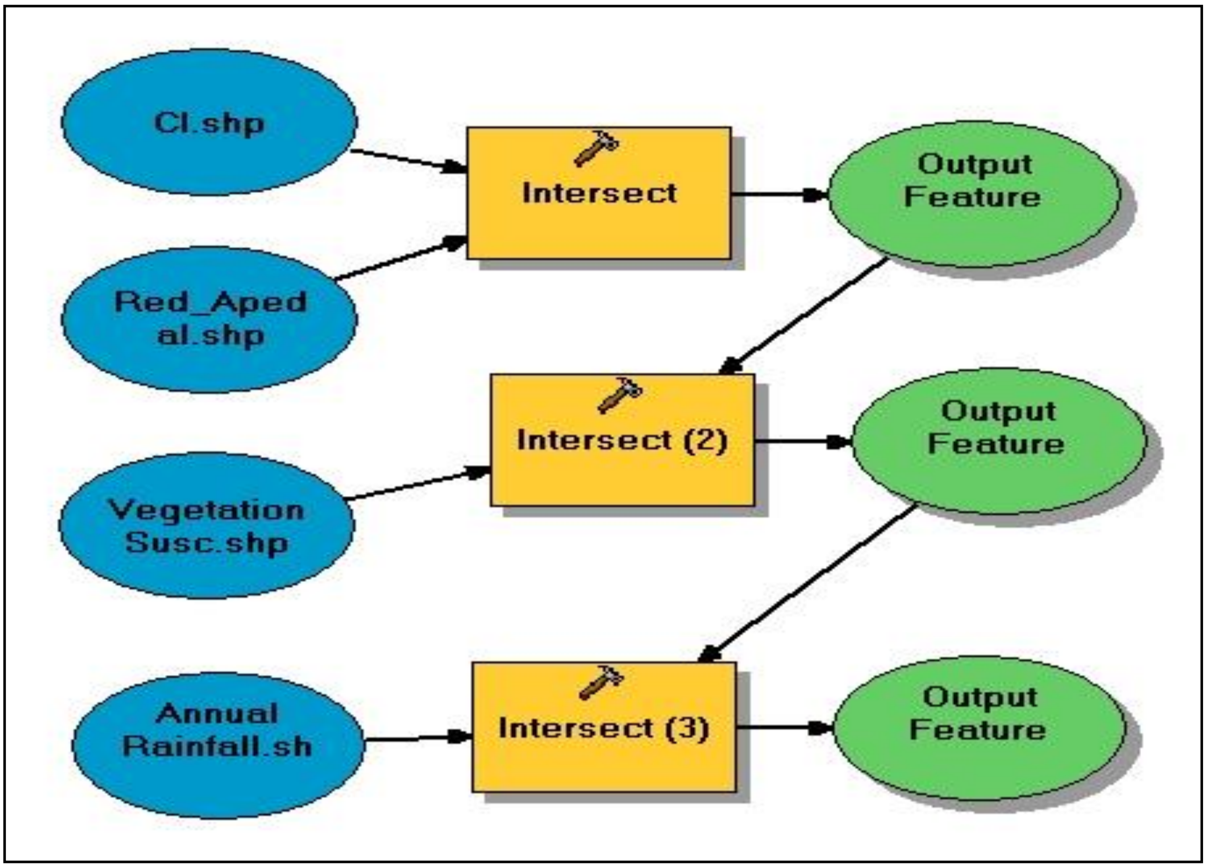

Figure 3.8: Model run for the study area (see Appendix 1 for the script).

3.13 Data analysis

To address objectives 1 and 2 relating to the determination of vulnerability of Free State soils to wind erosion, the data was manipulated and overlaid to achieve this. In doing these, a new layer was created showing areas of red-yellow apedal, freely drained soils; yellow, high base status, usually < 15% clay from the soil and clay shapefiles. Similarly from the vegetation shapefile, all other areas were included except areas with Cymbopogon – Themeda combinations which are justifiably flourishing in high rainfall areas to the east of the province. The final result was obtained by overlaying the clay, soils, vegetation and land-use to determine areas vulnerable to wind erosion.

Descriptive statistics was employed to analyse farmers' perceptions of wind erosion along the two transects. This included the use of SPSS (SPSS Inc 2009), multiple regression analysis and analysis of variance (i.e. one way between the groups, namely ANOVA) was applied after specifying a confidence level of 95% to determine the nature, direction and strength of interactions between critical variables in the land management practices against wind erosion.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots\ldots\beta_n X_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

where y = erodibility,

β = parameter, (i.e. volume of soil loss),

X = independent variables (i.e. economic, agro-technical, institutional and climatic-related variables).

Identification of the critical technical and managerial limitations in the efficient land management practices against wind erosion programme was done using results from objectives 1, 2, 3 and 4. A set of limitations were extracted for further use in the discussion section of the dissertation. Finally, interview data was analysed in order to assess farmers' perceptions and practices reflecting the extent to which land is exposed to wind erosion.

3.14 Summary

GIS was employed to address spatial variability of wind erosion across the province while interviews and observations addressed management issues used by farmers to curb the effects of wind erosion across the province. The selected mixture of techniques was to determine the reality of wind erosion existence as a problem. The results and findings are given in the next chapter.

CHAPTER 4

RESULTS

4.1 Introduction

In this chapter the presentation of the results and findings of the study will be addressed. The results will be presented as map overlays together with descriptive texts. The investigated variables include clay content of the various soil types, characteristics of various soils in the study area that are known to influence wind erosion, vegetation characteristics, annual rainfall and the KAPs of farmers along systematically pre-selected transects across the province. The last result would be to produce a final vulnerability map for the region in which all variables investigated have been intersected.

4.2 Assessment of erodibility or susceptibility of soils to wind

The results obtained from GIS data manipulation to exclude all areas in the study area that have clay content levels above 15% is presented in Figure 4.1. The general distribution of clay in the province is shown along two strips of land running in a near north-to-south orientation across the province. One stretch of strip of land is the Reitz – Bethlehem – Ficksburg – Ladybrand – Wepener – Smithfield and the other one is the Bothaville – Boshof – Jaggersfontein (including its west) strip. The former strip of land lies in a high rainfall area and thus wind erosion is not problematic there. The latter strip of land lies in a low to extremely low rainfall area and is generally seen to be susceptible to wind erosion.

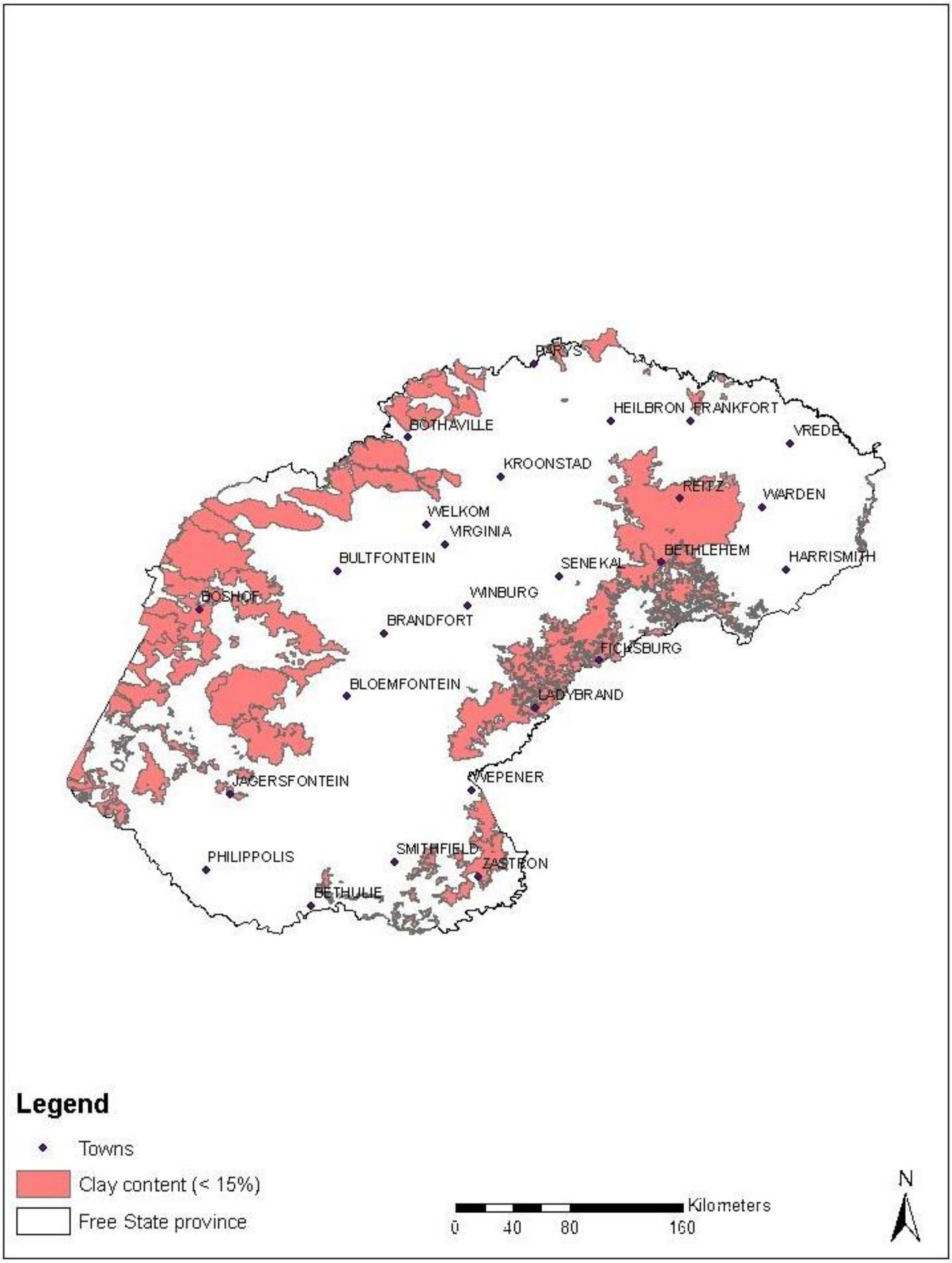

Figure 4.1: Clay content level below 15% across the Free State province.

Figure 4.2 presents all areas in the study are that have vegetation susceptible to wind erosion. These areas are dominated by Bankenveld, Cymbogon-Themeda Veld (Sandy), Dry Cymbogon-Themeda Veld, False Arid Karoo, False Orange River Broken Veld, False Upper Karoo, Highland Sourveld and Dohne Sourveld, Highland Sourveld to Cymbogon-Themeda Veld (Eastern Free State Highveld), Kalahari Thornveld and Shrub Bushveld, Kalahari Thornveld Invaded by Karoo, North Eastern Sandy Highveld, Pan Turf Veld invaded by Karoo, Pan-Turf Veld of Western Free State, Southern Tall Grassveld, Themeda Veld (Turf Highveld), Themeda Veld to Cymbogon-Themeda Veld Transition (Patchy), Themeda Veld to Highland Sourveld Transition, Themeda-Festuca Alpine Veld and Transitional Cymbogon-Themeda Veld.

All the vegetation types referred to in the section above are observed to be susceptible to wind erosion. The characteristics of these vegetation types include among others a sparse or widely scattered distribution that does not effectively protect the soil from wind erosion. The vegetation types generally have leafless and woody bases that allow wind to pass through easily and scoop loose soil under the canopy from the ground. Another factor that influences this sparse distribution of vegetation is the fact that this area is a low to an extremely low rainfall zone and as such vegetation does not thrive well. On the average annual rainfall is lower than 300mm in this part of the study area.

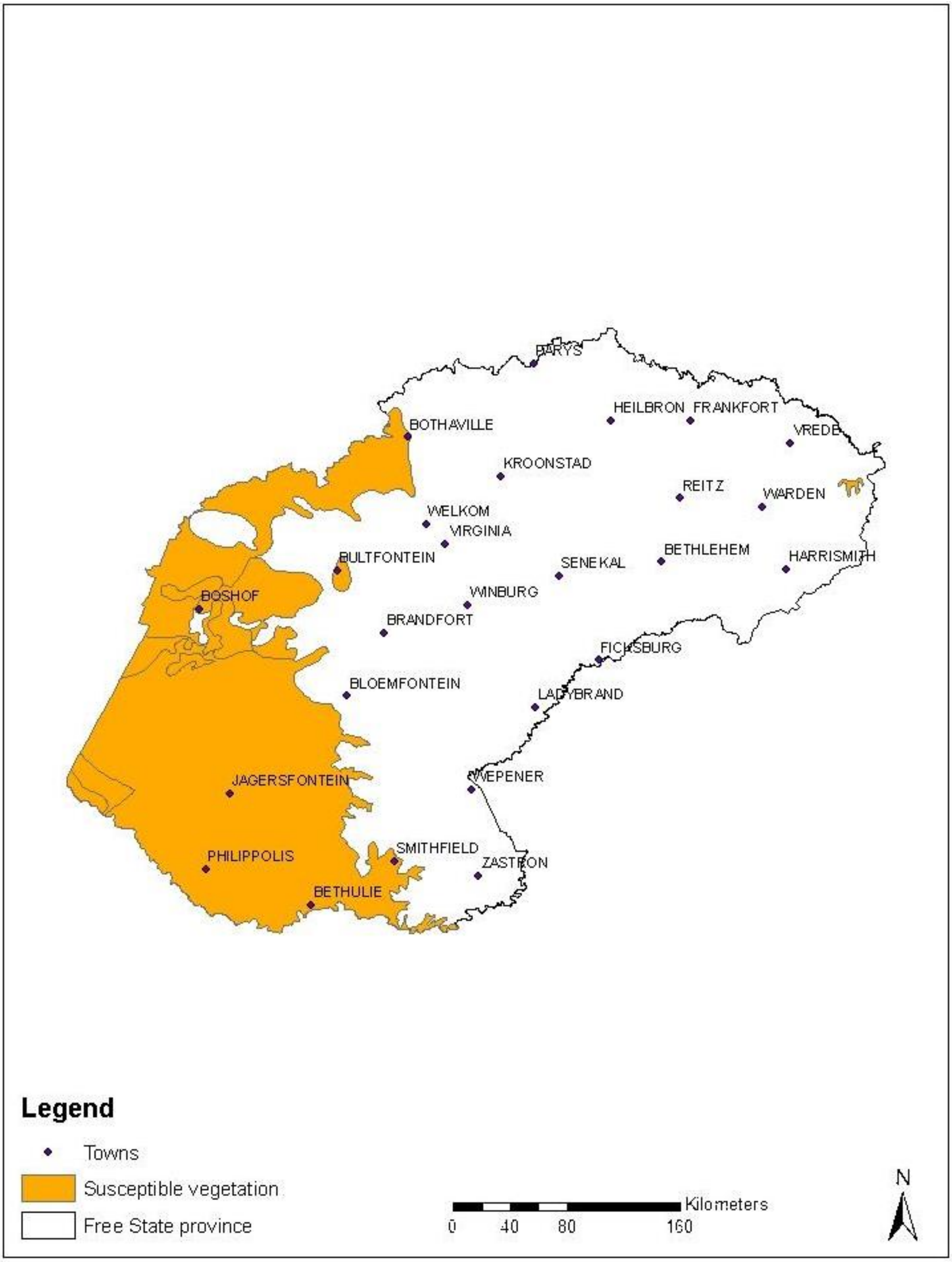

Figure 4.2: Susceptible Vegetation types in the Free State province.

Soils that are susceptible to wind erosion (Le Roux, pers. comm. 2014) are shown Figure 4.3. These are primarily Land type A soils and these are:

1. Red-yellow apedal, freely drained soils; yellow, high base status, usually < 15% clay,
2. Red-yellow apedal, freely drained soils; yellow, dystrophic and/or mesotrophic,
3. Red-yellow apedal, freely drained soils; red, high base status, > 300 mm deep (no dunes),
4. Red-yellow apedal, freely drained soils; red and yellow, high base status, usually < 15% clay,
5. Red-yellow apedal, freely drained soils; red and yellow, dystrophic and/or mesotrophic and
6. Red-yellow apedal, freely drained soils, red, high base status, < 300 mm deep.

Generally these soils mentioned above are predominantly located to the west of imaginary line-transect that could connect the Virginia – Brandfort – Bloemfontein – Jaggersfontein urban areas. These soils are characteristically freely drained because they have a loose structure, have a high sandy base and also possess less than 15% clay content. A higher clay content could increase their ability to resist wind erosion because clay is known to increase aggregate stability of soils. Another factor is that the west of the province is a semi-arid to an arid area such that these dryness is in favour of wind erosion. The vegetation in the area is widely spaced and poor on the overall thus rendering less protection to the soil from wind erosion. This characteristic vegetation allows winds to have even a greater fetch as well particularly when the province's slope is generally flat. This part of the study area is also a notable dust source area such that dust observations done around the Bloemfontein area indicate a distinctly red colour.

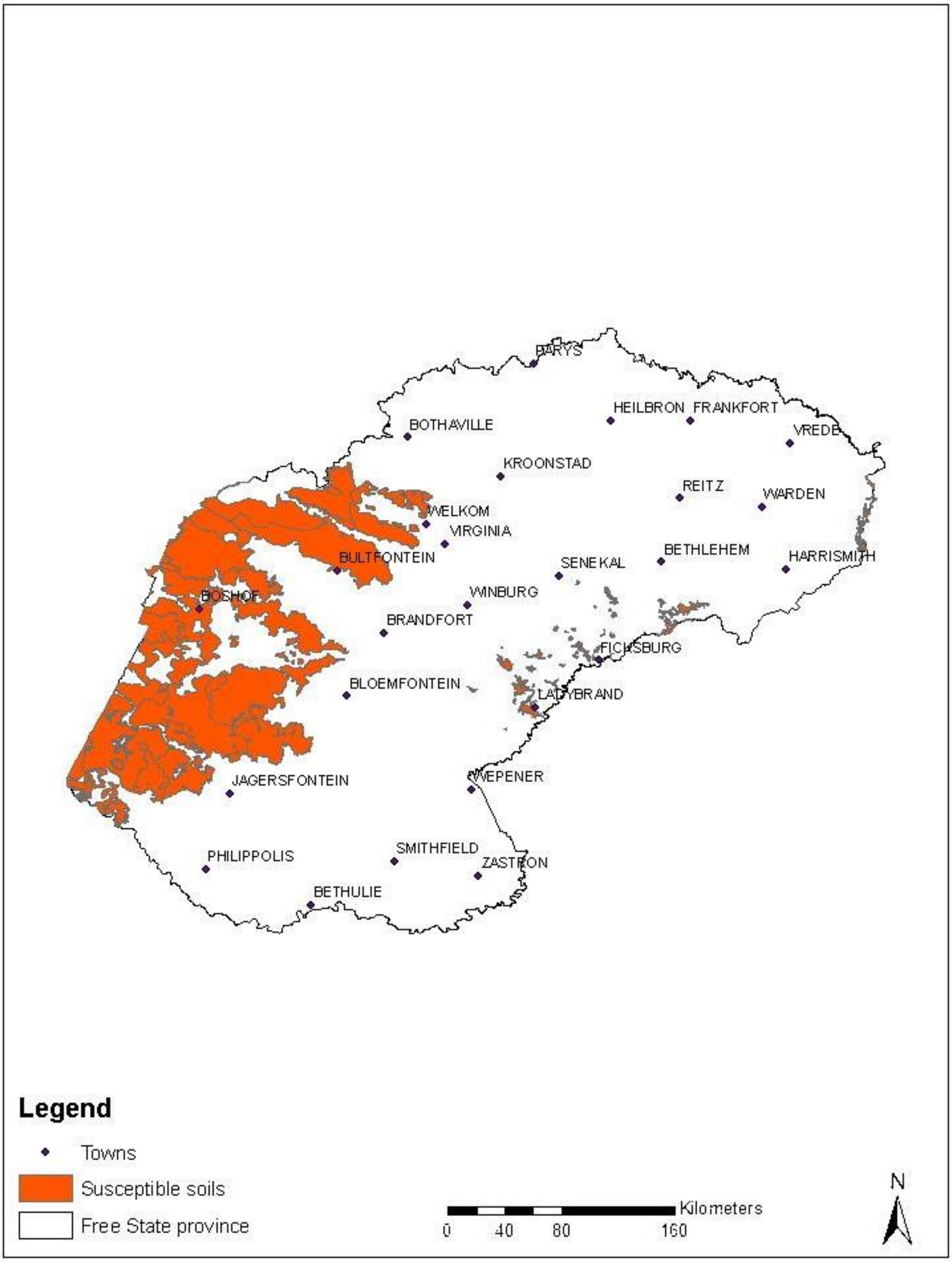

Figure 4.3: Soil types that are susceptible to wind erosion in the Free State province.

Distribution of rainfall in the province is presented in the Kriging shown in Figure 4.4 with annual rainfall given in Figure 4.5. The east of the province experiences higher rainfall amounts that come generally as orographic rain whereas the west is generally dry and largely relies on the frontal rain.

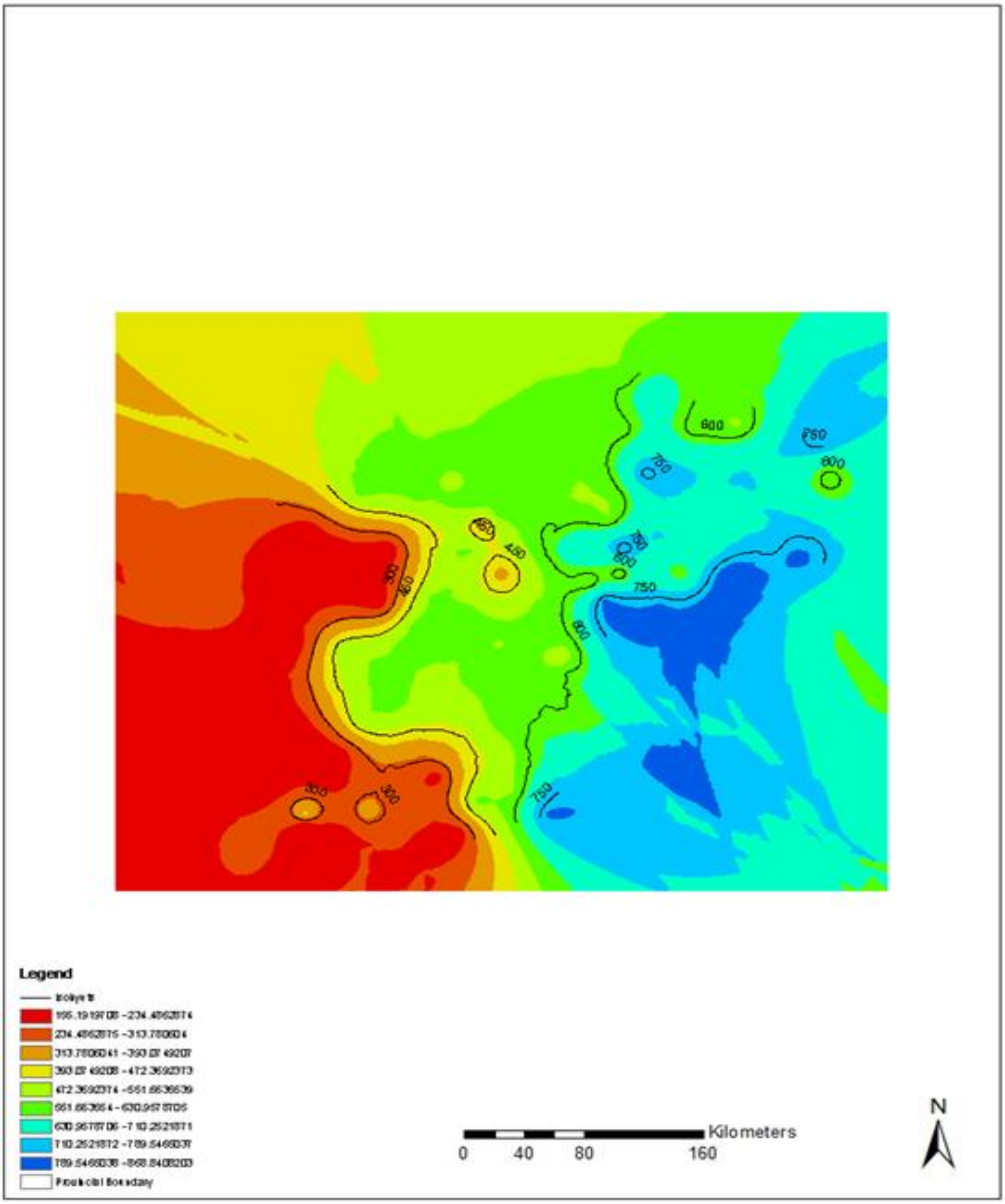

Figure 4.4 Distribution of rainfall in the province

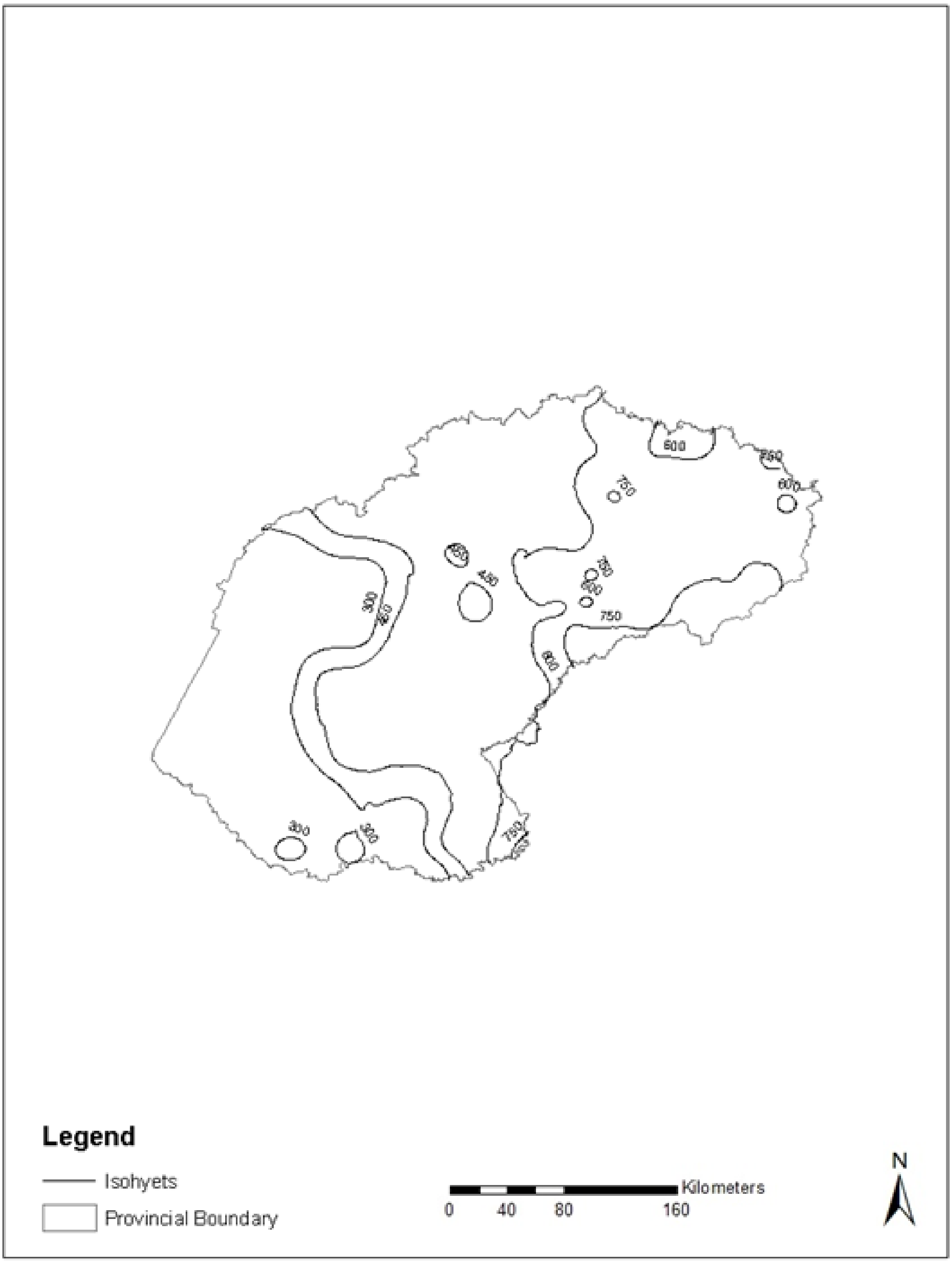

Figure 4.5: Annual rainfall in the Free State province

It was necessary to determine other combinations of variables responsible for wind erosion vulnerability in an attempt to rank their relative importance in influencing wind erosion. These were the combined effects of (i) Clay content and susceptible vegetation, (ii) Land Type A (Red Apedal) and Susceptible vegetation and (iii) Clay content and Land Type A (Red Apedal). The results of these combined effects are presented in Figures 4.6 to 4.8. From all of these combinations, one deduction is observed to emanate from them. The west of the Free State province has less clay content to inhibit wind erosion, has little rainfall to sufficiently moisten the soil and thus curb wind erosion, and also has widely spaced or sparse vegetation that could adequately protect the soil from erosive winds in the area.

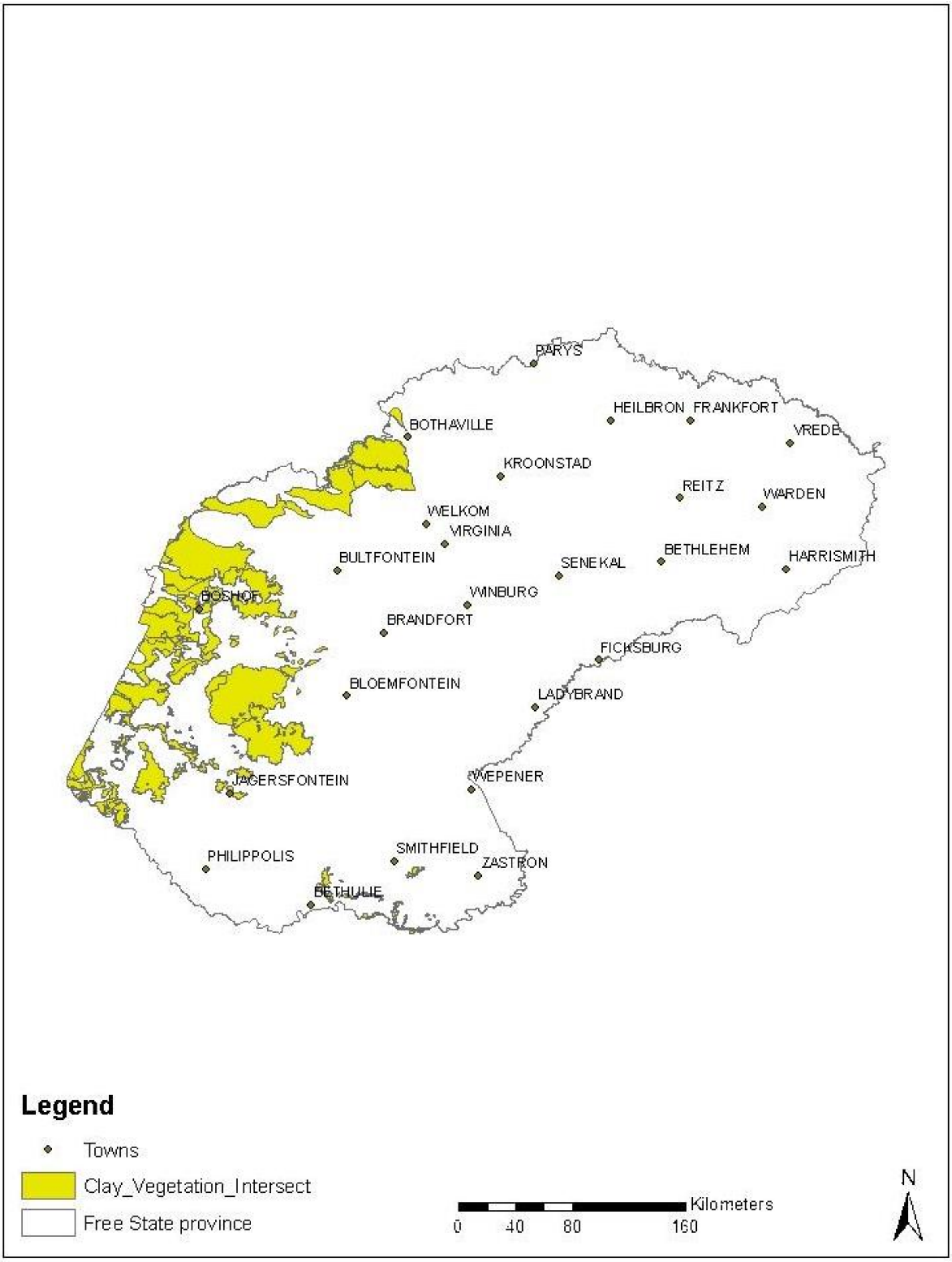

Figure 4.6: Combined effects of clay content and susceptible vegetation

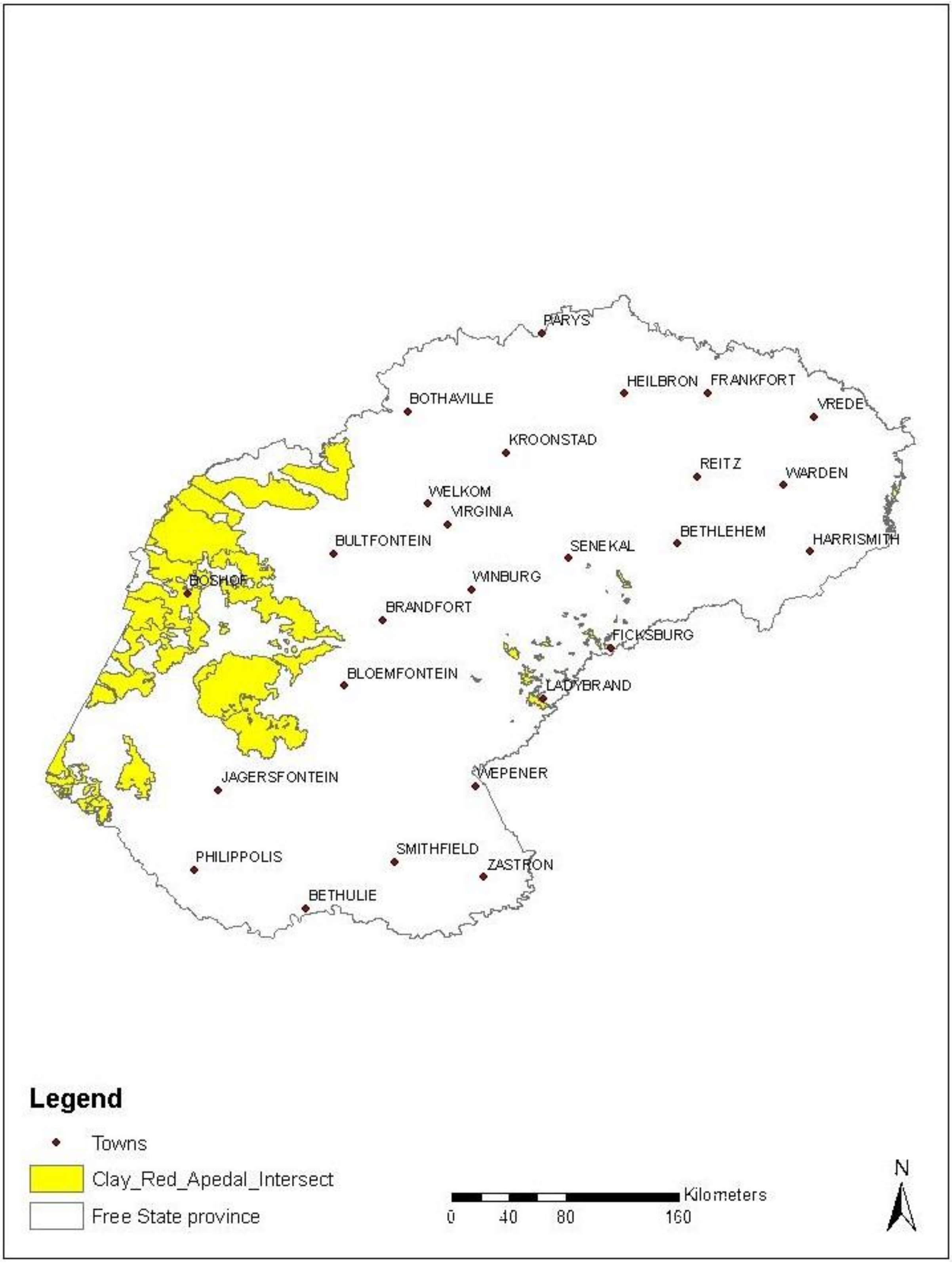

Figure 4.7: Combined effects of clay content and Land Type A (Red Apedal)

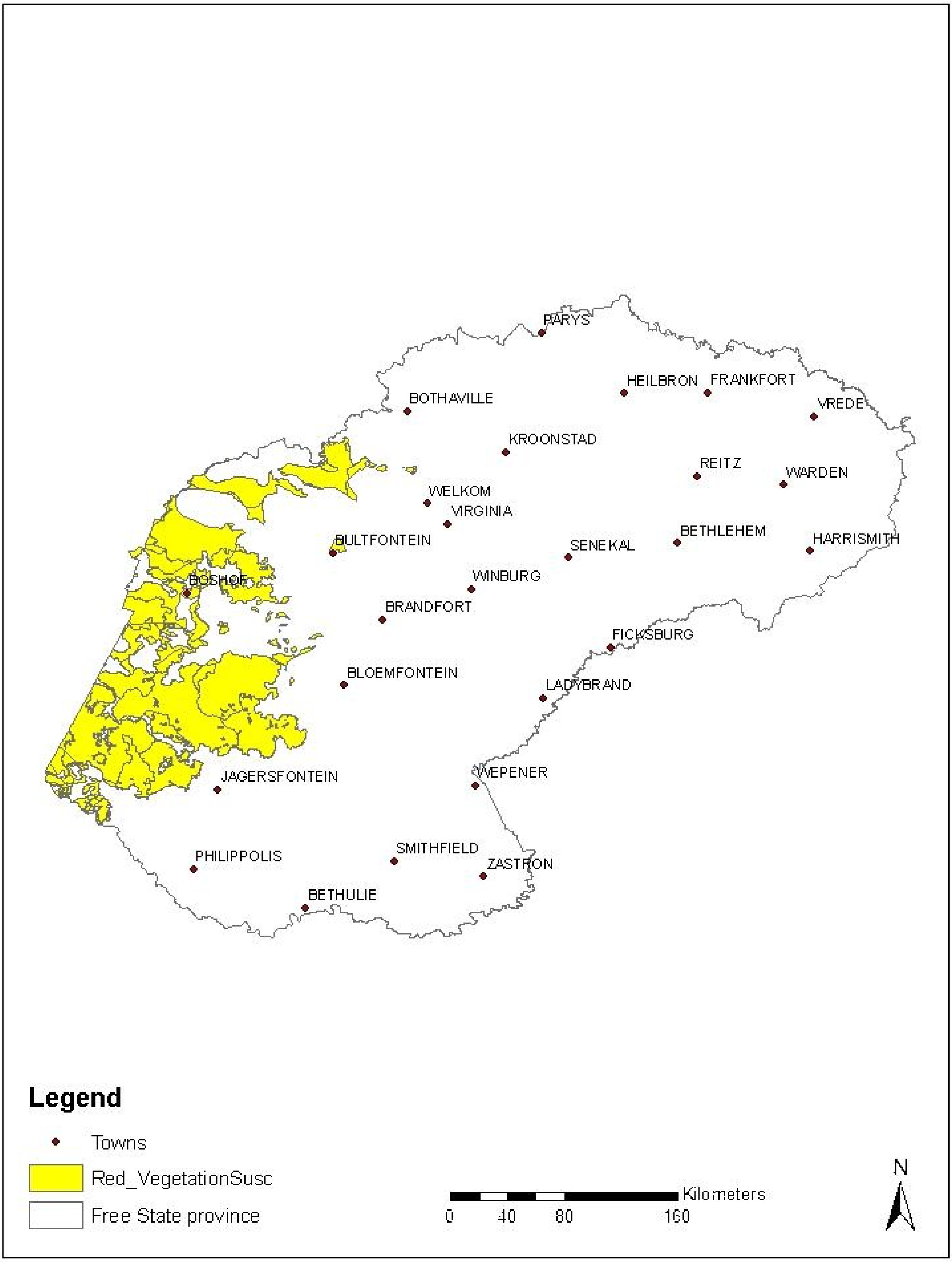

Figure 4.8: Combined effects of Land Type A (Red Apedal) and Susceptible vegetation

4.3 Identifying areas that are susceptible to wind erosion.

When all the factors investigated are considered, the areas that are identified to be affected by wind erosion are to the extreme west of the province around Boshof, to the west of both Bloemfontein and Jagersfontein. It can be clearly observed that wind erosion affects all areas to the west of the Bultfontein – Bloemfontein – Bethulie transect. The final vulnerability map showing all combined effects of clay content, susceptible vegetation and characteristic soil types that are prone to wind erosion is presented in Figure 4.9. This area is notably a little rainfall area, has sparse vegetation and generally soils are sandy with less than 15% clay. All these conditions compounded together make an area to be susceptible to wind erosion.

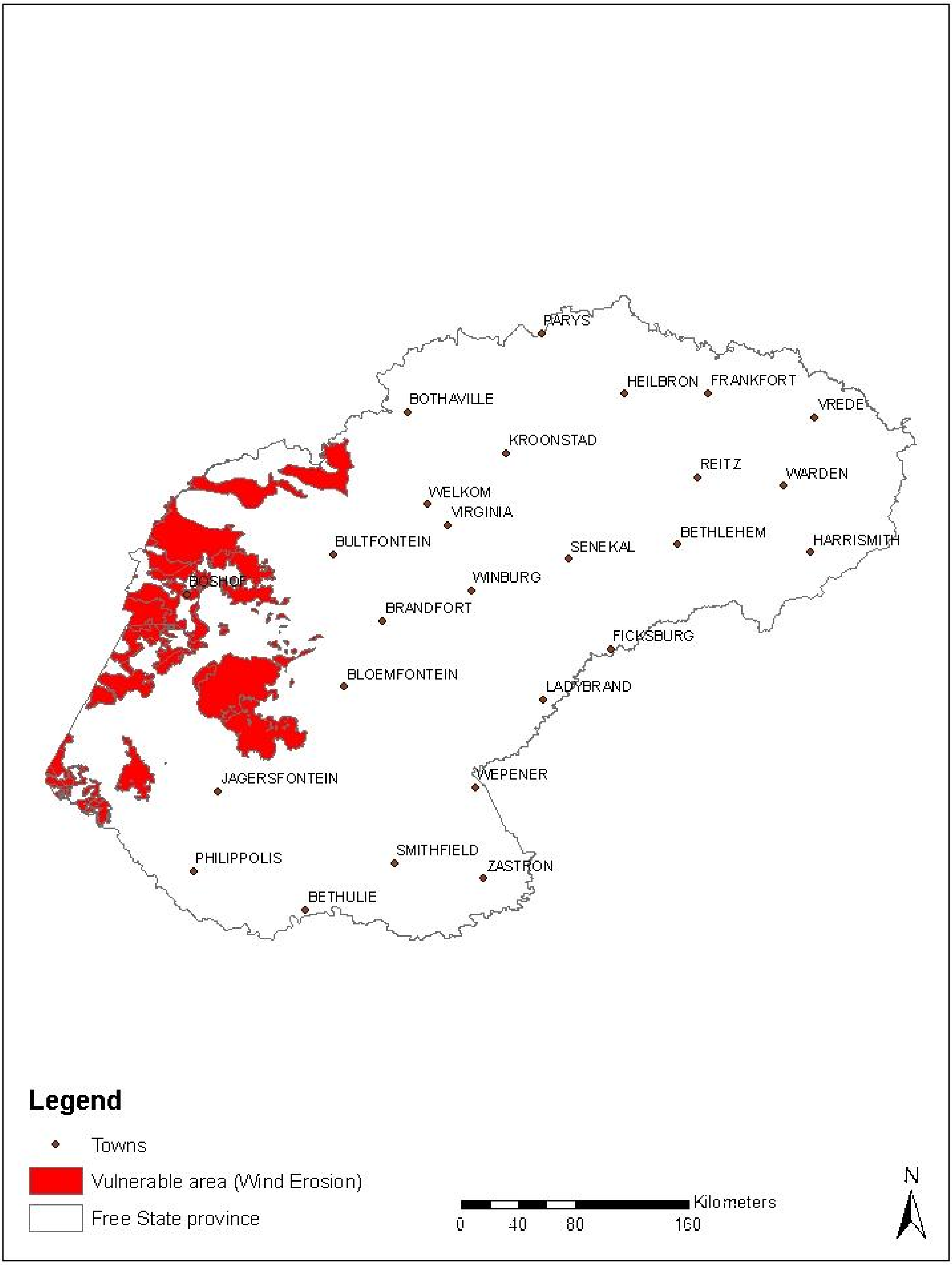

Figure 4.9: Final vulnerability map

4.4 Assessment of farmers' perceptions about wind erosion and determine how these perceptions shape the decisions they make in land management.

The farmers in the province along the transects indicated that they were faced with several compounded challenges due to wind erosion. These challenges ranged from those related to the environment, climate, resource to human – induced ones. Whilst wind erosion was central to all the responses but other factors were also noted. Observations indicated that the most dominant factor influencing the responses the farmers offered were centred around their perception of unsuitability of the place due to vulnerability to wind erosion.

Farmers in the study area are also aware that in the process of wind erosion, vegetation coverage above a certain threshold can protect the surface soil, reduce the wind velocity and thus prevent dust entrainment and transport as shown in the results herein. The responses of the farmers were treated as indicated in the section to follow. A 5-point Likert scale was used for the questions, ranging from 1 for strongly disagree to 5 for strongly agree. These responses were then added and divided by the number of respondents, giving a MEAN (average) value ranging from 1.00 to 5.00 with 3.00 the middle value (lower than 3.00 indicated respondents fundamentally disagree - thus, the closer the MEAN is to 5.00, the more positive were the respondents regarding the specific issue). However, because the researcher was working with categorical variables the researcher could not interpret the mean as it was. Therefore, the MEAN for each question had to be changed into a factor value (FV) or an Average Score (AS). The FVs were then calculated. A Mean of 3.00 was therefore equal to a FV of 0.5 (or 50%). A low FV (< 0.5) indicated that the majority disagree with the statement. Figure 4.10 gives the factor values for response on direct causes of land degradation.

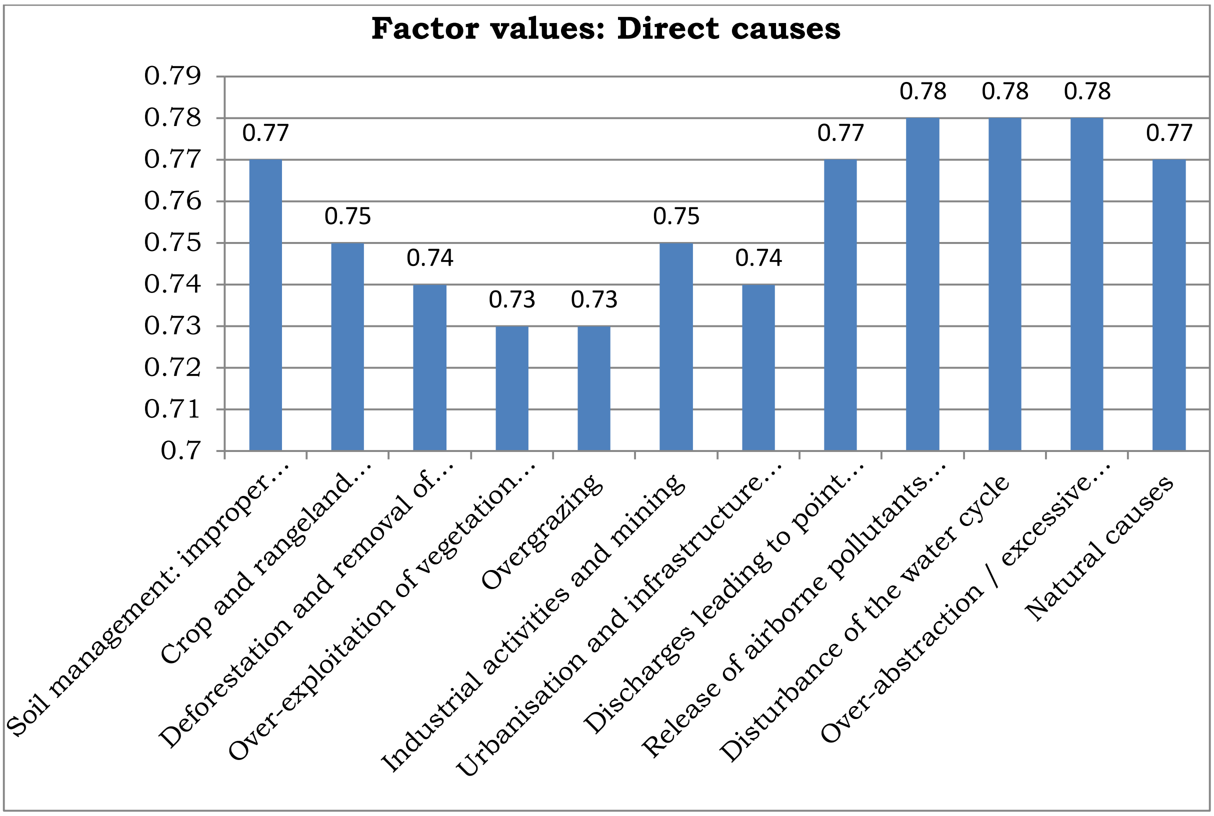

Figure 4.10: Factor values for response on direct causes of land degradation.

The F.V.s indicate that population pressure and conflicts rank highest whereas land tenure, governance, institutions and politics rank least. Industrial activities, the disruption of the hydrological cycles, or excessive abstraction of water account for the highest F.Vs whereas the over-exploitation of vegetation for domestic use and overgrazing account for the least. Figure 4.11 gives the factor values for response on indirect causes of land degradation (i.e. indirect pressure indicators). Indirect pressure indicators in Table 4.1 were obtained. The factor values are lowest in the western part and highest in the eastern part of the province indicting a direct relationship with wind erodibility determined from other investigated variables in the study.

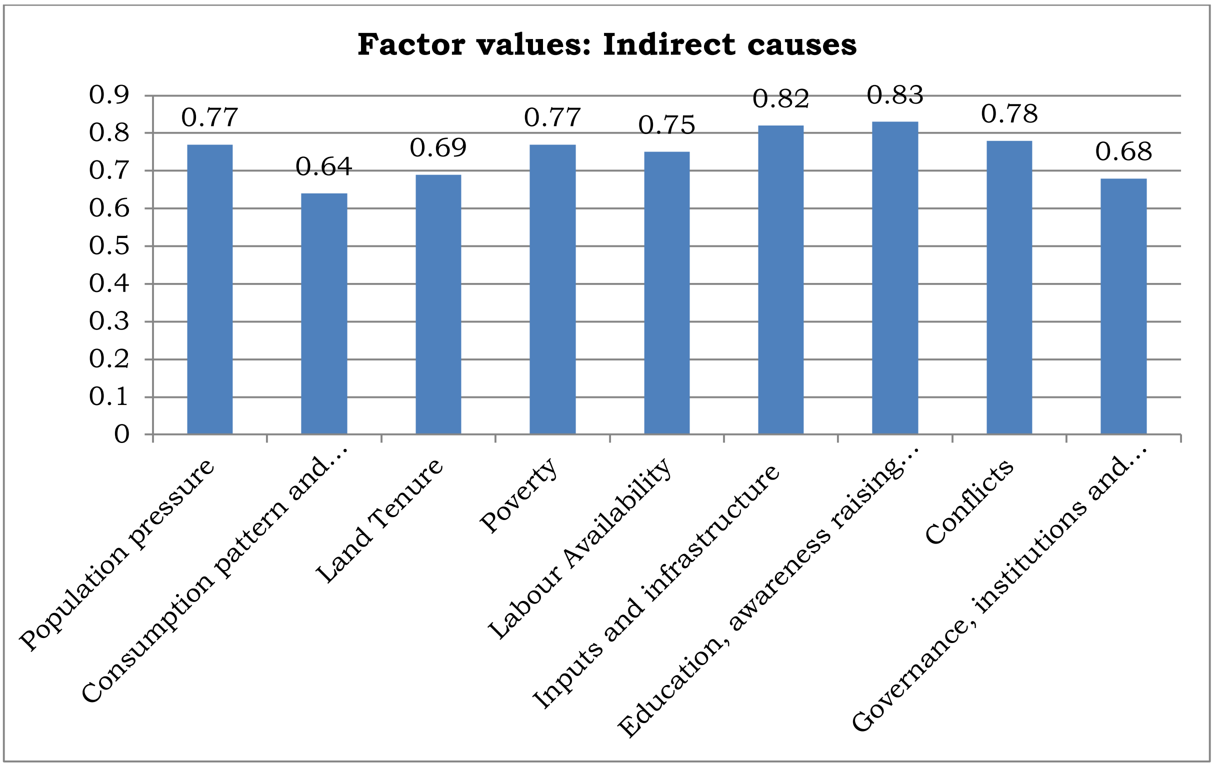

Figure 4.11: Factor values for response on indirect causes of land degradation in the Free State.

The variability of the F.V.s amongst the farmers shows that they are very much aware of challenges posed by wind erosion. These challenges, however, are observed to more concentrated and require more attention to farmers to the west of the province than farmers in the east. In many cases these F.V.s were translated to the need for interventions by the Government and the private sector alike. The notion of F.Vs was observed to be inversely related to the management styles, farming mode, environment and amount of rainfall across the province. On the overall the F.V.s bore more meaning in the west than in the east of the study area. The F.Vs endorsed the ranked values of susceptibility to wind erosion.

Table 4.1 Indirect Causes of Land Degradation in the Free State

Indirect Causes of Land Degradation	Factor value	Rank
Population pressure	0.78	1
Conflicts	0.78	1
Consumption pattern and individual demand	0.77	2
Education, raising awareness and accessing knowledge and support services	0.77	2
Poverty	0.77	2
Labour Availability	0.76	3
Inputs and infrastructure	0.75	4
Land Tenure	0.75	4
Governance, institutions and politics	0.75	4

Results obtained show that whilst most farmers were aware of the challenges posed to them by improper land use management practices, they did all they could to optimally manage their farmsteads in order to counter wind erosion and provide for their livelihoods. Results indicated by indirect causes of land degradation in the Free State province (Figure 4.12), which directly relate to education, and raising awareness have a high average FV of 0.77.

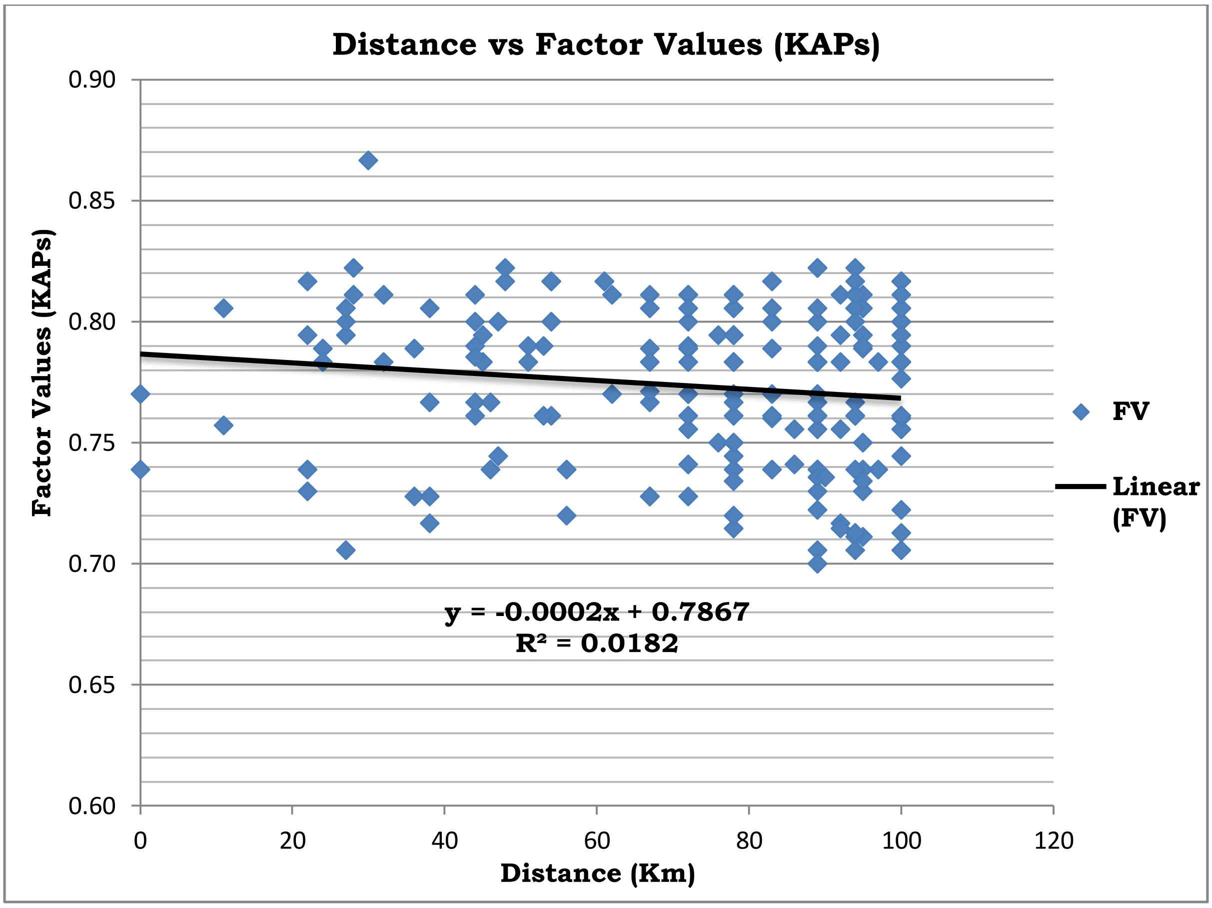

Figure 4.12: KAPs FV values for response on indirect causes of land degradation in the Free State.

4.5 Summary

The results presented show that erodibility of soils varies spatially from the eastwards across the province. This is also supported by the knowledge, attitudes and practices of the farmers across the province as well. Environmental and cultural factors determine local variations in land use strategies. Climate is an example of environmental factors while examples of cultural factors are political and economic structures local demographic characteristics. It is in this light that the Free State province is no exception.

CHAPTER 5

DISCUSSION OF RESULTS

5.1 Introduction

In this chapter the discussion of the results is presented. Bearing in mind that wind force is the dominant factor controlling the soil erosion and sediment transportation rate in semi-arid zones; assessment, modelling and prediction of wind erosion in such fragile ecosystems under different management actions and scenarios were vital.

5.2 Significance of assessment of erodibility or susceptibility of soils to wind erosion

The results of this research study indicate that soil erodibility is a complicated concept and as it is controlled by many soil properties that indicate the soil sensitivity to wind erosion (see Auerswald *et al.* 2014). Several variables investigated behaved differently and waivered around a common area as they pointed towards the most susceptible area. This is because the removal and amounts of soil is related not only on erosivity (caused by external factors, such as land cover/use, relief and climatic features), but also on the intrinsic properties of soils which influence how they resist wind erosion or potential wind erodibility.

Spatial variability of clay content was observed to be such that both east and west parts of the province had the characteristic clay content less than 15%. The exclusion of the area to the east is on the basis of rainfall amounts, vegetation types and dominant soil types. Rainfall amounts for this area are far in excess of 300mm which makes the area less susceptible to wind erosion as soils tend to be moist for longer periods, support a thriving wide array of vegetation types and thus curb wind erosion on the overall. These dominant vegetation types are not susceptible to wind erosion and also the soil types in the area are less vulnerable to wind erosion.

Similar justification holds true for the south and north areas of the province.

Clay content was observed to influence wind erosion susceptibility in the study area. Clay content as one of the main wind erosion variables controls properties that include bulk density, organic matter and chemical composition, particle size distribution, shape, stability and size of aggregates, shear strength, and porosity and permeability. These conditions were observed to vary spatially across the Free State province. The results have shown that erosion prediction, conservation planning, and the assessment of sediment related environmental effects on agricultural practices essentially require knowledge of soil erodibility. In semi-arid cultivated areas like the Free State, where conventional tillage is used, soil cloddiness and tillage ridges are the only soil roughness elements that reduce wind erosion because vegetation cover is limited. The results have pointed towards the west of Bloemfontein and immediate surrounds of Boshof to have soils that are susceptible to wind erosion. Susceptibility of soils to wind erosion is also noted for areas west of Bultfontein – Virginia – Welkom areas so well as to the west of Jaggersfontein.

Soils that are predominantly susceptible to wind erosion are those of sandy nature derived from the confluence of the Orange and Vaal Rivers (see Thomas *et al*. 2005). These soils are also freely drained and possess a quality of diminished clay content. Very small patches of these soils are observed for the east of the province stretching from Ladybrand to Fouriesburg. Otherwise soils that reflect highest susceptibility to wind erosion are found to the west of the province within the Bultfontein – Brandfort – Bloemfontein and Jaggersfontein arcade.

Vegetation is notably well documented in sheltering the ground surface from wind erosion. The results show a notable trend that the prevalence of wind erosion amongst the vegetation bioregions in the area indicated to be vulnerable to wind erosion diminishes eastwards in the order from the highest vulnerability in the Kimberley Thornveld, Northern Upper Karoo and

Schmidtdrift Thornveld, Western Free State Clay Grassland to the lowest vulnerability in the Bloemfontein Grassland (see Mucina and Rutherford 2011). A connection to this effect can be made from the fact that Kimberley Thornveld exists to the west of Boshof while the Western Free State Clay and Val-vet Grasslands are to the east and Schmidtdrift Thornveld is to the north of this town. Another feature is that Northern Upper Karoo exists to the north of Jaggersfontein. As pointed out in Li *et al.* (2013a: 288), "vegetation's impact on transport is dependent upon the distribution of vegetation rather than merely its average lateral cover and vegetation impacts surface shear stress locally by depressing it in the immediate lee of plants rather than by changing the bulk surface's threshold shear velocity." This leads to reductions in dust emission and transport though dust emission varies greatly across landscapes.

5.3 Areas vulnerable to wind erosion.

The combined effects of all parameters investigated, namely, clay content, vegetation and soil types together with rainfall indicate the most vulnerable area to wind erosion to be around the Boshof area and also to the west of Bloemfontein. Patches of vulnerable areas, however, still exist to the west of both Welkom and Virginia in the north together with those to the west of Jaggersfontein in the south. The pattern displayed indicates a mobile scenario with the area stretching from the west to east which is indicative of direction prevailing winds in the area (see Holmes *et al.* 2012). What remains to be seen in the near future is if the dust source areas could be extending towards the east of province.

5.4 Important decision-making considerations of farmers' perceptions about land management.

According to farmers' perceptions, the effective soil conservation measures, in order from the most desirable are: agronomic measure, structural and vegetative measures. These placed structural measures, advocated for by many farmers over long periods, are recognised as comparatively least effective. Findings elsewhere concur in that the efficiency of structural measures placed by farmers to curb wind erosion for soil conservation purposes is debatable but there is also need to address the issues related to determinants of soil erosion. This indicates that farmers are indeed aware of the fact that they are faced with immense challenges presented by wind erosion but they are not well-equipped to deal with the situation. Farmers are keen only to address the susceptibility of soils to wind erosion during the onset of windy periods. Farmers seem not to have any tangible management plans that could adequately address these challenges. This approach directly reflects that farmers are aware that this area is highly susceptible to wind erosion but have limited resource base to address the challenges.

As mentioned earlier on in this study, sophisticated technology or great costs are not necessarily a requirement for wind management practices implementation, but rather ability of farmers to adapt (Yue *et al.* 2015). Land use changes and mismanagement of natural resources were the main driving factors affecting degradation. One of the most important factors affecting such degradation is human activities, which exploit the natural resources beyond their ecological resilience threshold until land degradation is irreversible. Hunger and local energy needs seem to be the drivers of land use and management.

Similarities are evident from this study area with other studies elsewhere by Bonner *et al.* (2014), Mbow *et al.* (2014), Tengberg *et al.* (2014), who add on to suggest that farmers compensation payment could be encouraged for switching to more environmentally friendly land management practices and for subsidies, discounted loans and so on provided to the private sector for establishment of public-private partnerships (PPPs). This is in line with Miller *et al.* (2012), who emphasised that a purely biophysical approach is not sufficient to understand and implement suitable grazing management and that socioeconomic factors need to be taken into consideration.

For this study, it remains apparent that in the Free State as well that the severity of the degradation has made large areas unsuitable for crop production, thereby decreasing food security and increasing poverty throughout the region. According to Noellemeyer *et al.* (2013: 2), "the biophysical constraints that cause low yields in developing countries can be overcome with appropriate management; better farm-level management might mitigate agricultural droughts and crop failures." Many human activities have accelerated soil erosion throughout similar regions to the western Free State province, including clearing woodlands, complete removal of crop residues, and overgrazing, exacerbated by poor soil management and land use practices.

A general notion derived from the participants indicates that in order to guide sustainable development strategies and interventions, it is crucial to understand the functioning and causal relations of the coupled human - environmental systems on which local livelihoods depend – i.e. to get the mental models of these dynamics systems right. Only with a full understanding of the evolution and feedback mechanisms of social and productive systems will it be possible to assess the potential and vulnerability of food production vis-à-vis perturbations related to climate changes or other changes in external conditions and use of the suitability map for soil management.

5.5 Summary

GIS has been excellent in pointing towards areas prone to wind erosion in the study area, prompting informed decision-making. It is evident that there is need for the improvement in communicating science-policy and knowledge management, identification of land degradation hotspots could be expedited through the use of GIS to provide participatory and better decision-making on drylands development and land degradation such as in the case of Free State. In most cases, field observations showed that crops residues were used as animal fodder, for household fuel purposes or burnt and were not retained on the fields. This scenario is common in Sub-Saharan Africa. Disturbance and mismanagement by put pastures under increased levels of stress, making them more liable to land degradation than natural (non-pasture, non-cultivated) ecosystems. One other aspect that has an influence on the grass cover would be palatability of the grass or herbaceous plants as perceived by various livestock types.

This new scientific knowledge could serve as the beginning to challenge the mainstream narratives that described how human-environmental systems were changing in response to different pressures and determine the best policies against land degradation.

CHAPTER 6

CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

6.1 Introduction

In general, model representation of soil and land erodibility conditions has a wide array of requirements. These may include calculation of soil loss rates by empirically integrating interrelationships that exist between vegetation cover, moisture content and soil surface conditions (e.g. WEQ, RWEQ). Incorporating schemes and accounting for dynamic variations in the erodibility of the soil is an advantage of the empirically based models. The disadvantage of this approach is that these models are heavily reliant on field measured inputs that are unavailable at spatially coarse scales. Wind erosion modelling evolved from empirically based field-scale analyses to process-based regional- to global-scale research. This prompted research on dust entrainment and transport.

6.2 Conclusion

It is very conclusive that the study area is adversely affected by wind erosion. Though only a small set of available variables were investigated, all these variables pointed towards a common locality of the phenomenon in the province and the commonality was that only the Mid-western portion of the study area indicated a compounded wind erosion scenario. There were however slight deviations in the common locational area as the used variables were not measured in the same way and possibly that they were determined at different times as well. The susceptibility to wind erosion is highest in the western central region which is under commercial mixed farming. In the area bordering this, wind erosion decreases moderately in either directions and becomes least in the extreme east of the province.

Human activities in the area accelerate erosion through cultivation, overgrazing and controlled burning. Large scale farming and poor maintenance of wind-barriers lead to the observed wind erosion with increased intensity of land use. The researcher elutes that the low agricultural productivity and associated poverty in the study area similar to the rest of Sub-Saharan Africa (SSA) could be related to land degradation. Similarly the Classic or Neo-Malthusian approach argued that combination of poor agricultural practices, population growth and poverty, were causes of land degradation in these regions.

6.3 Limitations of study

The Free State agricultural land is under increasing improper land use. However, the perpetuation of these anthropogenic activities (mainly overgrazing and associated human and animal trampling) within such harsh environmental conditions may lead to significant deterioration of once well-developed grasslands. The impacts of anthropogenic activities are enhanced by prevailing harsh environmental conditions including draught. Degradation of these grasslands clearly indicates the enhancement of land degradation due to improper land-use. This is also witnessed by progressive severe and extensive degradation of the Free State grassland which is manifested by the drastic deterioration of the vegetation cover and consequently severe erosion.

Several limitations were evidenced during this study. It is of paramount importance to note that unavailability of key data was crucial in the application of empirical method in this study. Shortcomings of this study include: (1) The unavailability of data on wind force and the K-factor which made it impossible to carry out conventional modelling, hence the researcher ended up simulating the susceptibility of places using a selection of variables, (2) Another limitation of the study include the scope or extent of the study area. The extent is quite big and as such the researcher could not determine the very extrinsic properties of individual soil properties for every location in the study area. This would be time-consuming and would also involve taking soil samples to be analysed in the laboratory to determine all those parameters that would influence erodibility. Items under consideration here would entail the K-factor, evaporation, aggregate soil stability, organic matter content and various other soil properties, and (3) Another limitation was brought about whilst the available data was ranked by ratio thus introducing a transformation of some kind to make it ordinal and thereby seemingly making the study to be more qualitative.

6.4 Recommendations

While in the study area it seems likely that wind erosion as a problem is under the spotlight, strict adherence to wind erosion management guidelines including adopting to appropriate farming practices. Traditionally windbreaks control wind erosion. These windbreaks could be in vegetation planted around agricultural fields to reduce wind speeds. It is worth noting that in the study area; some windbreaks are severely damaged thus augmenting the envisaged wind erosion by channeling the erosive winds and making them more destructive.

Some wind erosion management practices include:

- Establishing windbreaks (trees and shrubs)
- Avoiding unnecessary and unwarranted burning of vegetative cover
- Maintaining a vegetative cover
- Reducing cultivation or ploughing during fallow
- Reducing localised grazing
- Minimising or eliminate tillage
- Reducing operational speed during ploughing
- Implementing and planting crops in strips and mulch tillage
- Roughening the soil surface and reduce field length
- Applying soil stabilisers or conditioners

This study, similar to the study by Gillies *et al.* (2013), has indicated that wind erosion and dust emissions occur from a range of soil surfaces at variable intensities though they could be having different types and amounts of vegetation. It still remains a research challenge to understand how vegetation cover modulates wind erosion and dust emissions processes.

Developing how a descriptor of the surface roughness and vulnerability of the sediment transport system could be related is another important aspect of research. With imminent climate change in mind, soil moisture is likely to decrease resulting in increased medium term drought, thereby creating high wind erosion areas (Blanka *et al.* 2013, Mezõsi *et al.* 2013). Field measurements on the plot level with more quantitative data could provide more detailed insights in future.

6.5 Summary

Wind erosion may be manageable when farming practices are appropriate. Best management practices to reduce wind erosion were given in the section above. As determined in this study, land degradation is dependent on individual's socio-economic and political circumstances (e.g. Röder *et al.* 2015, Tey *et al.* 2014, Shoshany *et al.* 2013 and Shinoda *et al.* 2011). Summarily, these findings indicate that the Free State province is highly affected by wind erosion and that adoption depends on a range of socio-economic, agro-ecological, institutional, informational, and psychological factors, as well as the perceived attributes of KAPs.

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Appendix 1

A. Personal characteristics

Sampling point No:

Age (in years):

Sex (1 = Male and 0 = Female):

Educational level (in Years):

Household Size (in Number):

Frequency of Extension Service (in a year):

Farmer to Farmer Extension:

Farm size:

Area under perennial crops:

Area under grazing:

B. Direct Causes of Land Degradation (Direct Pressure Indicators)

Always refer to this 5 point Likert scale

1 = Strongly disagree, 2 = Disagree, 3 = No comment, 4 = Agree, 5 = Strongly agree

Do(es) any of the parameter(s) listed promote wind erosion?

	1	**2**	**3**	**4**	**5**
S: Soil management: improper management of the soil including					
(S1) cultivation of highly unsuitable / vulnerable soils					
(S2) missing or insufficient soil conservation / runoff and erosion control measures					
(S3) heavy machinery (including timing of heavy machinery use)					
(S4) tillage practice (ploughing, harrowing, etc.)					
(S5) others (specify - Remarks)					
C: Crop and rangeland management: improper management of annual, perennial (e.g. grass), shrub and tree crops. This includes a wide variety of practices:					
(C1) reduction of plant cover and residues (including burning, use for fodder, etc.)					
(C2) inappropriate application of manure, fertilizer, herbicides, pesticides and other agrochemicals or waste (leading to contamination and washing out (non-point pollution))					
(C3) nutrient mining: excessive removal without appropriate replacement of nutrients					
(C4) shortening of the fallow period in shifting cultivation					

(C5) inappropriate irrigation (full and supplementary): inefficient irrigation method, over-irrigation, insufficient drainage, irrigation with salty water					
(C6) inappropriate use of water in rain-fed agriculture (e.g. excessive soil evaporation and runoff					
(C7) bush encroachment and bush thickening					
(C8) occurrence and spread of weeds and invader plants					
(C9) others (specify - Remarks)					
F: Deforestation and removal of natural vegetation: extensive removal of natural vegetation (usually primary or secondary forest), due to:					
(F1) large-scale commercial forestry,					
(F2) expansion of urban / settlement areas and industry					
(F3) conversion to agriculture					
(F4) forest / grassland fires					
(F5) road and rail construction					
(F6) others (specify - Remarks) Deforestation is often followed by other activities that may cause further degradation.					
E: Over-exploitation of vegetation for domestic use: in contrast to "deforestation and removal of natural vegetation", this causative factor does not necessarily involve the (nearly) complete removal of "natural" vegetation, but rather degeneration of the remaining vegetation, thus leading to insufficient protection against land degradation. It includes activities such as:					
(E1) excessive gathering of fuel wood, (local) timber, fencing materials					
(E2) removal of fodder					
(E3) others (specify - Remarks)					
G: Overgrazing: usually leads to a decrease in plant cover, a change to lower quality fodder, and/or soil compaction. This may in turn cause reduced soil productivity and water or wind erosion. It includes:					
(G1) excessive numbers of livestock					
(G2) trampling along animal paths					
(G3) overgrazing and trampling around or near feeding, watering and shelter points					
(G4) too long or extensive grazing periods in a specific area or camp leading to overutilization of palatable species					
(G5) change in livestock composition: from large to small stock; from grazers to browsers; from livestock to game and *vice versa*					
(G6) others (specify - Remarks)					
I: Industrial activities and mining: includes all adverse effects arising from industrialisation and extractive activities, such as loss of land resource and their functions for agriculture, water recharge, etc. It includes land used for:					

(I1) industry					
(I2) mining					
(I3) waste deposition					
(I4) others (specify - Remarks)					
U: Urbanisation and infrastructure development: includes all adverse effects arising from industrialisation and extractive activities, such as loss of land resources and their functions for agriculture, water recharge. It can cause considerable run-off on neighbouring areas, causing accelerated damage like erosion, as well as other types of degradation (e.g. pollution). It includes land used for:					
(U1) settlements and roads					
(U2) (urban) recreation					
(U3) others (specify - Remarks)					
P: Discharges leading to point contamination of surface and ground water resources, or excessive runoff in neighbouring areas:					
(P1) sanitary sewage disposal					
(P2) waste water discharge					
(P3) excessive runoff					
(P4) poor and insufficient infrastructure to deal with urban waste (organic and inorganic waste)					
(P5) others (specify - Remarks)					
Q: Release of airborne pollutants from industrial activities, mining and urbanisation leading to:					
(Q1) contamination of vegetation/ crops and soil					
(Q2) contamination of surface and ground water resources:					
(Q3) others (specify - Remarks)					
W: Disturbance of the water cycle leading to accelerated changes in the water level of ground water aquifers, lakes and rivers (improper recharge of surface and ground water) due to:					
(W1) lower infiltration rates / increased surface runoff					
(W2) others (specify - Remarks)					
O: Over-abstraction / excessive withdrawal of water:					
(O1) irrigation					
(O2) industrial use					
(O3) domestic use					
(O4) mining activities					
(O5) decreasing water use efficiency					
(O6) others (specify - Remarks)					
N: Natural causes: many occurrences of degradation are not caused by human activities. Although this assessment places the emphasis on human-induced degradation, natural causes may be indicated as well if of major importance. They include:					

(N1) change in temperature					
(N2) change of seasonal rainfall					
(N3) heavy/extreme rainfall (intensity and amounts)					
(N4) windstorms / dust storms					
(N5) floods					
(N6) droughts					
(N7) topography					
(N8) other natural causes (avalanches, volcanic eruptions, mud flows, highly susceptible natural resources, etc.)					
PP: Population pressure: density of population can be a driving force for degradation. High population pressure may trigger or enhance degradation, e.g. by competing for scarce resources or ecosystem services, but a low population density may also lead to degradation, for instance where it leads to a lack of labour force.					
CP & ID: Consumption pattern and individual demand: a change in the consumption pattern of the population and in the individual demand for natural resources (e.g. for agricultural goods, water, land resources, etc.) leading to degradation.					
LT: Land Tenure: Poorly defined tenure security / access rights may lead to land degradation, as individual investments in maintenance and enhancement can be captured by others and land users do not feel "owner" of the maintenance investments. Tenure systems are particular important factors when conservation practices have a long lag between investment and return, such as terracing and tree planting.					
HP: Poverty: poor people cannot afford to invest in resource conserving practices, so instead they continue to use inappropriate farming practices (such as ploughing hillsides and overgrazing), which again will lead to increased land degradation and worsen poverty. Whether poverty plays a role in land degradation needs to be assessed. It also includes situations where the need for bigger profits leads to over-exploitation and degradation of natural resources.					
LA: Labour Availability: Shortage of rural labour (e.g. through migration, prevalence of diseases) can lead to abandonment of traditional resource conservation practices such as terrace maintenance. Off-farm employment opportunities may, on the other hand, help to alleviate pressure on production resources, in the sense that land users can invest more in conservation infrastructure as income increases.					
I & I: Inputs and infrastructure (roads, markets, distribution of water points, etc.): inaccessibility to, or high prices for key agricultural inputs such as fertilizers, may render it difficult or unprofitable to preserve soil					

fertility or water resources. Access to markets and prices and good infrastructure may improve this. On the other hand, a road through a forest can lead to overexploitation and degradation.					
EAASL: Education, awareness raising and access to knowledge and support services and loss of knowledge: investing in human capital is one of the keys in reducing poverty (and thus land conservation practices). Educated land users are more likely to adopt new technologies. Land users with education often have higher returns from their land. Education also provides off-farm labour opportunities.					
W & C: War and Conflict: they lead to reduced options to use the land or to increased pressure.					
GIP: Governance, institutions and politics: laws and enforcements, organization, collaboration and support: government induced interventions may set the scene and be indirect drivers for implementation of conservation interventions.					
O: Others (specify - Remarks)					

(Source: Liniger *et al.* 2008)