DIGITAL SOIL MAPPING AS A TOOL FOR IMPROVED ROAD AND GAME DRIVE MANAGEMENT WITHIN PHINDA PRIVATE GAME RESERVE, KWA-ZULU NATAL

by

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Abstract

With the development of digital technology during the last decade and the improvement of Geographic Information Systems (GIS), it has become easier for various scientific fields to predict and extrapolate data. Various organisations and institutions continuously develop algorithms and software to assist with specific challenges in multiple fields of science. These technologies and principles have also been effectively applied in the soil science field of pedology. Traditional soil mapping, although effective, is time consuming, arduous and expensive. It is thus important to develop methods whereby the soil forms of an area can be identified faster while providing accurate information to the reader/ user. Conservation areas, such as Phinda Private Game Reserve (Phinda), which covers a large area (greater than 28 000 ha) can benefit from a soil map. The importance of a proper soil map has a great many uses in conservation, but not every organisation or individual can afford it. This is where digital soil mapping (DSM) or Predictive Soil Mapping (PSM) comes into its own. Substantial research and development have been done in the form of methodology and software systems for DSM although it has not been effectively applied to conservation management.

By applying these techniques, accurate and interactive soil maps were developed without the burdensome expenses or dangers associated with traditional soil observations in a conservation area. The application of DSM and the use of the soil land inference model (SoLIM) at Phinda resulted in maps based on the Fey soil-form classification as well as a soil sensitivity index (SSI). The SSI was developed based on the various soil forms present at Phinda and the factors that determine its sensitivity to various types of degradation. These digital maps indicated accuracies of 71% (Fey classification) and 72% for the SSI. The kappa values indicated a substantial agreement (0.63) for the Fey classification map and a moderate agreement (0.57) for the SSI map.

The SSI was then combined with the predator sightings and the location of infrastructure and commercial lodges to derive the agreement of activities, game drives, which includes off-road driving (ORD) on sensitive soils. As erosion is a concerning problem, predominantly caused by human activities within Phinda, it was necessary to use the SSI map as a base of comparison. This digitally produced soil map will be presented to the conservation management at Phinda whereby planning can be conducted, literally, from the ground up. Proper planning will thus prevent a loss of soil and consequently a loss of biodiversity. All the information was then combined to developed recommendations for Phinda as to improve the overall road network by upgrading, removing and rehabilitating certain roads and provide advice concerning ORD. These decisions, in turn, prevent long-term soil and biodiversity loss while still providing clients with a true African bush experience.

Key words: Soil management, pedology, conservation management, off-road driving, biodiversity.

Opsomming

Met die ontwikkeling van digitale tegnologie gedurende die afgelope dekade en die verbetering van Geografiese Inligting Stelsels (GIS), het dit vir verskillende wetenskaplike velde makliker geword om data te voorspel en te ekstrapoleer. Verskeie organisasies en instellings ontwikkel deurlopend algoritmes en sagteware om met spesifieke uitdagings op verskeie wetenskaplike terreine te help. Hierdie tegnologieë en beginsels is ook effektief toegepas in die grondwetenskap veld van pedologie. Tradisionele grondkartering, hoewel effektief, is tydrowend, moeiliker en duur. Dit is dus belangrik om metodes te ontwikkel waardeur die grondvorme van 'n gebied vinniger geïdentifiseer kan word, terwyl akkurate inligting aan die leser/ gebruiker verskaf word. Bewarings gebiede, soos Phinda Private Game Reserve (Phinda), wat 'n groot gebied beslaan (groter as 28 000 ha), kan baat by 'n grondkaart. Die gebruik van 'n behoorlike grondkaart is baie belangrikheid vir bewaring, maar nie elke organisasie of individu kan dit bekostig nie. Dit is hier waar Digitale Grond Kartering (DGK) of Voorspelbare Grond Kartering (VGK) tot sy reg kom. Wesenlike navorsing en ontwikkeling is gedoen in die vorm van metodologie en sagtewarestelsels vir DGK, hoewel dit nog nie effektief op bewaringsbestuur toegepas is nie.

Deur hierdie tegnieke toe te pas, is akkurate en interaktiewe grondkaarte ontwikkel sonder die lastige uitgawes of gevare verbonde aan tradisionele grond waarnemings in 'n bewaringsgebied. Die toepassing van DGK en die gebruik van die Grond Land Inferensie model (GLaIM) by Phinda het gelei tot kaarte gebaseer op die Fey grondvorm klassifikasie sowel as 'n Grond Gevoeligheids Indeks (GGI). Die GGI is ontwikkel op grond van die verskillende grondvorms wat by Phinda teenwoordig is en die faktore wat die sensitiwiteit daarvan in verband met verskeie soorte degradasie bepaal. Hierdie digitale kaarte het 'n akkuraatheid van 71% (Fey-klassifikasie) en 72% vir die GGI aangedui. Die kappa-waardes dui op 'n aansienlike ooreenkoms (0.63) vir die Fey-klassifikasie kaart en 'n matige ooreenkoms (0.57) vir die GGI kaart.

Die GGI is toe gekombineer met die waarnemings van roofdiere asook die ligging van infrastruktuur en kommersiële herberge om die ooreenkoms van aktiwiteite, wildritte, wat veldry (VR) op sensitiewe gronde insluit, af te lei. Aangesien erosie 'n groot probleem is, met menslike aktiwiteite in Phinda wat die hoof oorsaak is, was dit nodig om die SSI kaart as 'n vergelyking te gebruik. Hierdie digitaal geproduseerde grondkaart word aan die bewaringsbestuur op Phinda aangebied, waardeur beplanning letterlik vanaf die grondslag gedoen kan word. Behoorlike beplanning sal dus 'n verlies aan grond en gevolglik 'n verlies aan biodiversiteit voorkom. Al die inligting is daarna gekombineer om aanbevelings te ontwikkel vir Phinda met die doel om die algehele padnetwerk te verbeter deur die opgradering, verwydering en rehabilitasie van sekere paaie en ook advise te voorsien rakende ORD. Hierdie besluite voorkom op hul beurt langtermyn-verlies aan grond- en biodiversiteit, maar bied steeds 'n ware Afrika-boservaring.

Sleutelwoorde: Grondbestuur, pedologie, bewaringsbestuur, veldry, biodiversiteit.

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List of Symbols and Abbreviations

Abbreviation	Designation
CGS	Council for Geoscience
cLHS	Conditioned Latin hypercube sampling
DEM	Digital elevation model
DSM	Digital soil mapping
GIS	Geographic Information System
LANDSAT	Land satellite images
ORD	Off-road driving
Phinda	Phinda Private Game Reserve
PSM	Predictive soil mapping
QGIS	Quantum Geographic Information System
SAGA	System for automated geoscientific analysis
SANBI	South African National Biodiversity Institute
SoLIM	Soil land inference model
SSI	Soil sensitivity index
UTM	Universal Transverse Mercator

List of Definitions

Term	Definition
Apedal	- the term apedal is used in general to denote materials that are well aggregated although well-formed peds cannot be detected macroscopically.
Calcic	- a lime-enriched horizon (not indurated).
Calcrete	- a massive material enriched with and strongly cemented by sesquioxides, chiefly iron oxides (also known as ferricrete, diagnostic hard plinthite, ironpan, ngubane, ouklip, 88 laterite hardpan), silica (silcrete, dorbank) or lime (diagnostic hardpan carbonate horizon, calcrete).
Cutan	- cutans occur on the surface of peds or individual particles (sand grains, stones); they consist of material which is usually finer than and that has an organisation different to the material that makes up the surface on which they occur; they originate through deposition, diffusion or stress.
Dusticide	- lone standing liquid, or mixed with water and sprayed on roads; the liquid binds soil particles together creating a harder surface which prevents dust generation, erosion and ensures better driving conditions; various dusticides are environmentally friendly and assists with saving water.
Geotiff	- GeoTIFF is a public domain metadata standard, which allows georeferencing information to be embedded within a TIFF file; the potential additional information includes map projection, coordinate systems, ellipsoids, datums, and everything else necessary to establish the exact spatial reference for the file.
Humic	- a dark-coloured horizon with a moderate content of organic carbon, low base status and no signs of wetness.
Lithocutanic	- a horizon with distinct affinities with the underlying parent rock into which it merges; it has cutanic character expressed usually as tongues or prominent colour variations.
Melanic	- a dark-coloured horizon with a high base status.
Neocutanic	- a horizon that has developed in recent sediments and unconsolidated material (usually transported), showing little signs of pedogenesis and is non-calcareous.
Pedocutanic	- a horizon with strong blocky structure and clearly expressed cutans.
Pedology	- that branch of soil science dealing with soils as a natural phenomenon, including their morphological, physical, chemical, mineralogical and biological constitution, genesis, classification and geographical distribution.
Prismacutanic	- a horizon with an abrupt transition with an overlying A horizon with respect to texture, structure or consistence; the structure is strong prismatic or columnar.
Smectite	- a group of swelling clay minerals made up of 2:1 unit layers, each layer consisting of two silicon-oxygen tetrahedral sheets enclosing one aluminium-oxygen (or hydroxyl) octahedral sheet.
Vertic	- a dark coloured-horizon with high clay content and with swell-shrink properties.

Chapter 1
GENERAL INTRODUCTION AND THESIS OUTLINE

1.1 Title

Digital soil mapping as a tool for improved road and game drive management within Phinda Private Game Reserve, Kwa-Zulu Natal.

1.2 Introduction

Soil, in all its forms, plays an integral part in our world and every day practices. By knowing the soil type/ forms present in a certain area, decision makers can plan activities (such as agriculture, mining, conservation, etc.), literally, from the ground up (Foth, 1990). Identifying the soil types can be a tedious, time consuming and, depending on the size of the study area, an expensive process (van Zijl *et al.*, 2014). Phinda Private Game Reserve (Phinda), which is over 28 000 ha in size, would take weeks and hundreds of thousands of Rands to map using traditional soil mapping. Traditional soil mapping is the process of mapping an area by identifying the soil through hand auger observations on a grid of 100 m to 150 m apart (Zhu *et al.*, 2001). These soil observations are used to compile a soil map of the area by drawing lines in between the observation points (Zhu *et al.*, 2001). It is thus necessary to continually improve the manner in which we identify various soil types as technology and research improves. Studies have shown that the use of predictive digital soil mapping (DSM) has been increasing in the last few decades and has become much more accurate and cost effective (Hengl and Heuvelink, 2004), but it is not without its faults. The same goes for traditional soil mapping, this technique is very effective at identifying soil horizons and giving an accurate account of the study area but it is sometimes time consuming and expensive. To map the soils of South Africa's protected areas, a cost effective and less strenuous method must be used as to encourage the owners of these protected areas to map these soils as to improve the effectiveness of the management of these protected areas.

The DSM has been used quite effectively in recent years, to determine soil forms (alongside the extrapolation of other soil properties such as sensitivity, water holding capacity and susceptibility to erosion), as well as decrease costs and time spent in the field (van Zijl *et al.*, 2012). Larger areas (> 4000 ha) can also be mapped accurately and effectively (van Zijl, 2018). This then assists conservation areas (such as Phinda) to map out the soil types/ forms present in their area which results in better planning and decision making.

Traditional soil maps provide accurate data as to the soil classification because it can sample deep into the soil and evaluate the various horizon (Yang *et al.*, 2011). By making use of predictive DSM, it is possible to not only classify the soils but also to add spatial detail as well as soil attributes (sensitivity to erosion and compaction, agricultural potential, saturated soils etc.). Using current Geographic Information Systems (GIS), modelling software and electronic information, such as land satellite images (LANDSAT), these attributes can be included into the DSM system and an interactive soil map can be created. An electronic map can easily be overlaid over various maps, as well as modified to indicate soil areas with the same attributes or characteristics. Conventional soil sampling will still be required, as this information will be used to predict the gaps in soil types (Zhu *et al.*, 1997; Zhu *et al.*, 2007).

Due to the nature of protected areas, funding and time constraints, very little, if any, soil mapping has taken place in these areas (Nortjé and Nortjé, 2017). The mapping of soils in protected areas is extremely important as any construction (road or infrastructure) or activity (hiking, mountain biking, 4x4 driving, etc.) will have to be planned properly, as to do as little damage towards the soils and the biodiversity (Nortjé, 2017). It is thus important to find the most practical and accurate method of soil mapping to ensure that decision makers can formulate the best possible plans. Any activity takes place on sensitive soils can lead to long-term soil loss, which in turn results in a loss of biodiversity. A loss in biodiversity will eventually result in a decrease in visitors to the specific protected area (Nortjé, 2014; 2018a; 2018b).

Nortjé and Nortjé (2017) found that sensitive soils in the Serengeti National Park suffered environmental damage due to certain activities, such as off-road driving (ORD). These environmental damages included erosion and the encroachment of invader plant species. The loss of sensitive soils will have long-term impacts on not only the natural environment, but also on the eco-tourism business, as a loss of land will eventually result in a loss of biodiversity. The best possible action for game reserves is to have their soils mapped, so that proper management can take place (Nortjé and Nortjé, 2017). This will ensure that eco-tourism continues while sensitive soils are protected and the biodiversity of the area does not diminish.

An area like Phinda, the area studied, presents a unique challenge for soil surveying due to its varying soil cover, vegetation cover, underlying geology, topography and financial constraints. Not only does this game reserve offer varying challenges as mentioned above, but also not all the reserve can be accessed on foot or with a vehicle due to the wild fauna and dense vegetation. Thus, taking as many traditional soil observations as necessary must be complimented with digital predictive soil mapping (PSM). Implementing the developed methodology (Van Zijl, 2013; van Zijl *et al.*, 2013; Van Zijl and Botha, 2016) and using DSM software, an accurate soil map can be created of Phinda.

The purpose of this research is to implement DSM at Phinda, which decreases the costs of soil mapping, combine this soil map which was grouped into soil sensitivities with the current road network used by game rangers, locals and other parties within Phinda and then redesigning this road network to ensure sustainable ecotourism while providing an enjoyable experience for tourists.

1.3 Research problem

The main problem identified was the lack of soil information in the form of a soil map and related information within Phinda. Although a lot of research has been done on various techniques of soil mapping, both traditional and digital, very little has been applied to most protected areas in South Africa (including Phinda). This is mainly due to time and funding constraints as smaller protected areas cannot afford soil scientists to perform an intensive traditional soil study while certain areas are only mapped once a project or infrastructure in planned for a specific area. This then leads to many other problems such as roads being constructed properly or poorly on sensitive soils and outdoor activities, especially ORD, also adding to the destruction of sensitive soils. Without a proper soil map, game reserves destroy sensitive soils, which result in a loss of biodiversity, erosion and subsequently less tourists visiting game reserves.

1.4 Objectives

The main objectives of this research were to:

- Create a soil form map and soil sensitivity map for Phinda using Digital Soil Mapping;
- Use these maps to redesign the road network at Phinda to assist with planning of sustainable eco-tourism activities (such as game drives).

1.5 Hypothesis

By classifying soils by way of digital soil mapping, and creating a cost-effective and accurate soil map, it would be possible to improve and manage game drives and ORD sustainable within Phinda.

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Chapter 2
LITERATURE REVIEW

2.1 Literature review

Phinda Private Game Reserve (Phinda) was the ideal study area for this research project with its size of over 28 000 ha, expansive road network, various landscapes, vegetation, geology and commitment of management to decrease their impact on the environment. The goal of Phinda is to return to its previous natural state (Varty and Buchanan, 1999). Thus, this goal provided the opportunity to apply digital soil mapping (DSM).

2.2 Soil forming factors

To understand the soils that are present at Phinda the factors that created the specific soils must be identified. Jenny (1941) described the five soil forming factors as climate, geology (parent material), organisms, time, relief and topography. Multiple studies have built upon the research done by Jenny and described these factors in detail, such as Foth (1990), who describes geology (parent material) as the most important factor of soil formation. The first factor that was discussed that affects soil formation is climate. Phinda is located within the humid warm temperate zone of South Africa (Conradie, 2012), which has warm temperatures year-round, high levels of evaporation and rainfall. The second factor that was discussed was geology (parent material). The geology at Phinda was broadly divided into a northern and southern area. The northern area consists largely out of sandstone and siltstone, which, over millions of years, have eroded into sandy and silty soils (Schaetzl and Thompson, 2015). The southern area on the other hand is underlain by volcanic rocks, which over time, has eroded into soils with higher clay content (Bowles, 1984) and greater variety of mineral composition.

Topography was the third soil forming factor that was discussed. Based on a study by the Institute for Soil, Climate and Water of the ARC, done between 1972 and 2006 by the Land Type Survey Staff (1972-2006), whereby the broad soil patterns and topography of South Africa was determined for the purposes of Agriculture, Phinda was divided into three topographical areas. The northern area of Phinda is relatively flat with low relief, the central and north-west regions are largely mountainous with steeper slopes, whereas the southern and western areas of Phinda consist of undulating plains.

Two other covariates, which are also discussed within this chapter but are not considered soil-forming factors, namely vegetation and the soil itself. Soil affects vegetation, but certain vegetation types will only be found on a certain soil forms. By understanding the vegetation types and their location within Phinda, it can be added to the DSM process. Phinda consists of various vegetation types but the reserve is mainly situated within the Savannah Biome of South Africa as well as the sub-tropical coastal region. As mentioned above, the Land Type Survey Staff (1972-2006) also identified the broad soil patterns situated across South Africa. Of the 17 land types that cover Phinda, the area was divided into seven broad soil patterns. Fey (2010a) grouped the multiple soil forms of South Africa into 14 forms, which was used for the purposes of this study. All these covariates are discussed in greater detail and were taken into account for the DSM process. These factors all contribute to the soil forming processes or are a result of the soil forming processes and provide information as to the soil forms that are present at Phinda.

2.3 Digital soil mapping process

Initially Phinda Private Game Reserve (Phinda) was divided into homogenous areas (van Zijl, 2013) based on predetermined factors. For the purpose of this study, Phinda was divided based on the land types as formulated by the Land Type Survey Staff (1972-2006). Various soil observations were then collected within these homogenous areas using three observation methods. Firstly, random soil observations were taken within each homogenous area, and secondly, the use of opportunistic observations were employed anywhere soil was exposed to a depth of 1 m or deeper. Thirdly, and the most effective method used for soil observations, is the conditioned Latin hypercube sampling (cLHS) method. This method was successfully used by Brungard and Boettinger (2010) and is considered the most accurate method for the inclusion of all environmental covariates when conducting soil observations for the purpose of DSM (Minasny and McBratney, 2006a; 2006b).

Soil observations were identified using the Soil Classification System for South Africa (Soil Classification Working Group, 1991). All observations were recorded on a data sheet and the location determined by GPS. McBratney *et al.* (2003) suggest that any form of soil sampling/ observations be done purposefully as to save time.

The next step was to prepare the other datasets that was required for the DSM process. These datasets include a digital elevation model (DEM), various land satellite images (LANDSAT) indicating different spectral indices (Flynn *et al.*, 2019) and hydrological and terrain metric outputs (Böhner *et al.*, 2006). These hydrological and terrain metric units were generated by the system for automated geoscientific analysis (SAGA). Another important step before the digital soil map was developed was to group the various soils at Phinda into functional groups. The first grouping was based on the Fey soil classification (2010a) that combines the 73 soils identified in the South African Soil Classification System (Soil Classification Working Group, 1991) into 14 groups. The second grouping was that of a soil sensitivity index (SSI) whereby the soils identified at Phinda were divided into five groups based on their sensitivity to water and wind erosion. A literature study was conducted and the area specific soil forming factors were taken into account during the development of the SSI.

2.3.1 Developing a SSI

Initially the geology was taken into account as soil is mainly derived from different parent materials (Sumner, 1957). These various parent materials will develop into soils with varying levels of soil erodibility. The geology that underlies the northern area consists predominantly of alluvium, sand stone and siltstone. The middle area consists of acid lavas (rhyolites) and minor tuffs whereas the southern area indicates a geology dominated by basic volcanic rocks such as tholeiites, picrate basalts and nephelinites (shape files format from the Council for Geoscience). The sandstone, acid lavas and basic volcanic geology that dominate at Phinda generally erode into soils with a higher susceptibility to erosion (Laker, 2004). Mudstone and shale (which are found in large parts of Phinda) develops into soils, which have a higher erodibility (Laker, 2004).

Laker (1990) found that the higher the rainfall in an area the more a soil will develop and advance. This will usually result in deeper and more stable soil formations. Phinda has an average rainfall of 703 mm (rainfall information received from Phinda from 1995 to 2017). This is above the average rainfall of South Africa but below the world average of 990 mm per annum.

Soil horizons, their contents, proportion of sand, clay and loam as well as other particles within the soil will assist with determining its sensitivity to erosion. Soils with a melanic A-horizon have increased susceptibility to erosion as the degree of weathering increases (van der Merwe *et al.*, 2001). The presence of certain clay mineralogy's within a melanic A-horizon, such as kaolinitic minerals will increase its erodibility. These clays are very predominant in the melanic soils of Phinda (Stern, 1990). By determining the composition of soil, it is possible to determine how easily it disperses when exposed to wind and water. If a soil disaggregates easily, it is more prone to erosion (van der Merwe *et al.*, 2001). Two primary factors protect soil particles from dispersing, namely: (i) the concentration of free iron oxides, and (ii) the organic matter present within the soil. Both factors will assist the stability of a soil even if the vegetative cover has been removed. Soils with red apedal B- and yellow-brown apedal B-horizons (Soil Classifications Working Group, 1991) are found at Phinda, but are derived from sandstones (which are prevalent in the northern part of Phinda). Not only are sandy soils susceptible to water erosion, but once the vegetative cover has been removed, winds will also erode large exposed areas. Although iron oxides assist with the stability of the soil, the amount of sand within the soil negates the ability of the free oxides to ensure a good stability of the soil particles. Based on the field soil observations, there are very few soils present at Phinda that contain a high soil organic content. A soil horizon with an exchangeable sodium percentage (ESP) of 15% or higher will erode easier as sodium is the cation that affects dispersion the most (Bühmann *et al.*, 1996).

Soils with an E-horizon indicate a fluctuating water table and periods of saturation. This process of wet and dry periods has leached out the clay particles (through eluviation) and iron oxides (often forming mottles) (Soil Classification Working Group, 1991). Both clay minerals and iron oxides provide stability to a soil horizon. Once the vegetative cover has been removed through ORD or other human induced practises the top soil becomes exposed. The E-horizon can be very shallow and quickly exposed or exposed after the first rain event. Once the E-horizon has been exposed, it erodes away quickly as it has already undergone various processes of destabilisation through long periods of saturation. Various soil forms with E-horizons, and other horizons with signs if wetness, were identified at Phinda.

Another important aspect take into account was the clay content and mineralogy. High clay content provides stability to a soil and decreases its erodibility (Laker, 2004). Due to the geology of South Africa, the majority of our clay minerals consist of ilinite or kaolinite clays. Bloem and Laker (1994) also found that there are numerous soils that are dominated by clays containing smectite. The dominant clay mineralogy will indicate the sensitivity of a soil to crusting, with smectite having a higher sensitivity to crusting, followed by illite and lastly kaolinitic clays. Smectitic clay mineralogy is present at Phinda due to its abundance in South Africa (Bloem and Laker, 1994) as well as the dominant geologies found at Phinda. A soil survey report by Nortjé (2017) describes the sensitivity of various soils to erosion. The following soils, which are mentioned in the Nortjé reports (Nortjé, 2018a; 2018b), are also found at Phinda. Valsrivier (with a pedocutanic B-horizon), Escourt (with an E-horizon and prismacutanic B-horizon) and Oakleaf (neocutanic B-horizon) are present at Phinda and very susceptible to erosion. This is because they are duplex soils and contain coarse blocky, platy or massive structures within the B-horizon.

Stable soils (against degradation) were also found at Phinda, even with geology that creates generally unstable soils. These soil forms such as Shortlands, which consists of a blocky structured B-horizon, high clay content and a high percentage of iron oxides (Soil Classifications Working Group, 1991), and Hutton (red apedal B-horizon due to a high percentage of iron oxides) is quite stable even when the vegetative cover has been removed and the topsoil has been compacted. In conclusion, the soils located at Phinda are generally highly susceptible to wind and water erosion once disturbed.

2.3.2 Grouping soils using the Fey classification

Another method for grouping soil was based on the soil grouping of Fey (2010a; 2010b). Fey combined the 73 soil forms of South Africa (Soil Classification Working Group, 1991) into 14 groups based on the diagnostic horizons and materials, which are present within the soil. Of these 14 groups described by Fey (2010a), the following 10 were identified at Phinda; calcic, cumulic, duplex, gleyic, humic, lithic, melanic, oxidic, plinthic and vertic. This grouping was effective for the study as less soil form/ group variables result in a more detailed map over such a large area. Fey (2010a) groupings also provide a comparison to the World Reference Base for Soil Resources (WRB, 2015) which is used in many countries around the world. As Phinda is owned by an international organisation (&Beyond) and with the world being connected and the exchange of information taking place freely, soil groupings that can be compared to international soil forms will allow individuals and organisations from across the world to understand the soil forms and horizons found at Phinda.

The various datasets along with the Fey grouping (2010a) and SSI grouping was then used to developed rules which was utilised by the SoLIM and was developed by Zhu *et al.* (1997). SoLIM converts the various datasets into raster files which consists of pixels or cells. Each pixel or cell contains specific information, obtained from the datasets loaded into SoLIM, which were associated with the identified soil type. The rules written within SoLIM are then applied to each pixel or cell (van Zijl, 2013; Zhu *et al.*, 2001; Zhu *et al.*, 2007) and a digital soil map was produced. The resulting soil maps indicated the Fey soil grouping (2010a) and the SSI grouping, respectively.

2.3.3 SoLIM and modelling

Zhu *et al.* (1997), Zhu *et al.* (2001) and Zhu *et al.* (2007) developed the SoLIM to produce high quality, cost effective soil maps with limited information. This software was used to compile the soil maps of Phinda. The following paragraphs provide a brief overview of the purpose and workings of SoLIM.

The SoLIM soils maps' using GIS, fuzzy logic and expert knowledge (Zhu *et al.*, 2001). The software is based on three central parts or steps: firstly, a model is developed that describes the similarities of soils as to why they are located at that point or area; secondly, rules are formulated that were applied to the entire study area; and lastly, this information was applicable and useable. The first part of the process was based on the fact that soil is not distributed randomly within the landscape. Various factors and environmental conditions produced different soils; similar soils are present within the study area where these conditions are similar (Zhu *et al.*, 2007). Soils and their distribution within the landscape are determined though field observations, expert knowledge and other forms of remote sensing. The development of soils is best described by a formulation developed by McBratney *et al.* (2003). McBratney *et al.* (2003) developed the SCORPAN model, which is based on the Jenny (1941) model. This formulation was used to describe the relationship between soils and the factors that produce them as well as the spatial distribution of the soil. The SCORPAN formulation is described as:

$S_c = f\ (s, c, o, r, p, a, n)$

Where S_c refers to the soil form/ type and:

s: soil (which uses the properties of the soil itself at the specific point or area)

c: climate of the area

o: organisms (flora, fauna and humans)

r: topography

p: geology (parent material)

a: age (time)

n: spatial position of the soil (McBrantey *et al.*, 2003).

2.4 Combining covariates with DSM

The last step was to combine the Fey soil grouping (2010a) map and the SSI grouping map with the location of predator's sightings within Phinda, the position of commercial lodges and the roads surrounding these locations. It was important to combine this information as off-road driving (ORD) on the incorrect soils can lead to soil loss through erosion and the long-term loss of biodiversity (Nortjé and Nortjé, 2017).

Applying the developed rules (van Zijl, 2013) within the soil land inference model (SoLIM), two raster maps were produced. These maps indicated the predicted positions of the soils grouped into the Fey classification and the soil sensitivity index (SSI). To achieve as accurate maps as possible, any soils of the Fey classification and SSI with three or less observations were not included in the mapping process (van Zijl *et al.*, 2012) but were added to the final soil map as these observations were not completely discarded. The results are in line with the soil forming factors, especially with regards to the geology and topography. There is marked difference between the northern and southern areas of Phinda Private Game Reserve (Phinda), as the geology differs between the two. An example of this is the presence of free iron within the soils of the northern area due the geological formations. The presence of free irons in the soils ensures a stronger bond between the particles and a decrease in its sensitivity to erosion (van der Merwe *et al.,* 2001).

2.5 Accuracy determination and use of a DSM

Before these maps could be used, their accuracy was determined (van Zijl *et al.*, 2019). Two methods were used to determine the accuracy of both maps, i.e. the accuracy matrix and the kappa coefficient. The accuracy matrix assesses the performance of an algorithm by determining the percentage of correctly predicted instances (Powers, 2011; Næsset, 1996). Van Zijl (2013), states that a percentage of 65% or higher is ideal, especially for large areas. The kappa coefficient is a statistical measure that is used to determine the inter-soils dependability with other qualitative units (McHugh, 2012) and it indicates how well the map represents reality. According to Viera and Garrett (2005), a moderate agreement (0.41 to 0.60) or higher is acceptable.

Once the acceptable accuracies were achieved for the Fey (2010a) soil-grouping map and the SSI map, the raster files were converted to vector files. The SSI map was then combined with the predator sightings, commercial lodges' locations and all roads which fall within a 2.5 km radius of these locations. By combining these covariates, recommendations were developed as to which roads must be rehabilitated, maintained or upgraded.

DSM has been used to successfully update traditional soil maps on a national level. Abdelfattah and Pain (2012) used DSM to update the soil maps of the United Arab Emirates. Because the maps were created on a national scale predictive DSM was effective to identify the major soil groups, but on a larger scale map there will always be a need to take field observations as well. A digital soil map of Phinda was not only be used for the identification of soil, but also when incorporated into planning many problems can be avoided.

The main goal of this study was to develop recommendations concerning the road network of Phinda Private Game Reserve (Phinda) based on a soil map (Nortjé and Nortjé, 2017). The soil map in question being the one soil sensitivity index (SSI) map that was produced. These recommendations will, over time, improve the road network at Phinda, decrease the impact of the current road network, protect the soils and natural environment and ensure long term sustainable tourism. Various recommendations can be applied to Phinda, some very specific to the area whereas others have been affectively used in multiple instances across the world. These recommendations will range from basic actions such as decreasing tyre pressure within vehicles and maintaining vehicles so that engine vibration remains as low as possible (Nortjé, 2018a), to replacing the current vehicles with lighter vehicles (Nortjé *et al.*, 2012; Nortjé *et al.*, 2016) as to limit the impact on soil compaction.

Other recommendations are not necessarily physical in nature but begin with management and the employees of Phinda. Off-road driving (ORD) must be managed, as it can lead to large-scale soil and vegetation loss (Nortjé, 2017). ORD must only take place when there has been a confirmed sighting of a predator and multiple vehicles must then drive in each other's tracks to limit the impact of ORD (Nortjé, 2019). Game rangers can educate tourist on the impacts off ORD on soils and the environment (Nortjé and Mearns, 2017) as tourists enjoy the experience of driving off-road. In certain cases, such as Phinda where the reserve has an extensive road network, the road network can be redesigned (Nortjé, 2017; Nortjé and Nortjé, 2017) as to remove and rehabilitate, upgrade, maintain and construct roads.

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Chapter 3
STUDY AREA

3.1 Phinda Private Game Reserve

Phinda is owned and operated by an international ecotourism and wildlife experience company called &Beyond. Phinda is situated in Kwa-Zulu Natal, approximately 15 km north of Hluhluwe, 20 km southeast of Mkuze and borders the western boundary of the St. Lucia Isimangaliso Wetland Park (Figs. 3.1 and 3.2). The N2 highway runs along its southern border whereas the R22 road runs along its eastern border.

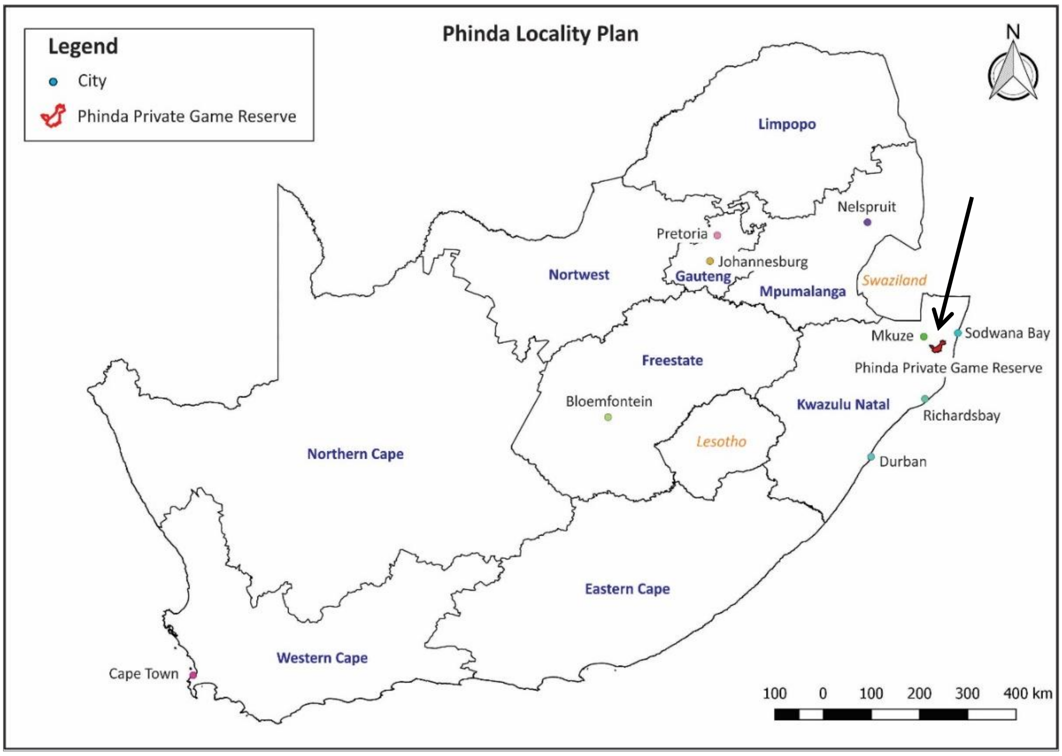

Figure 3.1: Phinda's locality within South Africa

Phinda translates to "The Return" (Varty and Buchanan, 1999) which indicates the nature and the goals of the reserve. Phinda is a collection of plots and previous agricultural land in extent of 28 840 ha that was bought or obtained from farmers and is being returned to its previous natural state. The game reserve boasts 28 555 ha of rewilded land as well as 230 ha of protected, ancient sand forests. Thus, Phinda is a combination of various land uses that are being restored to ensure that the conservation of nature continues while giving tourists an enjoyable experience of Africa's beautiful fauna and flora.

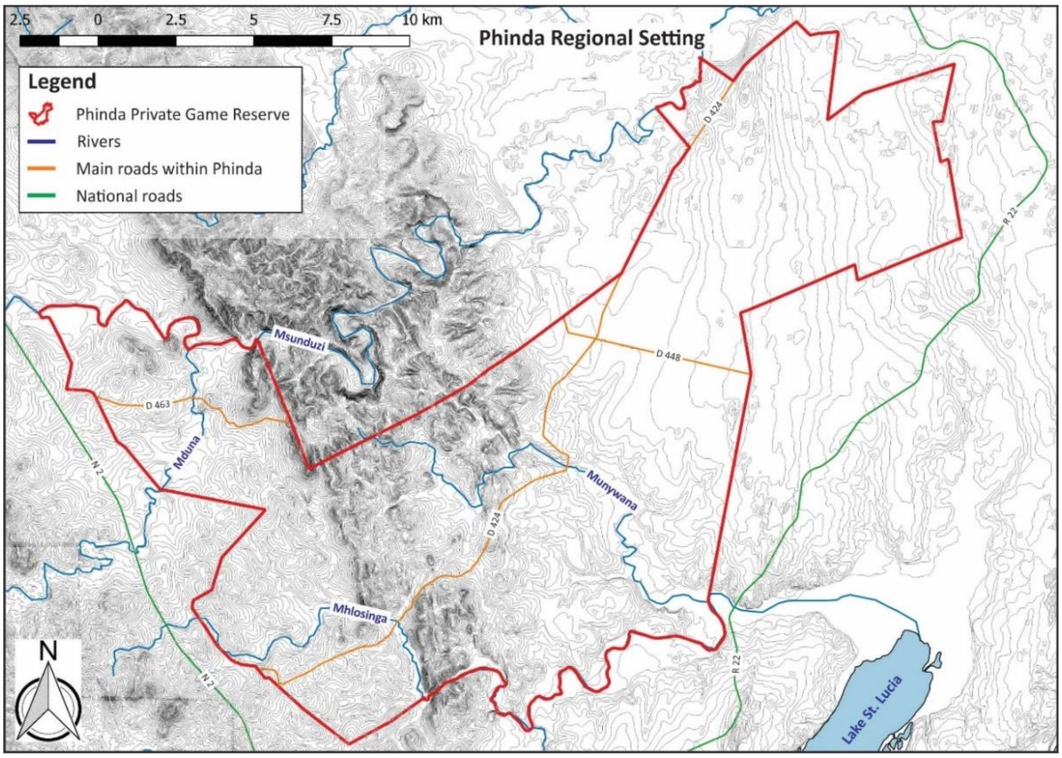

Figure 3.1: Phinda regional setting

Phinda is located in the bushveld (Savannah biome) of South Africa which also falls within the sub-humid climatic region.

Figure 3.3 indicates the road network within Phinda (the map, in shapefile format, was provided by Phinda). Many of these roads are unused and within sensitive areas and result in soil degradation, such as erosion, and the resulting loss of biodiversity.

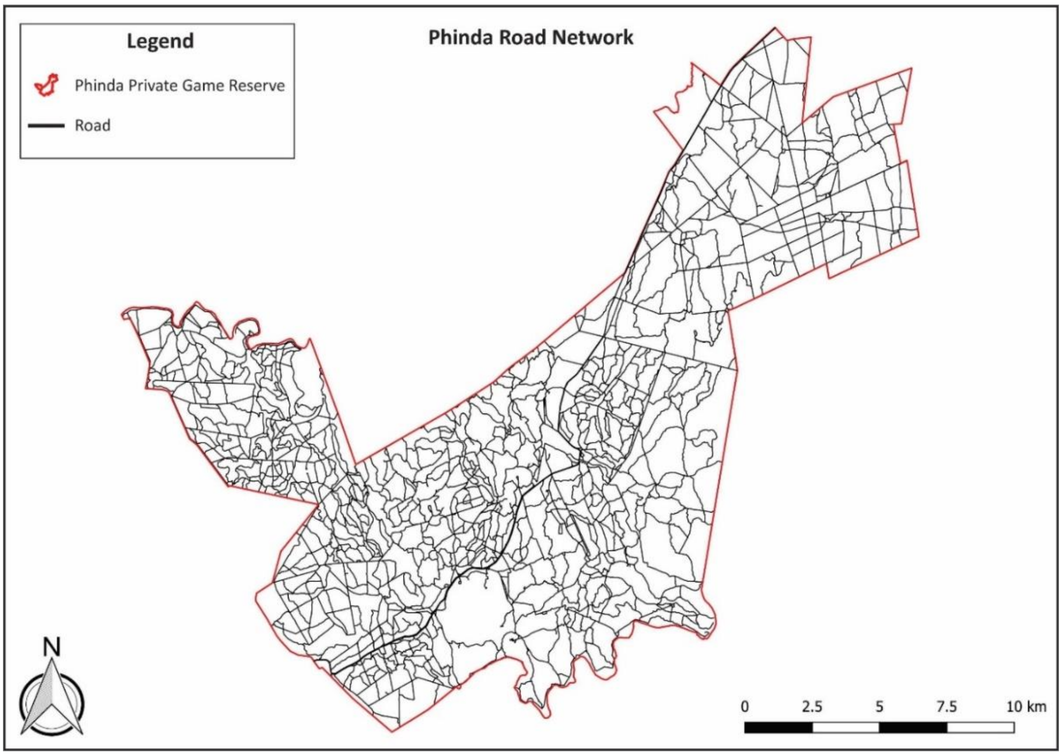

Figure 3.2: Phinda road network

3.2 Baseline information

3.2.1 Climate

Phinda falls within the sub-tropical coastal region of South Africa. Phinda receives an average of 703 mm of rainfall a year, with an average of 291 mm during summer from January to March and an average of 54 mm during winter from June to August (Conradie, 2012). This was an important factor to consider as rainfall can eliminate the presence of certain soils, and assist with the soil identification process. Figure 3.4 indicates the average rainfall per month at Phinda spanning from 1995 to 2017 (rainfall data collected by Phinda), the average temperature (minimum and maximum) measured at the St. Lucia Weather Station, as well as the average evaporation between 1963 to 2018 as sourced from weather station W3E002, of the Department of Water and Sanitation.

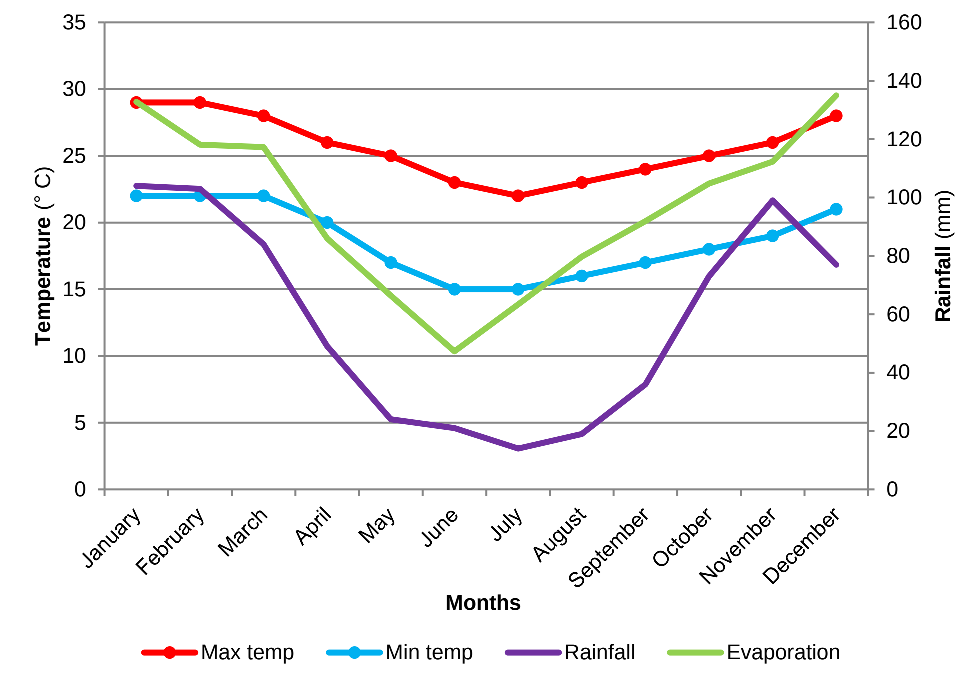

Figure 3.3: Graphical representation of the average weather at Phinda

Phinda also experiences high temperatures during the year with average temperature ranging from 20°C to higher than 22.5°C. It also receives more than 60%, on average, of daily sunshine on an annual basis.

A study by Conradie (2012), found that by using the Köppen-Geiger classification (Kottek *et al.*, 2006), South Africa could be more accurately divided into 30 climatic areas based on weather data (1985 to 2005) from the South African Weather Service. This climatic classification describes the area in which Phinda falls as fully humid warm temperate with hot summers and some areas being hot and arid (Conradie, 2012).

Climate (temperature and rainfall) plays an important role in the formation of soil, as it is one of the five soil forming factors. The other factors are organisms, parent material, time, relief, and topography (Foth, 1990).

3.2.2 Geology

The geology (Fig. 3.5) of the area is complex, as determined by geological maps of South Africa, from the Council for Geoscience (2019), and splits Phinda into three very general areas. The northern area, which is predominantly sandstone and siltstone, the middle area consisting of rhyolites and the southern, which consists of basic volcanic rock. The geology was used, alongside the above-mentioned rainfall, weather, land type maps and vegetation data, to assist in the DSM process.

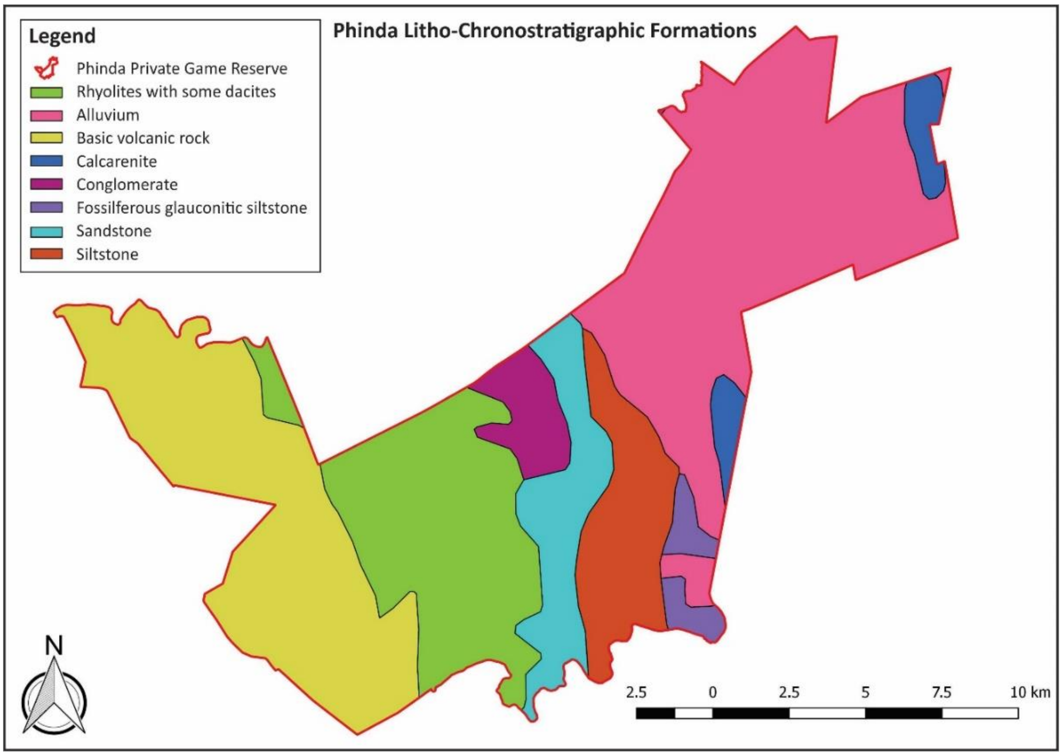

Figure 3.4: Phinda geological formations (Council for Geoscience, 2019)

Parent material is important as the soils present will inherit the characteristics of the rock from which it develops such as mineral composition, colour, structure and texture. The sandstone and siltstone found within the northern areas of Phinda generally weather into sandy and loamy soils with less clay content (Schaetzl and Thompson, 2015). The various volcanic rocks situated within the southern parts of Phinda generally weather into soils with a higher clay content, higher alkalinity and with different mineralogy (Bowles, 1984). The geology at Phinda was divided into three areas, namely: the northern area, which is predominantly sandstone and siltstone, the middle area consisting of rhyolites and the southern, which consists of basic volcanic rock (Fig. 3.5).

3.2.3 Soils

The following section describes the broad land types as determined by the Land Type Survey Staff. This survey was done from 1972 to 2006 whereby the soil forms of South Africa were mapped on a scale of 1:250 000. This scale was useful for dividing Phinda into homogenous areas for soil sampling (Section 4: Materials and Methods) but it was not useful for road planning as the scale was to small (not enough detail) and the soil forms too broad.

Based on the Land Type Survey Staff (1972-2006) land types of South Africa, Phinda was divided into 17 land types. These 17 land types were grouped into seven broad soil patterns:

- Ae: red and/ or yellow, freely drained soils are dominant, with red and/ or yellow soils making up more than 10% of the soil pattern. Mostly red soils, with yellow soils making up less than 10% of the broad soil pattern. The eutrophic properties are greater than that of the mesotrophic and dystrophic properties;
- Ah: red and/ or yellow, freely drained soils are dominant, with red and/ or yellow soils making up more than 10% of the soil pattern. The soils are usually sandy with less than 15% clay content. The eutrophic properties are greater than that of the mesotrophic and dystrophic properties;
- Ai: red and/ or yellow, freely drained soils are dominant, with red and/ or yellow soils making up more than 10% of the soil pattern. This soil pattern consists of mostly sandy, yellow soils (red soils less than 10%) with a clay content of less than 15%. The eutrophic properties are greater than that of the mesotrophic and dystrophic properties;
- Db: this soil pattern is made up of more than 50% duplex soils, consisting of non-red subsoils;
- Dc: as with the pattern above, this area is also made up of more than 50% duplex soils, but consists of less than 10% vertic, melanic and/ or red structure soils.
- Ea: dark, blocky clay soils (vertic and melanic topsoils) often with swelling clays and/ or red structured clay (>50%);
- Ib: consists of mostly rock (60 to 80%), usually with shallow and/ or rocky soils on steep slopes.

As seen from the seven broad soil patterns mentioned above, Phinda consists of various soil types/ forms and provides for an interesting study area. It was thus paramount that field observations are taken in all these land types as to assist with the mapping process. Figure 3.6 shows the seven broad soil types of Phinda (Land Type Survey Staff, 1972-2006), as mentioned within this section.

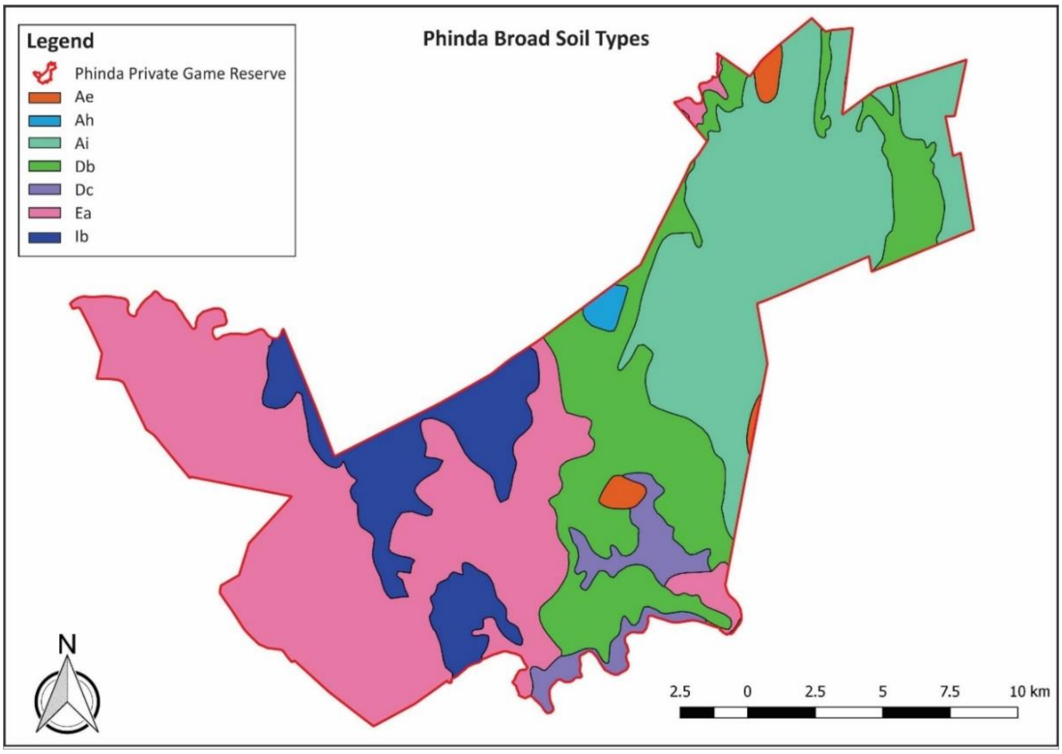

Figure 3.6: Broad soil types at Phinda (Land Type Survey Staff, 1976-2006)

Fey (2010) grouped the 73 soil classifications (Soil Classification Working Group, 1991) of South Africa into 14 groups as to improve their identification and description as well as provide a manner in which soils can be related to those of the World Reference Base for Soils, WRB (2015). According to Fey (2010), the following soils are present within the study area: oxidic (iron enriched soils), gleyic (soils with a G horizon), cumulic (accumulation of sand or clay through wind or water deposition), vertic (soils with a vertic A-horizon), melanic (soils with a melanic A-horizon), calcic (subsoils containing carbonates), plinthic (subsoils containing hard or soft plinthic material), lithic (lithocutanic B-horizon or hard rock), duplex (pedocutanic or prismacutanic B-horizon) and humic (soils with a humic A-horizon).

The grouping of the broad soil types as well as its use within the DSM process is described in more detail in Section 4.

3.2.4 Vegetation

Phinda is located in the bushveld (Savanna biome) of South Africa which also falls within the sub-humid climate region. The study area lies within the coastal plain of South Africa. A previous vegetation study conducted at Phinda (van Rooyen and Morgan, 2007) indicated the following vegetation types: palm veld, floodplain grasslands, sandveld woodlands, sand forest, mixed Lebombo woodlands, mixed acacia woodlands, bush clump thickets and mixed Zululand lowveld savannah (Fig. 3.7).

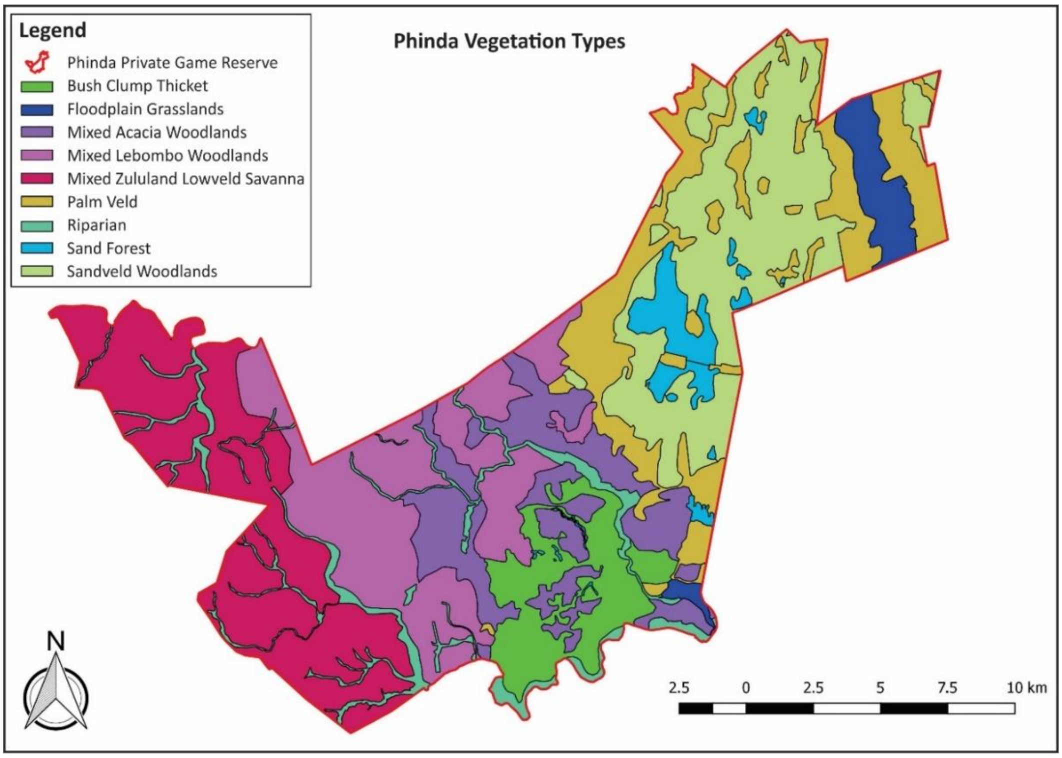

Figure 3.7: Phinda vegetation types (Van Rooyen and Morgan, 2007)

3.2.5 Topography

The study area was broadly divided into three topographical areas (Land Type Survey Staff, 1972-2006). These areas are as follows:

- The largest area consists of plains with low relief with slopes that are relatively straight. The relief ranges from 4 to 130 metres above sea level;

- The second largest topographical area has slightly undulating plains with low relief. The slopes in this area can be concave or convex with the relief ranging from 32 to 200 metres above sea level;
- The smallest topographical area within the study area consists of low mountains and closed hills with moderate and high relief. The slopes in this area can be concave, convex or straight with the relief ranging from 450 to 900 metres above sea level. Figure 3.8 indicates the three general topographical areas into which Phinda was divided.

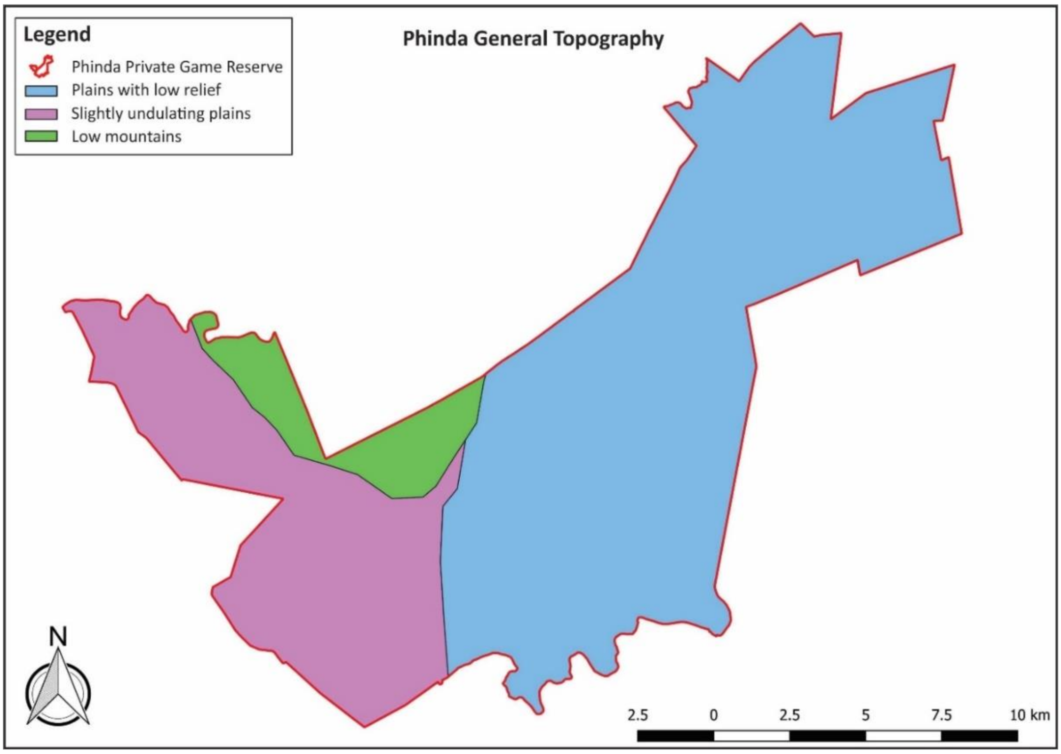

Figure 3.5: Broad topographical areas of Phinda (Land Type Survey Staff, 1976-2006)

The north-eastern parts of Phinda form part of the southern tip of the Lebombo Mountains, which is an 800 km long range stretching from the Limpopo province in the north of South Africa to Hluhluwe in Kwazulu Natal. The northern parts of Phinda were historically used for pineapple production (Varty and Buchanan, 1999), and were modified extensively by human activities. The eastern and south-eastern parts of Phinda forms part of drainage basin of the Munyawana river (this includes the associated floodplain) which flows into lake St. Lucia.

The Munywana, Mhlosinga and Mduna rivers flow through Phinda adding to the uniqueness of the study area. These rivers, as well as various spruits, dams and fountains create many wetland and riparian zones within the study area. The National Wetland Map 5 spatial datasets indicate the wetland ecosystem types of South Africa (sourced from the South African National Biodiversity Institute, SANBI, 2018) indicate that there is channelled-valley bottom-, seep, floodplain-, bench- and depression wetlands present within the Phinda boundary. This ensures that plenty of hydromorphic soils have also developed at Phinda.

Phinda, as described above, provided the perfect conditions for this study. Its size, more than 28 000 ha, complex history, past developments and extensive road network yields a challenge to mapping its soils. Combine this with the humid climate that influences the development of certain soils, varying geology, with a stark contrast between the northern and southern area, that leads to a wide range of possible soil forms. Adding to this is the wide range of vegetation types found within Phinda, this includes interesting occurrences such as the sand forests, and a topography that changes from a relatively flat area in the north of the study area to a mountainous southern area. All these conditions and challenges have been taken into account during the development of a digital soil map for Phinda.

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Chapter 4
METHODS AND MATERIALS

4.1 Site and sampling location selection

Research for this proposal makes use of both the qualitative and quantitative research techniques. A literature study was done and identified the most practical and cost-effective method of digital soil mapping (DSM). This method is based on research done by Zhu *et al.* (1997), Zhu *et al.* (2001), Zhu *et al.* (2007) and van Zijl (2013; 2018). Various materials and methods were used to determine the sampling locations, soil sampling and identification, the preparation of data and finally the modelling of information in the soil land inference model (SoLIM) to develop the digital soil maps.

The first step was to divide Phinda into homogenous areas (van Zijl, 2013). These areas can be delineated, based on geology, vegetation, topography or the land type survey areas. For the purpose of this study, the homogenous areas were selected based on the land type survey broad soil type areas (Fig. 3.6). The land type survey areas were used as it incorporates various topographies, catenae and slopes which are a proper representation of Phinda (Land Type Survey Staff, 1972-2006; van Zijl 2013; 2018). It was important that soil observations taken within these homogenous sampling areas must represent all the environmental variants as these was used as a base for the DSM process.

Once the homogenous areas have been delineated, the amount and location of soil observations were determined. Van Zijl (2013) suggests that a minimum of 25 observations (including seven validations observations) be taken to achieve an accurate as possible digital soil map. The location of these observations must consider the study area, as not all areas are accessible. Phinda, for example, has many densely vegetated areas in which soil observations couldn't be taken. The sampling locations (Fig. 4.1) within the various homogenous areas were chosen using two methods.

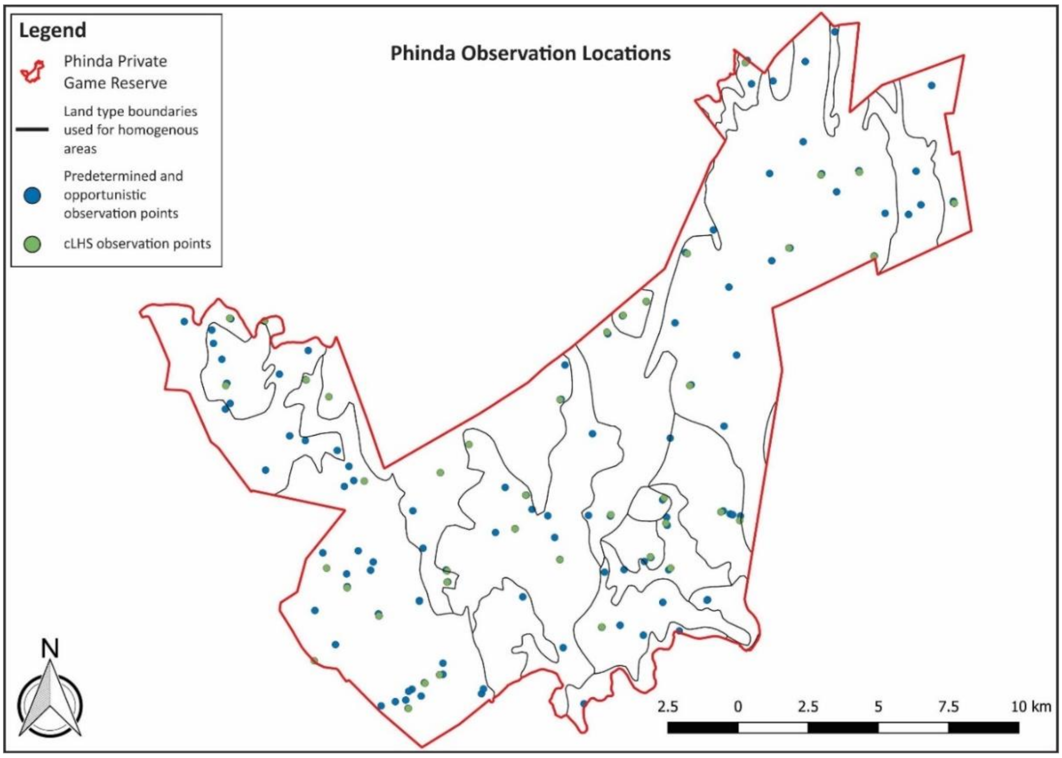

Figure 4.1: Soil observation locations at Phinda

Soil observation points were chosen at random (before the site visit) within the homogenous areas (van Zijl, 2013) to include all the topographic variations and ensure that soil observations were taken next to existing roads. Additional soil observations were taken at areas where natural soil profiles exist (streambeds, erosion gullies, dongas and other natural or manmade areas where the soil is exposed). Opportunistic soil observations were also taken during the site visits based on field observations. Because of the size of Phinda, access to various areas, and to ensure the effectiveness of this study, sampling was done in a minimalistic way, yet effectively (Zhu *et al.*, 2001). This minimalistic way of sampling is described in the following paragraph.

The second method consisted of the cLHS method. This method was used to determine the optimal sampling points within a study area that represents the multiple environmental covariates (Brungard and Boettinger, 2010). These sampling points then provide the necessary information that was used within SoLIM to infer the soil types. The cLHS is a type of stratified random sampling (sampling from a variable that can be divided into sub-variables, known as strata) that represents the variability of environmental covariates accurately within the study area (Phinda) (Brungard and Boettinger, 2010). The cLHS is derived from the concept of Latin hypercube sampling (LHS) where a sample is determined based on the covariates such that each variable is optimally stratified. Minasny and McBratney (2006a) then improved upon the LHS by adding the condition that the sample must be within the sampling area; it cannot be located in an area where the represented data does not exist. Minasny and McBratney (2006b) demonstrated that cLHS is the most accurate method of determining sampling point which encapsulates the environmental co-variates. Figure 4.2 indicates the concept of LHS.

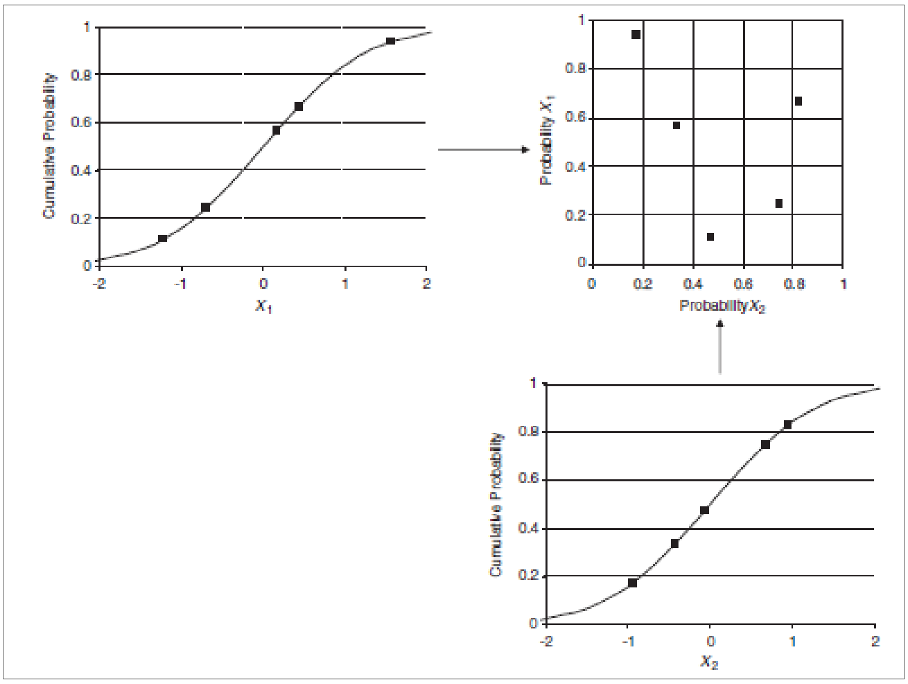

Figure 4.2: LHS point selection (Minasny and McBratney, 2006a)

4.2 Sampling and soil form identification procedure

Once the soil observation locations have been determined, the soil observations were taken at Phinda. The coordinates of the sampling sites were entered to a GPS to locate their position. Fieldwork forms an important part of DSM, as a map cannot be extrapolated without field observations (Zhu *et al.,* 1997).

Hand augers (both bucket- and open- augers) were used to drill to refusal or a depth of 1.5 m, whichever came first (Soil Classification Working Group, 1991), to identify the underlying soil horizons. These soil horizons were then identified based on the South African Soil Classification System (Soil Classification Working Group, 1991). Soil horizons that were not identified according to this System was described per horizon and grouped with similar soil form. This was done as not all of the soils found in South Africa are described within the South African Soil Classification System and these unknown soil forms are then grouped to soil forms with similar horizon characteristics. All soil observations were noted on a field data sheet, which identifies the soil forms, describes the horizons, depth of horizons, clay content and other relevant information. A GPS location was taken at every sampling point to correlate the position with the predicted position as well as to ensure an as accurate map as possible. As mentioned above, any natural erosion trench, exposed soil, rocky outcrops etc. which can be used in the identification of soil forms and boundaries can were used and was captured (with a GPS coordinate) as to be used in the extrapolation and digitizing process. It is important to remember that the information gathered during fieldwork must be task specific, as gathering unnecessary information can be time consuming and financially impractical (McBratney *et al.*, 2003). Figure 4.1 indicates the identified sampling points, cLHS observation points as well as the points of opportunity taken during the site visits.

4.3 Data preparation

The final step was to create the digital soil map (van Zijl *et al.*, 2012; van Zijl *et al.*, 2013; van Zijl *et al.*, 2014) for Phinda using the field data collected as well as other sources of digital information. This digital soil map was created using software such as SoLIM. SoLIM extrapolates a digital soil map based on the information entered into it; this information includes a DEM of Phinda, previous soil studies, the underlying geology of the area, topography, the land type surveys as well as the field soil observations. SoLIM is discussed in detail in Section 4.4. The paragraphs that follow describe the digital information that was used for creating the soil maps of Phinda as well as the preparation of this data.

The first digital source of information required was a DEM. The DEM used was sourced from the Earth Explorer website using the SRTM 1 Arc - Second Global Dataset. The Shuttle Radar Topography Mission (SRTM) was flown abroad the space shuttle Endeavour between 11 and 22 February, 2000. The purpose of this mission was to collect topographical data to create a DEM of more than 80% of the earth's land surface. These datasets were collected at 30 m resolutions, making it one of the highest qualities, free of charge DEMs available. A site-specific portion of the above-mentioned DEM could be run through Geographic Information Systems (GIS) such as Quantum Geographic Information System (QGIS) (open-source software from the QGIS), to create a DEM of Phinda. The values obtained from the generated DEM indicate the height above sea level in metres and is an important tool for DSM. Not only for SoLIM, but other covariates can be generated within SAGA using the DEM such as slope, topographic wetness index and valley depth. A basic terrain analysis algorithm, as developed by the SAGA (open-source software), uses a DEM to generate the previously mentioned slope, topographic wetness index and valley depth. The results obtained from SAGA is discussed in greater detail in this Section. Figure 4.3 indicates the DEM that was generated for Phinda using QGIS.

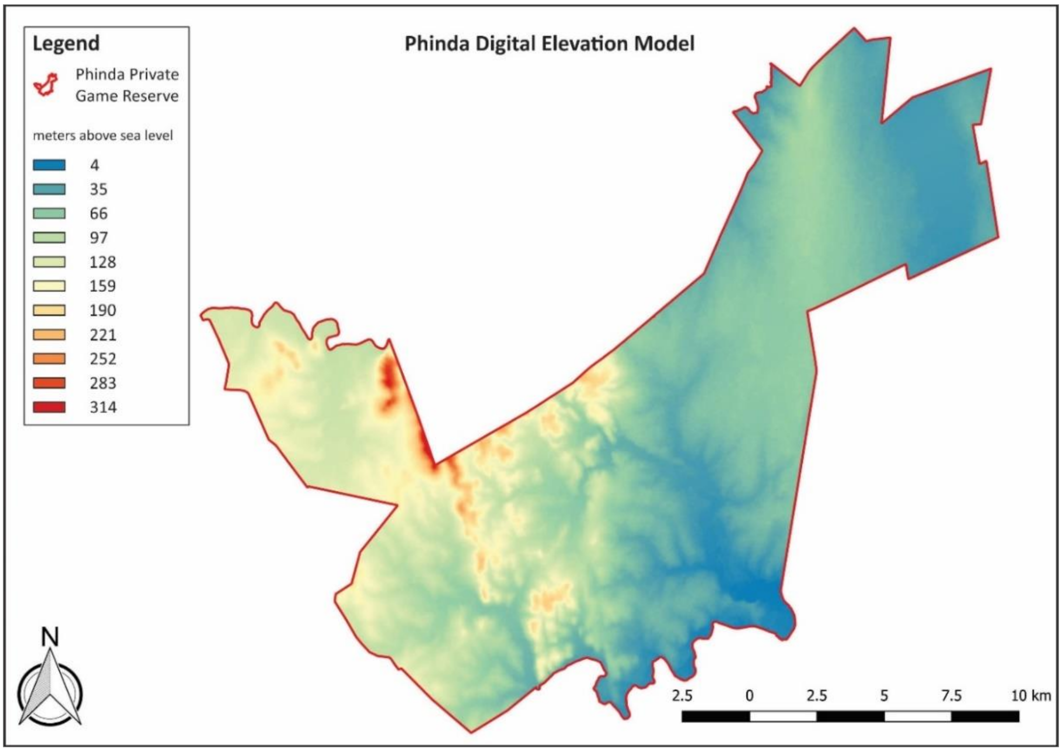

Figure 4.3: DEM of Phinda

Before the DEM was exported from QGIS, it was re-projected. Firstly, a projection is a visual representation of a curved surface, planet earth in this instance, on a flat surface with the use of coordinate lines (intersecting lines of latitude and longitude) for mapping purposes (Lapaine and Frančula, 2016). There are three main projections that are used in cartography. Because digital information is sourced from various sources, they are in different projections. It was thus important to re-project them into the same projection. By projecting all the digital information into a single projection (as a GIS application cannot compare information which is in different projections), information was extracted, compared, combined, etc., using various GIS applications.

Once the digital spatial information, most importantly the DEM, has been re-projected the next step commences. The DEM was exported from QGIS as a geotiff file. Another GIS application, named SAGA (as mentioned above), is used to run a Basic Terrain Analysis using the DEM generated in QGIS. SAGA was developed at the Department of Physical Geography, University of Göttingen, Germany for editing spatial data. Basic Terrain Analysis is one of the core functions of SAGA that generates 16 hydrological and terrain metric outputs (Böhner *et al.*, 2006) based on the DEM. Table 4.1 indicates the hydrological and terrain metric outputs that were used for the DSM process (Zhu *et al.*, 2001) with a short description of each. Figure 4.4 indicates the difference (visually) between plan- and profile curvature. Whereas Fig. 4.5 represents a graphical illustration of each output from the descriptions in Table 4.1.

Table 4.1: SAGA hydrological and terrain metric outputs (Böhner et al., 2006)

Output	Description
Slope gradient	Measure of steepness or the degree of inclination of a feature relative to the horizontal plane.
Slope aspect	Compass direction that a slope is facing (north, east, south and west).
Plan curvature	Plan curvature: expresses the rate of change of aspect along a contour, it is the differentiation of hillslopes/valleys and ridges/summits.
Profile curvature	Profile curvature: differentiates between convex (slope increasing downhill) and concave (slope decreasing downhill) slope profiles.
Topographic wetness index	Used to quantify topographic control on hydrological processes. Indicates where water will accumulate in the terrain.
Valley depth	Indicates the vertical distance to a channel network base level from the highest points within the area.

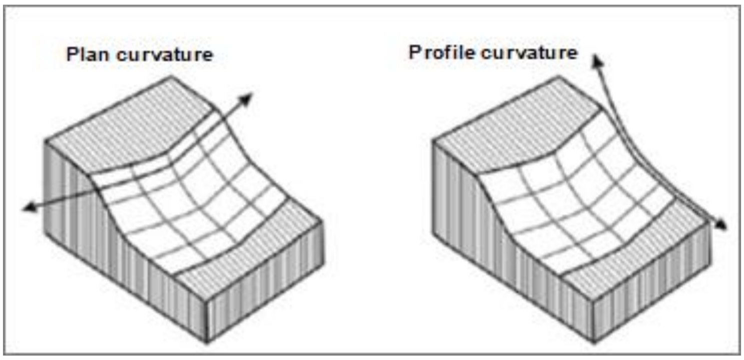

Figure 4.4: Plan- vs. profile- curvature (SAGA, n.d.)

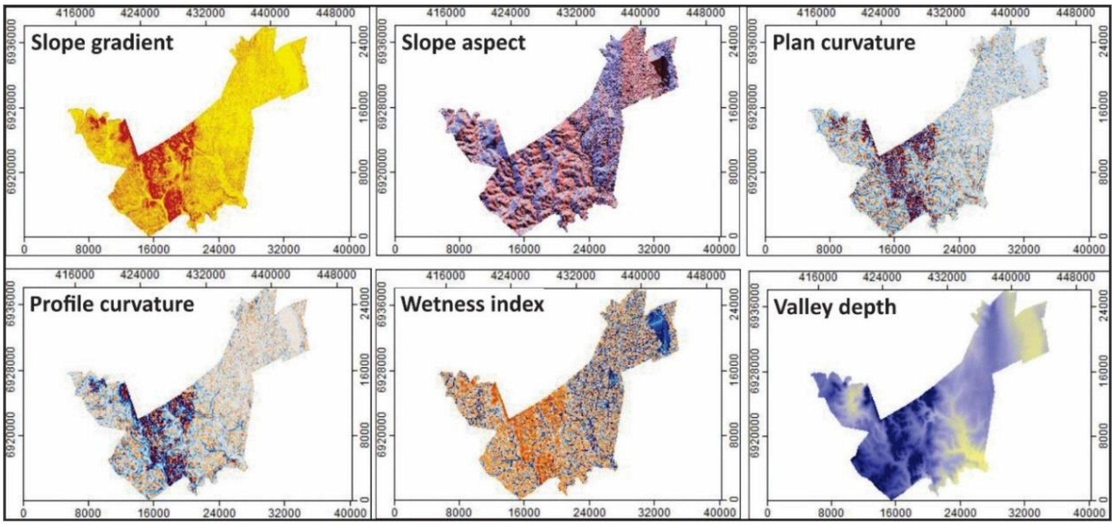

Figure 4.5: SAGA hydrological and terrain metric outputs

These various outputs are important for the digital mapping process, as soil does not appear randomly within the landscape. Each soil type and its location are based on the environmental factors, which formed the specific soil type. Slopes with a steeper gradient will produce more rocky soils whereas low lying; shallow gradient slopes will produce deeper, higher in clay content soils. Wetter areas, as determined by the topographic wetness index, will allow the development of hydromorphic soils with its unique characteristics. Thus, each hydrological and terrain metric output is useful for the DSM process as it describes the study area in various details that can be missed during normal soil mapping. Combining this information with field data observations, geology, vegetation and the land type surveys ensures that accurate digital soil maps are generated at a much lower cost of time and money.

Additional environmental covariates that are used are acquired from LANDSAT images (from the Earth Explorer), which indicate pixels with various colour bands (Table 4.2). Each colour indicates a different set of environmental information and was then combined to produces various instances (Flynn *et al.*, 2019). These derived spectral indices are provided in Table 4.3, and are used to develop the soil landscape rules.

Table 4.2: Colour bands (Flynn et al., 2019)

Band number	**Band name**	**Band origin** (um)	**Band designation**
2	Blue	0.490	B
3	Green	0.560	G
8	Near infrared	0.842	NIR
4	Red	0.665	R

Table 4.3: Spectral indices (Flynn et al., 2019)

Indices	**Equation**	**Property**
Brightness index (BI)	$(R^2 + G^2 + B^2) / 30.5$	Reflectance
Colouration index (CI)	$(R - G) / (R + G)$	Soil colour
Normalized difference vegetation index (NDVI)	$(NIR - R) / (NIR + R)$	Chlorophyll
Redness index (RI)	$R^2 / (B \times G^3)$	Hematite
Saturation index (SI)	$(R - B) / (R + B)$	Spectral slope

After running the basic terrain analysis, spectral indices grid calculations, hydrological and terrain metric outputs are exported from SAGA in ascii format. These files are then imported into QGIS, and layered on top of each other. The sampling positions are then added and layered on top of various covariates. The DEM, slope gradient and aspect, plan and profile curvature, wetness index, valley depth, and various spectral indices (BI, CI, NDVI, RI and SI) are all raster files. This means that the metric output was divided into cells (30 m x 30 m) which makes up the raster file. Every cell has a value, which was extracted and added to the sampling points. This was done by running a SAGA algorithm found within QGIS, where each sampling point was given the various values of the cell in which it as located. Thus, every covariate layer, with its various cells, on which a sampling point falls, gets the value of that cell. The combination of information was then saved in Microsoft Excel work-sheet or comma separated value format (CSV), the latter being the preferred option as this file was imported into SoLIM at a later stage.

The final step was to convert all the required covariates into a format that SoLIM understands (Zhu *et al.*, 2007; van Zijl, 2013). This was done through a tool within SoLIM that converts GDAL supported raster formats (including ascii) and shape files into 3dr files.

4.3.1 Grouping soils to assist with mapping and developing SSI

Due to the size and variations in topography, vegetation and land type surveys, it was decided to divide Phinda based on grouping of the broad land types (Zhu *et al.*, 1997; Zhu *et al.*, 2001; van Zijl and Botha, 2016). Figure 3.6 and Section 3.2.3, indicate the broad land types that make up Phinda (Land Type Survey Staff, 1972-2006).

The seven broad land types were then dissolved into four groups/ areas based on their similarity and was used as boundaries for the soil mapping process in SoLIM and SAGA. Broad land types are effective and practical to use as the land survey staff originally grouped areas within the landscape based on similar properties. For the purpose of this study the broad land types were dissolved as follow: For Area 1 the smaller Ae land types were dissolved into the larger Ai land type as both consist of oxidic soils (soil forms with a red/ yellow subsoil) (Fey, 2010a; 2010b). Broad land types Ah, Ae, and Dc were dissolved into the larger Db to form Area 2. The large Ea land type (Area 3) was kept unchanged as it predominantly consists of clay topsoil of the vertic and melanic soil form. The Ib land type (Area 4) was also unchanged as the steep slopes of the area lead to the formation of shallow soil forms (Land Type Survey Staff, 1972-2006).

Figure 4.6 indicates the original broad land types (image on the left) of Phinda whereas the image on the right indicates the combined/ dissolved land types into the four groups/ areas as discussed above.

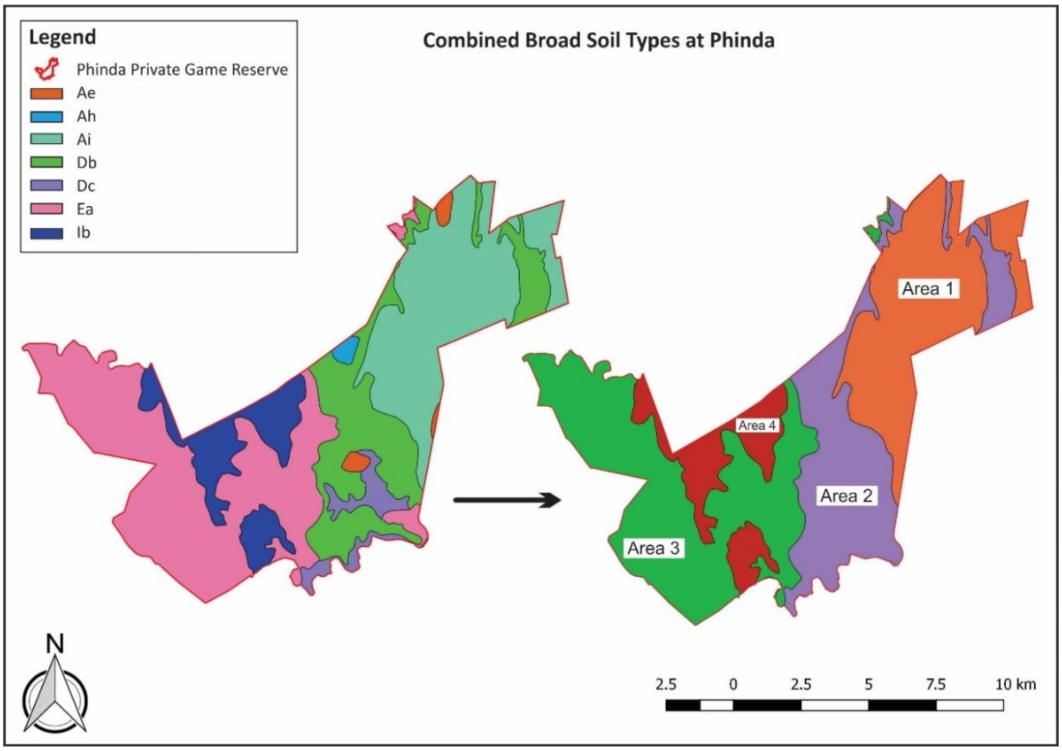

Figure 4.6: Grouped broad land types at Phinda

As the main purpose of this research was to apply DSM to Phinda and allow it to be recreated and applied to other nature- and game reserves, the outcome was very important. The main outcome was to develop a soil map that indicates the sensitivity of the soils found at Phinda as to manage and update their extensive road network. These sensitivities indicate how stable a specific soil is and how easily it can erode through the movement of water once the natural vegetation has been removed. The sensitivity to compaction of soil is also important as ORD takes place regularly at game- and nature reserves (Nortjé, 2017; Nortjé and Nortjé, 2017). Soil sensitivity will also indicate how easily a soil can be compacted and how resilient it is towards the various impacts. Once the soil sensitivity map has been developed, various other covariates can be overlain upon soil sensitivity to assist decision makers. The SSI was developed for Phinda taking into account the geology, soil horizons identified, soil particles sizes and concentrations and topography specific to Phinda (as based on a literature study and conditions at Phinda). The soils identified were divided into five soil sensitivity groups ranging from low (1) to very high (5) and are indicated in Table 4.4. In Table 4.5, the Fey (2010a) groupings are compared to the World Reference Base for Soil Resources (WRB, 2015) which is used in many countries around the world.

Table 4.4: SSI of soil forms identified at Phinda

Soil forms	Sensitivity to erosion
Shortlands	1 (low)
Hutton	2 (moderate)
Arcadia, Avalon, Bainsvlei, Bloemdal, Immerpan, Inhoek, Kimberley, Mayo, Nomanci, Pinedene and Rensburg	3 (medium)
Clovelly, Dresden, Katspruit, Vilafontes and Westleigh	4 (high)
Bonheim, Brandvlei, Escourt, Fernwood, Glenrosa, Longlands, Mispah, Namib, Oakleaf, Sepane, Steendal, Sterkspruit, Swartland and Valsrivier	5 (very high)

Table 4.5: Soil-grouping and WRB comparisons (Fey, 2010a)

Soil forms	Description of diagnostic horizon	Fey classification	WRB classification
Brandvlei	Sepiolite or amorphous silica that causes cementation.	Calcic	Calcisols, Gypsisols, Luvisols and Lixisols
Escourt, Fernwood, Longlands, Namib, Oakleaf and Vilafontes,	Soil formations that are developing in aeolian, alluvial and colluvial sediments.	Cumulic	Cambisols, Arenosols, Fluvisols, Luvisols, Acrisols and Lixisols
Sepane, Swartland and Valsrivier	Soils horizons with a contrast in texture due to the enrichment of clay.	Duplex	Planosols, Solonetz, Luvisols, Albeluvisols and Lixisols
Katspruit	Saturated soils that result in prolonged reduction.	Gleyic	Gleysols, Stagnosols and Planosols
Nomanci	A horizon, which is enriched with humus, has a low base status and drains freely.	Humic	Umbrisols, Ferralsols, Acrisols, Luvisols, Lixisols and Cambisols
Glenrosa, Mayo and Mispah	Young, developing soils formed upon saprolite or weathering rock.	Lithic	Leptosols, Cambisols, Acrisols and Lixisols
Bonheim, Immerpan, Inhoek and Steendal	Humic A horizon, contains dark, structured clay.	Melanic	Chernozems, Umbrisols, Gleysols, Phaeozems, Kastanozems, Luvisols, Calcisols, Leptosols and Fluvisols
Avalon, Bainsvlei, Bloemdal, Clovelly, Hutton, Kimberley, Pinedene and Shortlands	Red and yellow soils, which indicates iron enriched soils.	Oxidic	Acrisols, Alisols, Ferralsols, Luvisols, Lixisols, Arenosols, Cambisols and Nitisols
Dresden and Westleigh	High densities of iron enrichment, mottling or cementation occur due to hydromorphic segregation.	Plinthic	Plinthosols, Ferralsols, Acrisols, Stagnosols, Lixisols and Arenosols
Arcadia and Rensburg	Contains a high percentage of cracking and swelling clay, slick and sides.	Vertic	Vertisols, Gleysols and Phaeozems

4.4 SoLIM modelling

By providing SoLIM with rules based on the information entered, it combines and infers information to create the digital soil map. The rules that were developed and applied within SoLIM are based on the training data information (training data observations combined with the various raster layers from the resulting basic terrain analysis). The purpose of the map was important as this will determine the rules written for SoLIM. Using the two groupings, soil sensitivity and the Fey (2010a) classification, as described in the above section, similarities are developed as to compile the digital soil map and infer data onto pixels without field observations. SoLIM uses these rules and applies it to the entire study area, which then generates a digital soil map. After inferring the rules within SoLIM to determine the location of the various soil forms and soil sensitivities, the maps were hardened within SoLIM. Hardening of a map is the process whereby each pixel was given the value of the soil form or soil sensitivity that indicated the highest membership with that specific pixel (Zhu *et al.*, 1997; van Zijl, 2013).

The initial raster maps (Fey classification and soil sensitivity grouping, 2010a) were inferred using the rules entered in SoLIM. These rules were based on the various covariates extracted from the basic terrain analysis and combined with the sampling points. The main covariates used for developing the rules were depth to valley bottom and terrain wetness index with the boundaries determined by the combined broad land types. Before the sampling points were combined with the covariate layers, 25% of the points were removed at random and were used as validation points within the accuracy matrix (van Zijl, 2013). Rules were written for each soil group based on the Fey classification as well as the SSI that was developed. After inferring the rules within SoLIM to determine the location of the various soil forms and soil sensitivities, the maps were hardened within SoLIM. Hardening of a map is the process whereby each pixel is given the value of the soil form or soil sensitivity that indicated the highest membership with that specific pixel (Zhu *et al*., 1997; van Zijl, 2013).

4.5 Determination of the accuracy matrix and kappa coefficient

Once the validation observations mentioned earlier, as well as the training data were done, they were then used to determine the accuracy of the digital soil map. These observations are compared to the inferred digital soil map to indicate how accurately SoLIM extrapolated the relative information. The aim was to reach an accuracy of 70% and higher (van Zijl, 2013). For this study, two methods were used to determine the accuracy of both the Fey classification and soil sensitivity maps. The first method was to make of use of an accuracy matrix (Zhu *et al.,* 1997; van Zijl, 2013; van Zijl *et al.*, 2019) with the second method the use of the kappa coefficient (van Zijl *et al.,* 2019; Næsset, 1996; Rossiter, 2014; McHugh, 2012; Viera and Garrett, 2005). Both methods are discussed in detail under Section 5.2.

After the maps have been inferred and hardened within SoLIM, the accuracy thereof was determined (Zhu, 1997; van Zijl, 2013; van Zijl *et al.*, 2019). Determining the accuracy of the digital soil maps will assist the assessor in evaluating whether the maps are usable or whether adjustments to the rules within SoLIM was required. This was done to ensure an as accurate and practical map as possible. For this study, two methods were used to determine the accuracy of the various soil maps. The resulting values that were for determining the accuracy are the training data observations and validation point observations (van Zijl, 2013; van Zijl *et al.*, 2014; Zhu *et al.*, 2001). Both the training data observations and validation point observations were taken during the same site visits but used for different purposes. It was determined that 25% of the validation point observations were selected randomly and removed from the rule writing process. Only the training data observations are used for the purpose of rule writing within SoLIM and the consequent inference of the soil map units to produce the various soil maps (van Zijl, 2013). Thus, accuracy was tested based on the final soil map in comparison with the training data observations and the validation point observations separately. This was executed for the Fey classification map and the soil sensitivity map. Four datasets (two training data observations and two validation point observations) were used to determine the accuracy.

The first method to determine the accuracy was the accuracy matrix (Zhu *et al.,* 2001; van Zijl *et al.*, 2019). The accuracy within the accuracy matrix was calculated based on the percentage of correctly predicted observations for both the training data observations and the validation point observations for the Fey classification and the soil sensitivity maps (van Zijl *et al.*, 2014). The accuracy matrix thus assesses the performance of an algorithm (in this instance the rules written within SoLIM). The accuracy matrix was divided into rows and columns where each row (labelled observations) represents the instances of the actual class (either the training data observation or the validation point observations) and each column (labelled map units) represents the predicted instances (which will either be the Fey classification or the SSI) (Powers, 2011; Næsset, 1996). It was then possible to determine the percentage of correctly predicted instances compared to incorrectly predicted (or confused) instances. The diagonal within the accuracy matrix indicates the correctly predicted instances. Because the validation point observations were not incorporated into the rule writing process, their accuracy carries more weight as it reveals the certainty by which the algorithm was developed (Zhu, 1997). Marsman and de Gruijter (1986) determined that the accuracy of a traditional soil map was around 65%, thus achieving a map accuracy based on the accuracy matrix of 65% or higher was acceptable (van Zijl, 2013).

4.6 The application of DSM at Phinda

The final digital soil map was then used in combination with other GIS programmes such as QGIS and Google Earth as it provides a visual and geospatial representation of the data. Using the digital soil map as a base layer, other datasets, such as roads, vegetation and planned development can be overlaid over the soil information which will assist decision makers. Combining this information will ensure that eco-friendly tourism can continue at Phinda, and provide a baseline from which Phinda can update their road network as well as conserve their soils (Nortjé, 2017; Nortjé and Nortjé, 2017).

Phinda has provided the population estimates (from 2011 to 2018) of large mammals within the game reserve. These population estimates include heat maps of animal sightings (conducted through helicopter transects flown over the reserve and driving within certain areas) as well as the percentage of animals within the various vegetation types/ habitats. A summary of the percentage of animals (this table will only include elephants, giraffes, buffalo, wildebeest and hippos) within the various vegetation types/ habitats are given in Table 4.6. Due to the nature and seriousness of rhino poaching, no rhino sighting or relevant information was used within this dissertation. The green highlighted cells in Table 4.6 indicate the vegetation types/ habitats in which the largest percentage of the specific animal was located during the population estimates (2011 to 2018). The Mixed Acacia Woodland vegetation type/ habitat also show the greatest average percentage of animal species located within it. This information was incorporated into the final mapping procedure to establish which roads are important to reach the vegetation types/ habitats where these animals are situated.

Table **4.6:** Animal percentages within vegetation types/ habitats (Phinda population estimates, 2011-2018)

	Vegetation types/habitats (%)								
Animals	Bush Clump Thicket	Floodplain Grassland	Mixed Acacia Woodland	Mixed Lebombo Woodland	Mixed Zululand Lowveld Savanna	Palm Veld	Riparian	Sand Forest	Sandveld Woodland
Buffalos	14.4	10.7	14.2	23.9	21.5	19.3	1.5	0	3.5
Elephants	13.7	11.9	20.2	4.4	7.1	16.1	14.5	6.6	44.7
Giraffes	13	6.4	16.7	26.2	11.8	15.8	5.1	1.4	7.2
Hippos	24.7	0	29.4	28	3.4	34.1	36.3	0	0
Wildebeest	7.5	20.3	25.3	12.1	16.8	14.2	3.1	0.1	2.4
Average Total	14.7	9.9	21.2	18.9	12.1	19.9	12.1	1.6	11.6

Most importantly, predator sightings (2 to 5 years of population estimates), was combined with the SSI as game guides will drive off-road especially for big predators. The average area where predators have been sighted was given a 2.5 km radius and all roads within that area was identified (Nortjé, 2019; Nortjé and Mearns, 2017). The same was done for commercial lodges as these are the areas where the highest traffic volume occurs and the highest potential for ORD. Even though 2.5 km is a short distance relative to driving on a freeway, it can become a long distance when driving slowly within a game reserve in search of animals. The roads were also divided into groups (Nortjé, 2019) to make the management thereof easier (Table 4.7).

Table 4.7: Definition of road categories (Nortjé, 2019)

Road Category				
Class	**A**	**B**	**C**	**D**
Description	- road that link important areas, such as the main district roads that run from entrance to entrance, and roads to the main tourist lodges.	- roads that can be used in all-weather conditions, these roads connect maintenance infrastructure, research housing, staff accommodation and regularly visited areas to the main roads; - popular game drive roads also fall within this category.	- all-weather roads that are lightly trafficked, used for monitoring, patrolling, game drives and as ring roads.	- roads that are lightly trafficked, two road tracks that link various category C and D roads together; - many of these roads are overgrown.
Importance/ Usage	- these roads are very important and used regularly by tourists and staff alike.	- these roads are important and used regularly; - due to the users of this road, it is placed within category B.	- these roads are less important, and used only as needed; - some of these roads are used on a daily basis.	- little importance, only used when required by individuals other that reserve staff.

Additional information obtained from Phinda, which was layered together for the final road management recommendations (Chapter 7), will include game drive heat maps, the location of lodges, reserve infrastructure, maintenance areas and other areas where access is a necessity. Additionally, the average game drive length, time and speed can be included to assist with road management and planning.

By applying DSM to Phinda, and developing an effective and accurate method of mapping game reserves much more can be done for the protection and conservation of soil. Soil, as mentioned earlier, is a non-renewable resource that influences every aspect of our life. Everything from our food, minerals to medicines and clothing either comes from, or is dependent on the soil. It was thus important to develop a method of mapping, and then mapping the soils of protected areas as to protect this natural resource.

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Chapter 5
RESULTS

5.1 Initial raster maps from SoLIM

Figures 5.1 and 5.2 indicate the initial results of the Fey (2010a) soil classification and Soil Sensitivity Index (SSI) groupings, respectively from SoLIM after the rules were inferred and the maps were hardened.

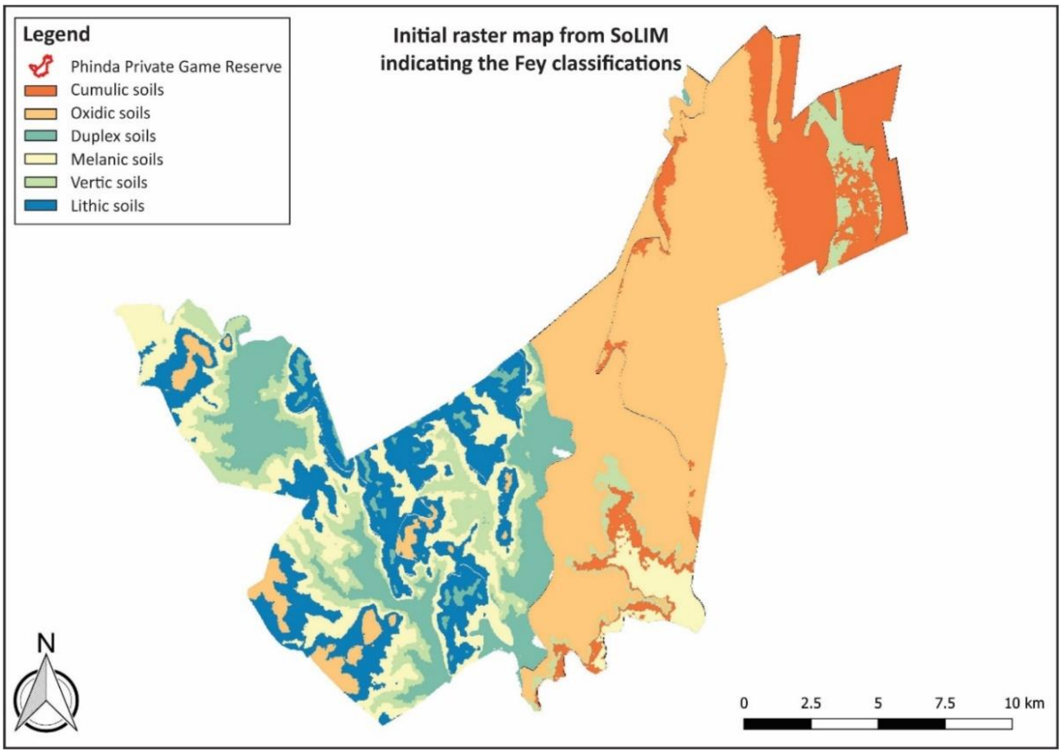

Figure 5.1: Fey soil classification (2010a) from SoLIM

As in Fig. 5.1, the soil sensitive map generated from SoLIM also indicated various areas and pixels with the pixelated affect (Fig. 5.2). These outliers were removed during the creation of the final soil sensitivity map. Unlike the Fey classification map, no soil forms were removed from the rule writing process as the SSI (as described in Section 4.6) groups the identified soil forms based on other characteristics. As with the Fey classification map, the northern area of Phinda consists of less sensitive soils due to the shallow slopes, iron containing sandy soils and the presence of free irons in the apedal B-horizons. These free irons within the apedal B-horizon ensure a stronger bond between soil particles and decrease its sensitivity to erosion (van der Merwe *et al.*, 2001; Soil Classifications Working Group, 1991). The southern area, with different geological formations and thus parent material, which, in the case of Phinda, led to the development of a higher percentage of clayey soils (Sumner, 1957; Stern, 1990; van der Merwe *et al.*, 2001) and steeper slopes produced soils, which have a higher affinity to erosion. The blue areas within Fig. 5.2 indicate moderately stable soils. The only soil form identified at Phinda that fell within this grouping was the Shortlands soil form. The stability and resistance to erosion of the Shortlands soil form is due to the high iron within the red structured B-horizon (Soil Classifications Working Group, 1991) as well as the high clay content within the B-horizon (which gives it the characteristic structured B-horizon).

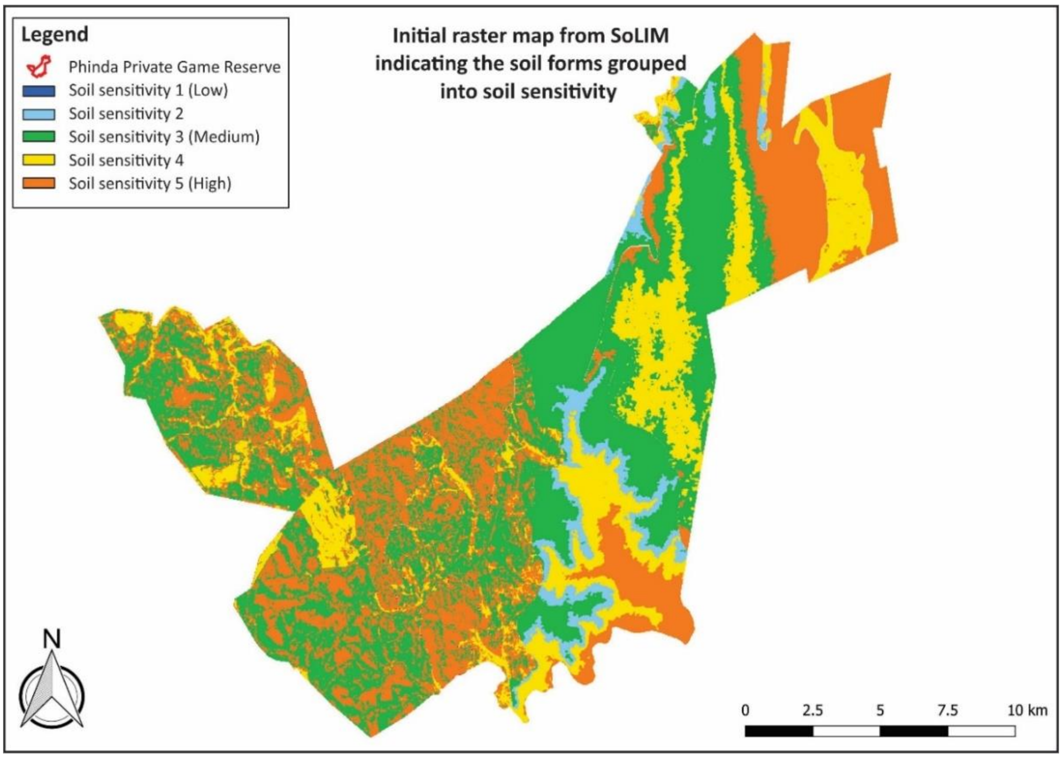

Figure 5.2: SSI grouping from SoLIM

5.2 Accuracy matrix and kappa coefficient

Tables 5.1 and 5.2 indicate the accuracy of the Fey soil classification for training data observations and validation point observations, respectively. The training data observations achieved a good accuracy of 71% whereas the validation point observations also achieved a good accuracy of 70%.

Table 5.1: Accuracy matrix for Fey soil classification (2010a) (training data)

		User (map units)								
		Cumulic	Oxidic	Melanic	Vertic	Duplex	Lithic	Correct	Total	%
Producer (observations)	Cumulic	**7**	2	-	-	-	-	7	9	78
	Oxidic	2	**29**	1	-	2	2	29	36	81
	Melanic	-	2	**11**	2	2	1	11	18	61
	Vertic	-	-	1	**6**	1	2	6	10	60
	Duplex	-	-	4	-	**5**	-	5	9	56
	Lithic	-	-	1	-	1	7	7	9	78
	Correct	7	29	11	6	5	7	**65**	-	-
	Total	9	33	18	8	11	12	-	**91**	--
	%	78	88	61	75	45	58	-	-	**71**

Table 5.2: Accuracy matrix for Fey soil classification (2010a) (validation points)

		User (map units)								
		Cumulic	Oxidic	Melanic	Vertic	Duplex	Lithic	Correct	Total	%
Producer (observations)	Cumulic	**2**	3	1	-	-	-	2	6	33
	Oxidic	1	**7**	-	1	-	-	7	9	78
	Melanic	-	-	**6**	1	-	1	6	8	75
	Vertic	-	-	-	**2**	-	-	2	2	100
	Duplex	-	-	1	1	3	-	3	5	60
	Lithic	-	-	-	-	-	**3**	3	3	100
	Correct	2	7	6	2	3	3	**23**	**-**	-
	Total	3	10	8	5	3	4	**-**	**33**	-
	%	67	70	75	40	100	75	-	-	**70**

Tables 5.3 and 5.4 indicate the accuracy of the soil sensitivity maps for training data observations and the validation point observations, respectively. The training data observations achieved a very good accuracy of 72%. The validation point accuracy was below the acceptable limit with an accuracy of 69%. Even though this accuracy of the validation point observations are below the acceptable limit (van Zijl, 2013) it was incorporated into the final map as the observations of both the training data observations and the validation point observations were given a one pixel buffer to ensure an as realistic as possible soil map (van Zijl *et al.*, 2014). This one-pixel buffer was applied to both the final soil maps (Fey classification and SSI map). A

difference in accuracy between training data observations and validation point observations was normal.

Table 5.3: Accuracy matrix for soil sensitivity map (training data)

		User (map units)						
		SS 2	SS 3	SS 4	SS 5	Correct	Total	%
Producer (observations)	SS 2	2	-	1	-	2	3	67
	SS 3	2	**29**	5	4	29	40	73
	SS 4	-	3	**8**	2	8	13	62
	SS 5	1	5	2	**26**	26	34	76
	Correct	2	29	8	26	**65**	-	-
	Total	5	37	16	32	-	**90**	-
	%	40	78	50	81	-	-	**72**

Table 5.4: Accuracy matrix for soil sensitivity map (validation points)

		User (map units)						
		SS 2	SS 3	SS 4	SS 5	Correct	Total	%
Producer (observations)	SS 2	1	-	-	-	1	1	100
	SS 3	-	**10**	-	3	10	13	77
	SS 4	-	2	**2**	1	2	5	40
	SS 5	-	3	2	**12**	12	17	71
	Correct	1	10	2	12	**25**	-	-
	Total	1	15	4	16	-	**36**	-
	%	100	67	50	75	-	-	**69**

The second method used to determine the accuracy of the maps was the kappa coefficient (van Zijl, 2018; van Zijl *et al.*, 2019). The kappa coefficient is a statistical measure used to determine the inter-soil dependability between two or more qualitative units (McHugh, 2012). Kappa coefficient was implemented to measure if the Fey classification map and soil sensitivity map represents reality accurately. The values of the kappa coefficient range from 0 to 1. When the calculated outcome (value) is high (thus closer to 1) it indicates a map that constitutes reality better. When the calculated outcome (value) is low (thus closer to 0) the opposite is true. This then constitutes a map that is prone to assigning pixels with random values (Grinand *et al.*, 2008). The kappa value takes the both the agreement and randomness (Viera and Garrett, 2005) of the information into account. It is expressed in the formula below:

1) Kappa (K) = $\frac{Po\text{-}Pe}{1\text{-}Pe}$

Where P_o = the observed agreement. The observed agreement indicates the observations where the instances were predicted correctly. The green highlighted cells in Table 5.5. This gives us an observed agreement of 0.75 ($P_o = \frac{\text{Total correlated observations}}{\text{Total samples}}$).

Table 5.5: Hypothetical matrix

Soils	Soil A	Soil B	Total
Soil A	60	10	70
Soil B	5	25	30
Total	65	35	100

Where P_e = expected agreement. The expected agreement then considers the random correlations into account by using the following formula:

2) $P_e = \frac{1}{N^2}\sum_k n_{k1}\, n_{k2}$

This formula can be simplified to:

3) $P_e = \left(\frac{n1}{total} \times \frac{n2}{total}\right) + \left(\frac{n3}{total} \times \frac{n4}{total}\right) + \ldots$

Where n_1 and n_2 represents both the totals of Soil A (orange highlighted cells within Table 5.5) and n_3 and n_4 represents both the totals of Soil B (blue highlighted cells within Table 5.5). The total is represented by the total amount of observations, which were 100 in this instance. The simplified P_e formula can be extended based on the amount of observations (Rossiter, 2014). This then equals an expected agreement of 0.57 (rounded off to the second decimal).

By substituting the values into Formula 1, a kappa of 0.42 (rounded off to the second decimal) is calculated. Thus, our hypothetical situation produced a map that is in fair agreement with reality (Table 5.6).

Table 5.6: Kappa value and agreement (Viera and Garrett, 2005)

Kappa value	Agreement
< 0	Less than chance agreement
0.01 - 0.20	Slight agreement
0.21 - 0.40	Fair agreement
0.41 - 0.60	Moderate agreement
0.61 - 0.80	Substantial agreement
0.81 – 0.99	Almost perfect agreement

Tables 5.1, 5.2, 5.3 and 5.4, which indicate the accuracy of the Fey and soil sensitivity maps, resulted in accuracies of 71%, 70%, 72% and 69%, respectively. Based on these results, which has provided an acceptable accuracy for each accuracy matrix (van Zijl, 2013), and with a confidence level of 95%, the inferred maps from SoLIM were utilised. This was the same for the resulting kappa coefficient results for the training data observations and the validation point observations. The kappa coefficient was applied to all four of the instances (both the training data observations and the validation point observations) and the outcomes are summarised in (Table 5.7). These outcomes resulted in kappa coefficients of 0.63, 0.63, 0.57 and 0.50 (Table 5.7). With the exception of the validation point observations (which produced a moderate agreement between the observations and map units), the kappa coefficient indicated a substantial agreement between the various observations and map units.

Table 5.7: Kappa coefficients for the various instances

Map unit	Observation type	Kappa coefficient	Agreement
Fey soil classification	Training data	0.63	Substantial agreement
	Validation point	0.63	Substantial agreement
Soil sensitivity	Training data	0.57	Moderate agreement
	Validation point	0.50	Moderate agreement

The raster maps were converted into vector maps for easier use and interpretation. These final soil maps are discussed in Section 5.3.

5.3 Final soil maps

As mentioned in Section 4.4, the two raster maps that were inferred within SoLIM and achieved an acceptable accuracy with both the accuracy matrix and kappa co-efficient were converted to vector-based maps. Vector maps (drawn within QGIS using the raster maps) and all the observations (training data observations and validation point observations) provide definite boundaries that will assist with the recommendation process and are easier to interpret (van Zijl, 2013). When drawing the vector boundaries for both the Fey classification map and soil sensitivity map, a one-pixel boundary was given to all of the observations (training data observations and validation point observations) to ensure the final maps are as accurate as possible (Zhu, 1997; van Zijl, 2013; van Zijl *et al.*, 2019). Vector boundaries were also drawn to incorporate as much of the specific soil classification or sensitivity area as possible by following the pixelated raster boundaries. During the rule writing process for the development of the Fey classification soil map, two soil classifications were removed from this process. These two soil classifications were calcic and humic soil classifications (Fey, 2010b). Due to the limited number of observations (two for the calcic soil and one for the humic soil), it was decided to remove them from the rule writing process (van Zijl, 2013). These two soil classifications were included within the final Fey classification soil map the observations cannot be completely ignored. Outlying pixels generated (mainly due to small variations within the DEM that were not removed during the sink and fill process within QGIS) from the inference process was incorporated into the large areas (whether it is the Fey classification soil map or the soil sensitivity soil map). Under Chapter 7 the various other layers are briefly discussed and presented.

The recommendations (Nortjé, 2017; 2018a; 2018b; Nortjé and Nortjé, 2017) will thus include the updated road network, indicating the roads which are to be removed or rehabilitated, maintained and/ or upgraded at Phinda-after combining with the Fey soil map, the SSI map and the predator sightings, lodge and infrastructure locations and vegetation types.

Various other recommendations (Nortjé and Nortjé, 2017; Nortjé, 2017; Nortjé, 2018a, 2018b) were added to address road maintenance and/ or upgrading, roads rehabilitation techniques and which areas are very sensitive to off-road driving (ORD). Figures 5.3 and 5.4 indicate the final Fey soil-grouping map and the SSI map, respectively. Tables 5.8 and 5.9 describe the legend of each map as to which soil form observations fall into which grouping (either the Fey classification or the SSI).

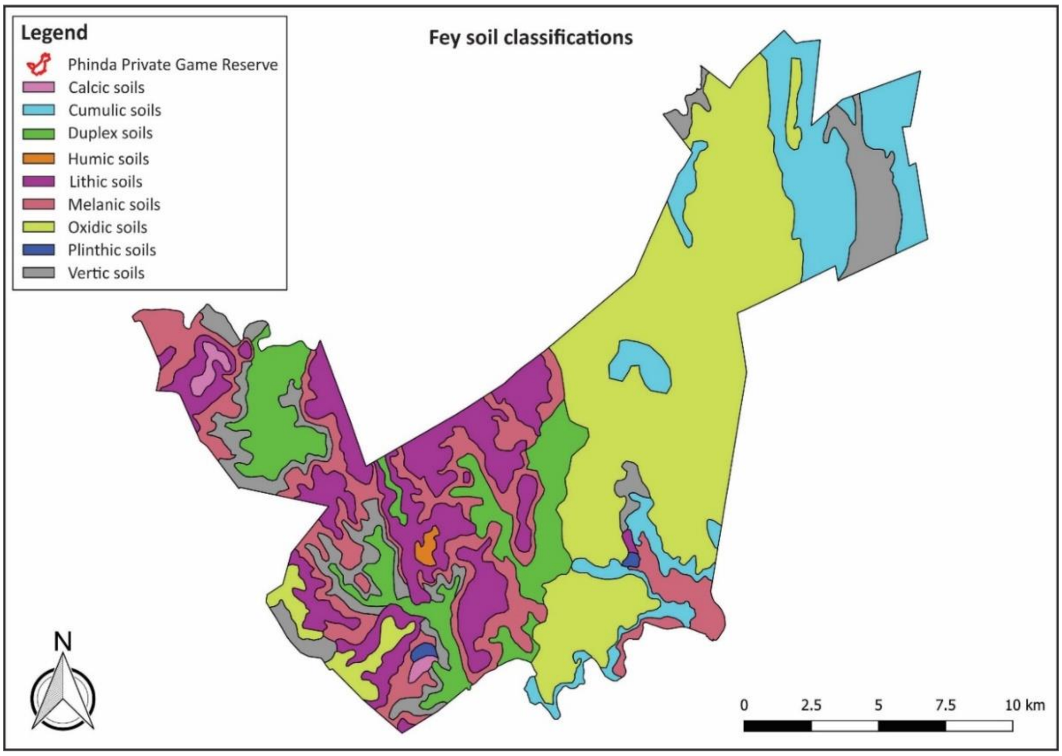

Figure 5.3: Final Fey soil-grouping map (2010a)

Table 5.8: Fey soil grouping of observed soil forms (2010a)

Soil forms	Fey classification
Brandvlei	Calcic
Fernwood, Longlands, Namib, Oakleaf and Vilafontes,	Cumulic
Escourt, Sepane, Swartland and Valsrivier	Duplex
Katspruit	Gleyic
Nomanci	Humic
Glenrosa, Mayo and Mispah	Lithic
Bonheim, Immerpan, Inhoek and Steendal	Melanic
Avalon, Bainsvlei, Bloemdal, Clovelly, Hutton, Kimberley, Pinedene and Shortlands	Oxidic
Dresden and Westleigh	Plinthic
Arcadia and Rensburg	Vertic

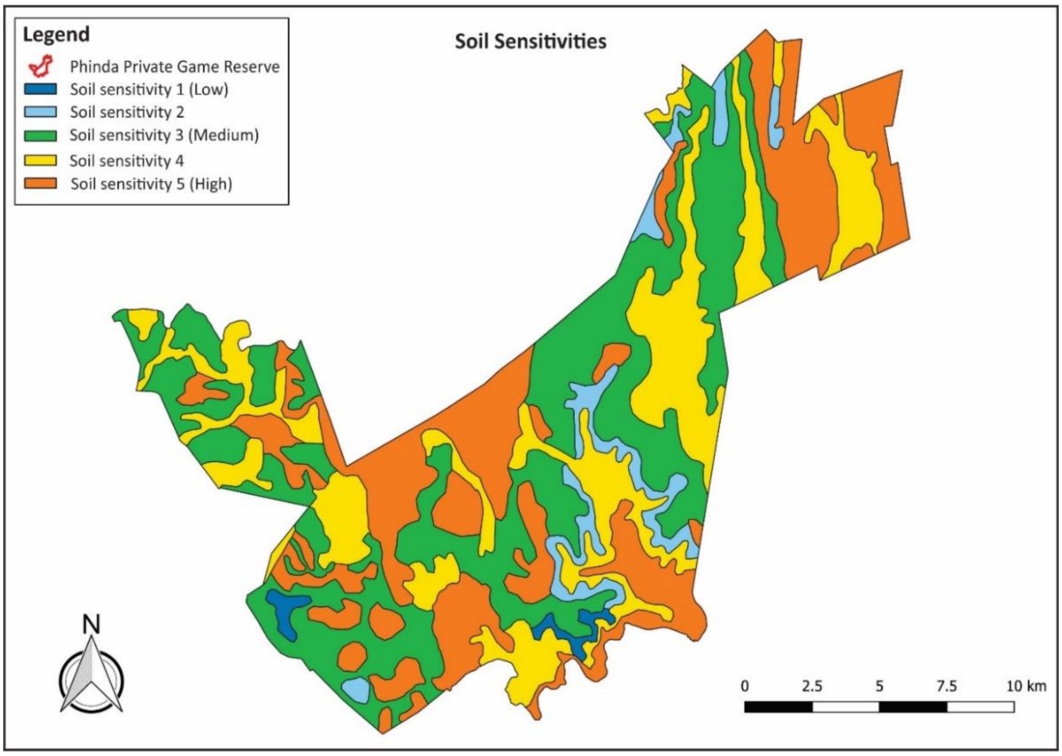

Figure 5.4: Final SSI map

Table 5.9: SSI of observed soil forms

Soil forms	Sensitivity to erosion
Shortlands	1 (low)
Hutton	2 (moderate)
Arcadia, Avalon, Bainsvlei, Bloemdal, Immerpan, Inhoek, Kimberley, Mayo, Nomanci, Pinedene and Rensburg	3 (medium)
Clovelly, Dresden, Katspruit, Vilafontes and Westleigh	4 (high)
Bonheim, Brandvlei, Escourt, Fernwood, Glenrosa, Longlands, Mispah, Namib, Oakleaf, Sepane, Steendal, Sterkspruit, Swartland and Valsrivier	5 (very high)

Tables 5.10 and 5.11 indicate the areas (in ha and percentage) and occurrences (in numbers and percentage) of both the Fey (2010a) classification and the SSI within Phinda. The Oxidic (10918 ha/36.2%) and Melanic soil forms (4761.7 ha/15.8%) are the most dominant Fey (2010a) soil classification present within Phinda (Table 5.10). When combining soil sensitivity 4 and 5 from Table 5.11, it was clear that 16792.88 ha/55.7% of Phinda consists of very sensitive soil forms.

Table **5.10:** Fey soil classification distribution (2010a)

Fey classification	**Area** (ha)	**Percentage of area** (%)	**Occurrences**	**Percentage of occurrences** (%)
Calcic	176	0.6	2	3.3
Cumulic	3893	12.9	9	15
Duplex	3142.9	10.4	5	8.3
Humic	78.7	0.3	1	1.7
Lithic	4322.27	14.3	15	25
Melanic	4761.7	15.8	10	16.7
Oxidic	10918	36.2	5	8.3
Plinthic	71.7	0.2	2	3.3
Vertic	2783.2	9.2	11	18.3
Total	30148	100	60	100

Table **5.11:** SSI distribution

Fey classification	**Area** (ha)	**Percentage of area** (%)	**Occurrences**	**Percentage of occurrences** (%)
SS 1	309	1.0	2	3.3
SS 2	1538.54	5.1	7	11.7
SS 3	11507.58	38.2	14	23.3
SS 4	7548.74	25.0	14	23.3
SS 5	9244.14	30.7	23	38.3
Total	30148	100	60	100

5.4 Phinda covariates and the SSI

The following paragraphs indicate the results of combining the general predator sightings (Fig. 5.5) and commercial lodges (Fig. 5.6) with the SSI map. These co-variates indicate that the predator sightings and commercial lodges are predominantly situated on sensitive soils. Predator sighting were determined by combining historic sightings with yearly population counts as to develop an overall position of predators. Even though other large animals are sought after during a game drive, ORD is predominantly utilised for predators as game drive operators (Nortjé, 2019) want to bring tourists as close as possible to these large predators.

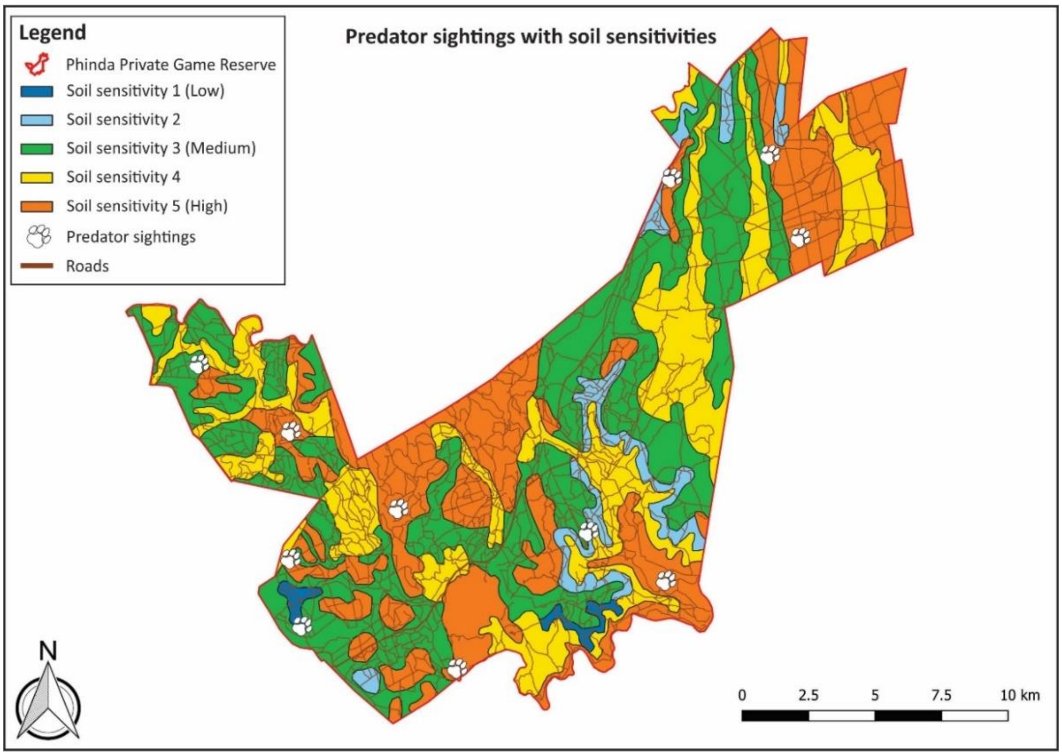

Figure 5.5: Predator sightings with SSI

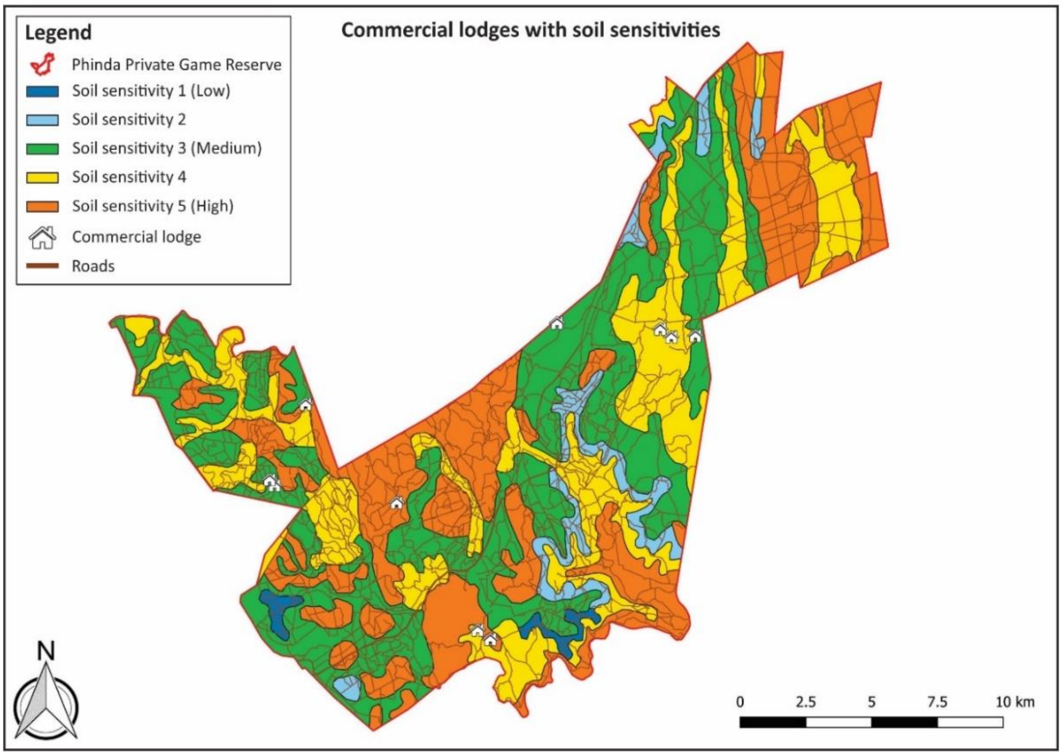

Figure 5.6: Commercial lodges with SSI

A 2.5 km radius was added to each general predator sighting and commercial lodge to assist with the management of roads and ORD within the specific area. Due to the high frequency of game drives and ORD within these areas, special attention was given within the recommendations (Nortjé, 2019). The 2.5 km radius was selected based on logistical information from Phinda. Due to the time spent during a game drive, distance travelled at a low speed in search of animals, as well as time spent within an area once a specific animal (such as a large predator) has been sighted. Even though game drives do extend outside of these radiuses, the highest concentration of driving and especially ORD takes place within these radiuses with the majority of ORD taking place within the predator radiuses. Table 5.12 indicates the percentage of the soil sensitivities within the predator radius as well as commercial lodges, respectively. The road network densities within these respective areas are also indicated. It is more practical to leave roads within an area as the damage has already been done opposed to rehabilitating certain roads and game rangers create new roads through ORD to view predators.

Table 5.12: Soil sensitivities within important radiuses

Soil sensitivity	**Within predator sighting radiuses**		**Within commercial lodges radiuses**	
	Area (ha)	**%**	**Area** (ha)	**%**
SS 1	157	1	60	1
SS 2	796	5	4	0.1
SS 3	5279	36	3400	38
SS 4	3349	23	2782	31
SS 5	5260	35	2678	30
Total	**14841**	**100**	**8924**	**100**

Within the radius areas of the predator sightings, 23% of the soils have a sensitivity of four and 35% a sensitivity of five. The same was true within the radius areas of the commercial accommodation with 31% of the soils having a sensitivity of four and 30% having a sensitivity of five. These values indicate how sensitive the areas within Phinda are and how important the proper management of game driving and ORD is. Figures 5.7 and 5.8 indicate the 2.5 km radiuses around all the predator sightings and commercial accommodation, respectively. Roads which fall within these radiuses were used for the ORD and general driving recommendations.

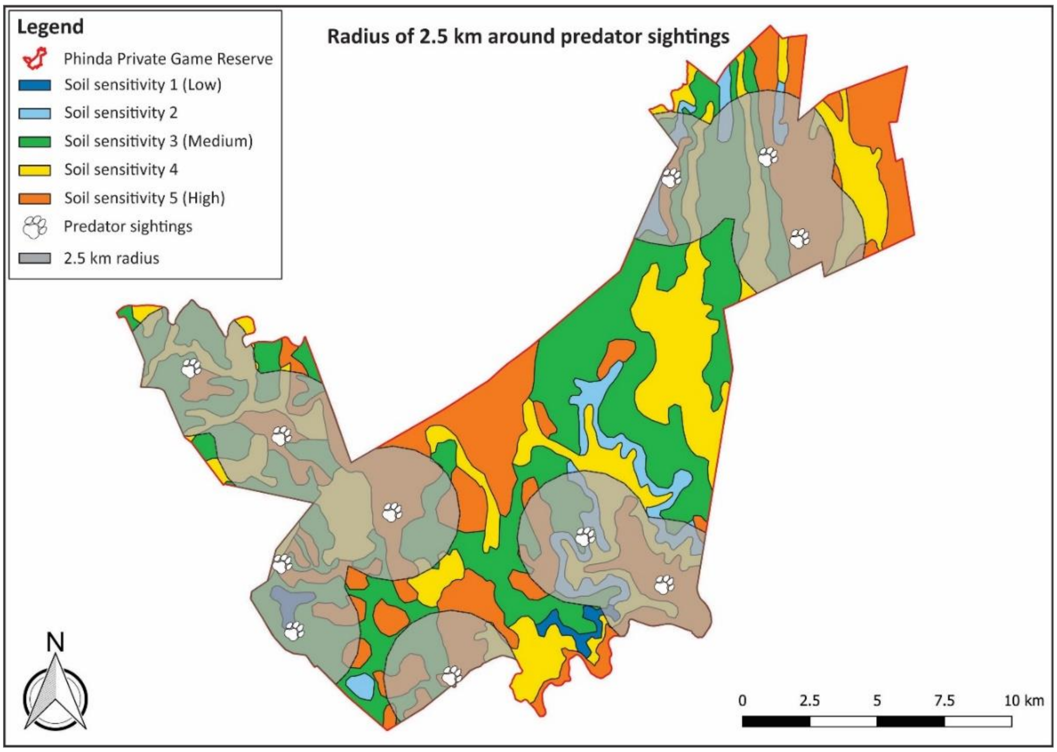

Figure 5.7: Radius of 2.5 km around predator sightings

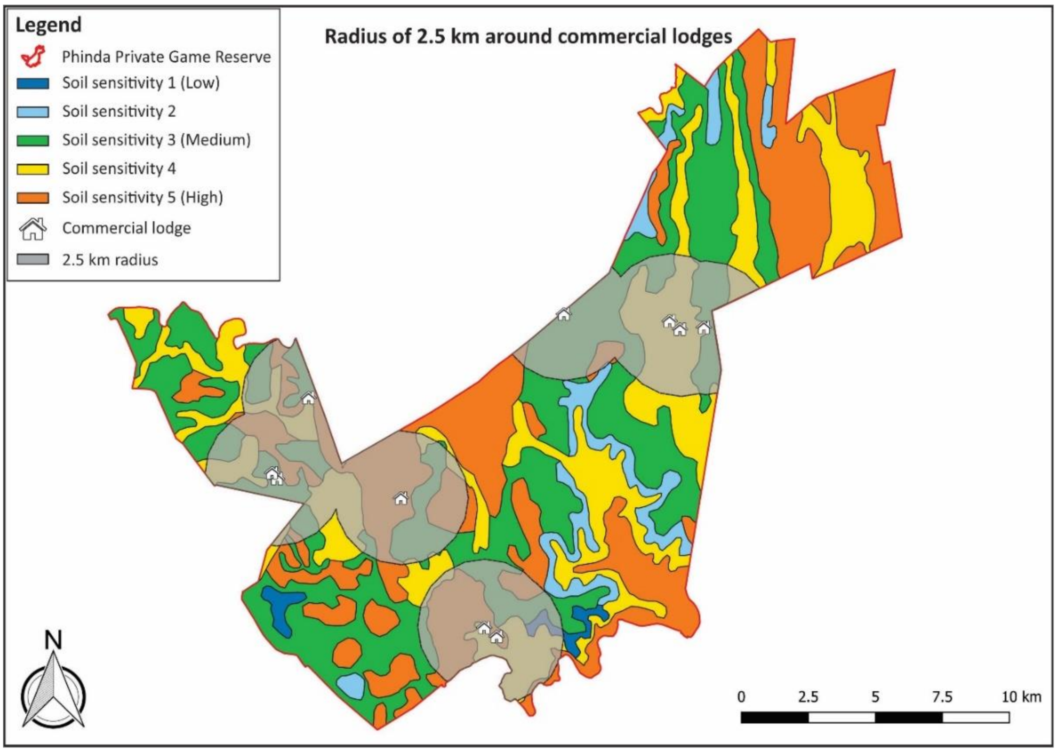

Figure 5.8: Radius of 2.5 km around commercial lodges

Table 5.13 indicates the length of the roads found within the 2.5 km radius of both the predator sightings and commercial lodges. The roads were divided based on the soil sensitivities within the respective radiuses. A total of 684.25 km of roads are present within the 2.5 km radius of the predator sightings. Of this 684.25 km of roads, the majority of roads (260.85 km/38.12%) are on soils with a sensitivity (SI) of three. When roads on soil sensitivities four and five are combined, as roads on these soils will have the greatest impact, we find that 54.66 % (374.02 km) of the roads are on the more sensitive soils. This trend was also true for roads within the 2.5 km radiuses of the commercial lodges. Although soils with a sensitivity of three have the majority of roads (174.17 km/42.43%) on top of it, we find that when soil sensitivities four and five are combined a total of 233.84 km (56.96%) of the roads are on top of these soils. These results indicate that the majority of the roads, that are used predominantly, have been constructed on sensitive soils.

Table 5.13: Roads within the 2.5 km radiuses

Soil sensitivity	**Within predator sighting radiuses**		**Within commercial lodges radiuses**	
	Road length (km)	**%**	**Road length** (km)	**%**
SS 1	7.16	1.05	2.35	0.57
SS 2	42.22	6.17	0.15	0.04
SS 3	260.85	38.12	174.17	42.43
SS 4	153.39	22.42	125.8	30.64
SS 5	220.63	32.24	108.04	26.32
Total	**684.25**	**100**	**410.51**	**100**

5.5 References

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Chapter 6
DISCUSSION AND CONCLUSION

6.1 Discussion

The final Fey classification soil map (2010) (Fig. 5.3) and soil sensitivity map (Fig. 5.4) were developed by writing rules using the various covariates and inferring this information within the soil land inference model (SoLIM). The rules within SoLIM were written based on the observation points, and the remaining 25% of soil observations were used as validation points. Values were given to each pixel (Zhu *et al.*, 2001; Van Zijl *et al.*, 2012) within the study area and thus resulted in the final two soil maps. The initial maps do indicate a pixelated effect in certain areas but this was due to the fluctuation in height within the DEM (even after a fill and sink algorithm was run using Quantum Geographic Information System (QGIS) to smooth the DEM as much as possible). These outliers are discarded within the final maps to produce higher quality soil maps that were easily used. Soil forms with limited observations (less than three) were removed from the rule writing process (van Zijl, 2013; van Zijl *et al.*, 2012*)* as to avoid incorrect mapping and prevent multiple outliers. The soil forms (calcic and humic classifications as per the Fey classification) were included within the final soil maps. The northern half of Phinda (Fig. 5.1) indicates more consistent Fey soil classification due to the nature of the topography and the underlying geography, whereas the southern half has a much greater variation in Fey soil classification due to the various slope angles and underlying geology. A one-pixel buffer was included around all the observations to produce increased map accuracy for the final Fey soil classification maps and soil sensitivity maps (van Zijl, 2013).

The accuracy of these maps was determined by populating a confusion matrix (van Zijl *et al.*, 2019) as well as implementing the kappa coefficient (Grinand *et al.*, 2008; McHugh, 2012; Rossiter, 2014; Viera and Garrett, 2005). Accuracy was determined based on the training data and validation soil observations for both the Fey classification and the soil sensitivity map outcomes. The Fey classification map compared to the training data achieved an accuracy of 71% (Table 5.1) whereas the soil sensitivity map compared to the training data achieved an accuracy of 72% (Table 5.3).

The Fey classification map (2010) was compared to the validation points and achieved an accuracy of 70% (Table 5.2) whereas the soil sensitivity map was compared to the validation points achieved an accuracy of 69% (Table 5.4). For the Fey classification maps the kappa coefficients (Table 5.7) indicated a value of 0.63 for the training data and a value of 0.63 for the validation points. The kappa coefficients for the soil sensitivity map was slightly different (Table 5.7) with the training data, producing a value of 0.57 and the validation points a value of 0.50. The final maps indicated acceptable accuracies (van Zijl, 2013). These final maps were then used for the second part of this study, which was to provide driving and road management recommendations to Phinda Private Game Reserve (Phinda) based on the soil forms and sensitivities.

Phinda possesses a vast road network with over a 1000 km off roads within the 28 000 ha reserve. A road density calculation (Nortjé, 2019) indicates that Phinda has a road density higher than 20 m/ha (based on the road network of 1000 km and the surface area of Phinda being 28 000 ha). The road density increases to 200 m/ha in certain areas of the reserve of which many roads are not in use. These levels of road densities are above average and large strips of road fall on sensitive areas (both soil and vegetation). These roads range from main roads that dissect the reserve to deserted roads that were used by the previous landowners.

To solve the problem the roads located within Phinda were divided into various categories based on their need and desirability. The road categories were combined with the Fey classification soil map (2010) (Fig. 5.3), soil sensitivity map (Fig. 5.4), various animal sighting (Table 3.6), location of infrastructure (ranging from commercial lodges to staff accommodation and workshops) within Phinda, vegetation types (Fig. 3.7) and general topography (Fig. 4.3 indicates the slope of certain areas within Phinda). Not only is this information used for road management but as also for off-road driving (ORD). ORD will cause irreversible damage (Nortjé *et al.*, 2012; Nortjé *et al.,* 2016) if not managed properly. By combining these covariates with the various roads within Phinda, recommendations were developed and a final road map was created (Chapter 7). This road map indicates which roads are to be kept, upgraded and ultimately rehabilitated. Phinda still requires various roads, as tourism is the main source of income for the reserve. It is thus important to ensure a proper balance between the road network, ORD, the environment in general, and providing an excellent experience for visitors. The various covariates were also applied to ORD to ensure the optimisation thereof and to prevent unnecessary damage to the soils and vegetation. Various road management recommendations are provided based on the various categories, as the roads are used for various purposes.

6.2 Conclusion

Large areas such as Phinda provide multiple challenges when it comes to soil mapping. Difficult terrain, the presence of dangerous animals, time and financial constraints would make traditional soil mapping challenging. Making use of digital soil mapping (DSM) solves this problem as less soil observations are needed, which saves on time and money, while an accurate soil map was produced. Combining DSM and road management, results in improved management opportunities, especially in Phinda with its vast road network. By combining the road network with various covariates, a system was developed whereby roads can be rehabilitated, upgraded and maintained while ensuring that business continues as normal at Phinda.

This information is valuable, not only for Phinda, but for other nature reserves as well, as it indicates that soils can be mapped accurately and affectively using DSM and then combined with various covariates. By applying the recommendations, Phinda will be able to decrease the road network density, prevent unnecessary soil erosion and ultimately a loss of biodiversity.

6.3 References

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Chapter 7
RECOMMENDATIONS

7.1 Recommendations

The following recommendations for the road network and ORD at Phinda have been developed based on the results and findings of this study. Table 4.7 describes the categories (Nortjé, 2019) into which the roads at Phinda have been divided. Recommendations are given for each category. The final recommendations are based on the SSI map, infrastructure located within and around Phinda, existing road network, important animal sightings and requirements received from the management and experiences of the employees. Figure 7.1 is a visual representation of the recommendations for the road network, as to which roads are to be removed, within the 2.5 km radiuses of both the predator sightings and commercial lodges.

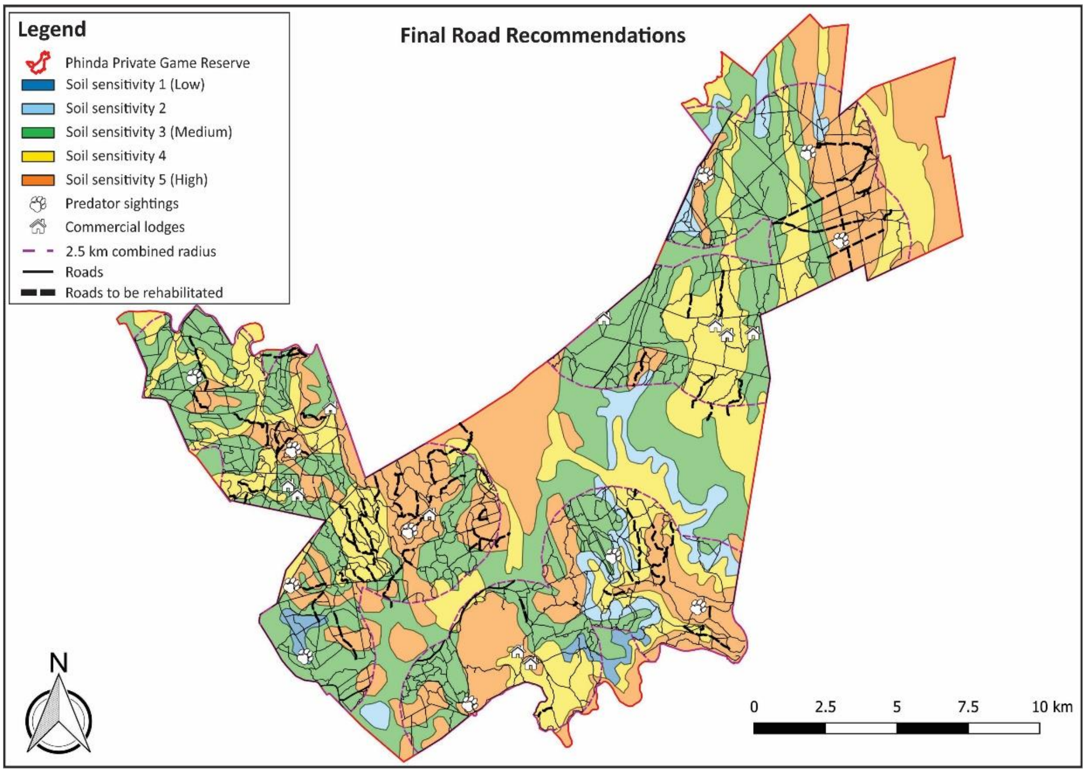

Figure 7.1: Final road network recommendations

Various other factors that are specific to Phinda were taken into account when developing the recommendations for the road network, as described in Chapters 2 and 3. A combination of sensitive vegetation (such as the sand forests) and the soils on which it is found (very sandy soils) create highly sensitive areas. Sandy soils can be prone to compaction and this limits the germination of seeds, root growth (Nortjé *et al.*, 2016) and the formation of soil crusting (Nortjé *et al.*, 2012). These impacts are worsened when driving off-road. Many tourists visit South Africa during the winter season (Nortjé and Mearns, 2017) and this is true for Phinda as well. Soils are less prone to surface crusting and subsoil compaction during the drier season (Nortjé and Mearns, 2017). Various portions of the northern parts of Phinda were used historically for pineapple farming. Many of these soils are already disturbed and any ORD will have a cumulative impact on the soils (Nortjé *et al.*, 2012). Another important factor is that Phinda is a business that relies on tourists for funds. Therefore, a balance must be obtained between the protection of the environment and customer satisfaction as the one is not sustainable without the other.

7.1.1 General road network recommendations applicable at Phinda

- All vehicles driving within the reserve must decrease their tyre pressure to as little as required to drive effectively. This will ensure that subsoil compaction (Nortjé *et al.*, 2016) is limited and root penetration of the surrounding vegetation is not prevented completely;
- As far as possible, limit unnecessary driving on sensitive soils to drier periods of the year as this will decrease (Nortjé and Mearns, 2017) a soils susceptibility to subsoil compaction and surface crusting;
- Only the important roads (Category A and B roads) on steep slopes must remain and be well maintained as the slope increases the erodibility of soils. Within Phinda, the majority of steep slopes coincide with sensitive soils, thus the extent and seriousness of the soil erosion is multiplied;
- Areas adjacent to roads where erosion has taken must be rehabilitated through revegetation or using structures such as gabions to halt erosion;
- Driving on sensitive roads, especially those with a melanic or vertic A-horizon, must be avoided during a rain event (Nortjé, 2019) or immediately after. Phinda has an affective system in place, and this system must be adhered to;
- Roads located on soils with a melanic and vertic A-horizon with a steep slope can be improved by adding rocky material to areas where ruts have formed and soil erosion has occurred;
- Vehicles must remain on the roads and limit unnecessary ORD as much as possible;

- Develop a land and soil management plan that can be used as a base for future endeavours. Ensure that all staff are informed on the importance of soil and which areas to avoid with regards to ORD (Nortjé and Nortjé, 2017);
- Speed limits must be enforced and all staff members to adhere to these limits.
- If possible, main roads (Category A roads) can be treated with special environmentally friendly dusticides to limit erosion and dust generation.

7.1.2 ORD recommendations applicable at Phinda

- All vehicles driving within the reserve as well as off-road must decrease their tyre pressure to as little as required to drive effectively. This will ensure that subsoil compaction (Nortjé *et al.*, 2016) is limited and root penetration of the surrounding vegetation is not prevented completely;
- Off-road driving must be avoided as much as possible on areas with Fey soil classifications (2010a) of vertic and cumulic (Fig. 5.3) as well as a soil with a sensitivity of five (Fig. 5.4). ORD must also be avoided in areas where the vegetative cover has been completely removed (Nortjé, 2017; 2018), wetlands and areas with very sandy soils;
- As far as possible, limit unnecessary ORD on sensitive soils to drier periods of the year as this will decrease (Nortjé and Mearns, 2017) a soils susceptibility to subsoil compaction and surface crusting;
- ORD on steep slopes must be prohibited as the slope increases the erodibility of soils. Within Phinda, the majority of steep slopes coincide with sensitive soils, thus the extent and seriousness of the soil erosion is multiplied;
- Areas where ORD has led to erosion must be rehabilitated through revegetation or using structures such as gabions to halt erosion.
- ORD on sensitive roads, especially those with a melanic or vertic A-horizon, must be avoided during a rain event (Nortjé, 2019) or immediately after. Phinda has an affective system in place, and this system must be adhered to;
- When ORD is unavoidable the following preventative measures must be applied to control the impact as much as possible:
  - Only perform ORD during a confirmed sighting (Nortjé, 2019);
  - Traffic ORD within the same area must be controlled (Nortjé *et al.*, 2012);

- Vehicles driving towards the same sighting must use the tracks of the vehicle that went off-road before it. Even though it ensures subsoil compaction, the impacted area of the ORD is limited greatly (Nortjé *et al.*, 2012) and;
- Any severe damage, such as rut formation or trench development must be repaired immediately;

- No ORD to take place from Category A roads, these roads are to be used for site access only (Nortjé, 2019);
- Instances where ORD takes place on a regular basis within an area would encourage the construction of a Category C road;
- Areas with sensitive soils and sensitive vegetation must not allow ORD, unless during a confirmed sighting or emergency;
- Develop a land and soil management plan that can be used as a base for future endeavours. Ensure that all staff is informed on the importance of soil and which areas to avoid with regard to ORD (Nortjé and Nortjé, 2017).

7.1.3 Recommendations for Category A roads at Phinda

- These roads must be well maintained and upgraded as they are used on a regular basis. Maintenance can consist of grading, compacting and sloping the road to ensure surface water runs off the road and not pool;
- These roads must have well defined boundaries, which will prevent vehicles from leaving the road;
- Dissipaters can be constructed into the side of the roads to limit soil loss on the road surface and ensure that surface water enters the surrounding environment.
- Dust suppression (with the use of an environmentally friendly substance), although expensive, can be applied on Category A roads;
- Speed limits can be enforced to reduce dust generation and soil loss;
- Rocky material can be applied to steep and wet areas to prevent rut formation and erosion trenches;
- No ORD allowed from Category A roads;
- No new Category A roads to be constructed.

7.1.4 Recommendations for Category B roads at Phinda

- Figure 7.1 will indicate which of these roads are too be removed and rehabilitated;
- These roads must be maintained through sloping to ensure surface water runoff;

- Define boundaries to prevent unnecessary ORD and limit impacts on the surrounding soils and vegetation;
- Limited ORD, see conditions above;
- Dissipaters to be constructed to decrease the impact of surface water runoff and ensure that water enters the surrounding environment;
- Rocky material can be applied to steep and wet areas to prevent rut formation and erosion trenches;
- Apply the Phinda wet conditions driving rule of thumb;
- Wooden bridges can be constructed in very wet and clayey areas;
- Any damage (ruts, erosion trenches and the loss of vegetation cover) to be rehabilitated immediately.

7.1.5 Recommendations for Category C roads at Phinda

- Figure 7.1 will indicate which of these roads are too be removed and rehabilitated;
- No defined boundaries to allow vegetation to grow at edges of the road;
- ORD from these roads are allowed, see conditions concerning ORD above;
- Rocky material can be applied to steep and wet areas to prevent rut formation and erosion trenches;
- Apply the Phinda wet conditions driving rule of thumb;
- Wooden bridges can be constructed in very wet and clayey areas;
- In severe instances of rut formation and erosion trenches, gabions can be implemented to stop further erosion and allow the rehabilitation of the impacted area;
- Any damage (ruts, erosion trenches and the loss of vegetation cover) to be rehabilitated immediately.

7.1.6 Recommendations for Category D roads at Phinda

- Many of these roads must be rehabilitated as they are used rarely and are of little importance.
- Roads that are to remain must be driven and inspected on a monthly basis to prevent them from being overgrown;
- ORD from these roads are allowed, see conditions concerning ORD above;
- Very little to no infrastructure to be added to the roads that will remain;
- Category D roads must consist of only jeep tracks;

- Any damage (ruts, erosion trenches and the loss of vegetation cover) to be rehabilitated immediately;
- If any new roads are planned, they must not be constructed on vertic and cumulic soils (Fig. 5.3) (Fey, 2010a, 2010b) or areas with a soil sensitivity (Fig. 5.4) of five.

7.2 References

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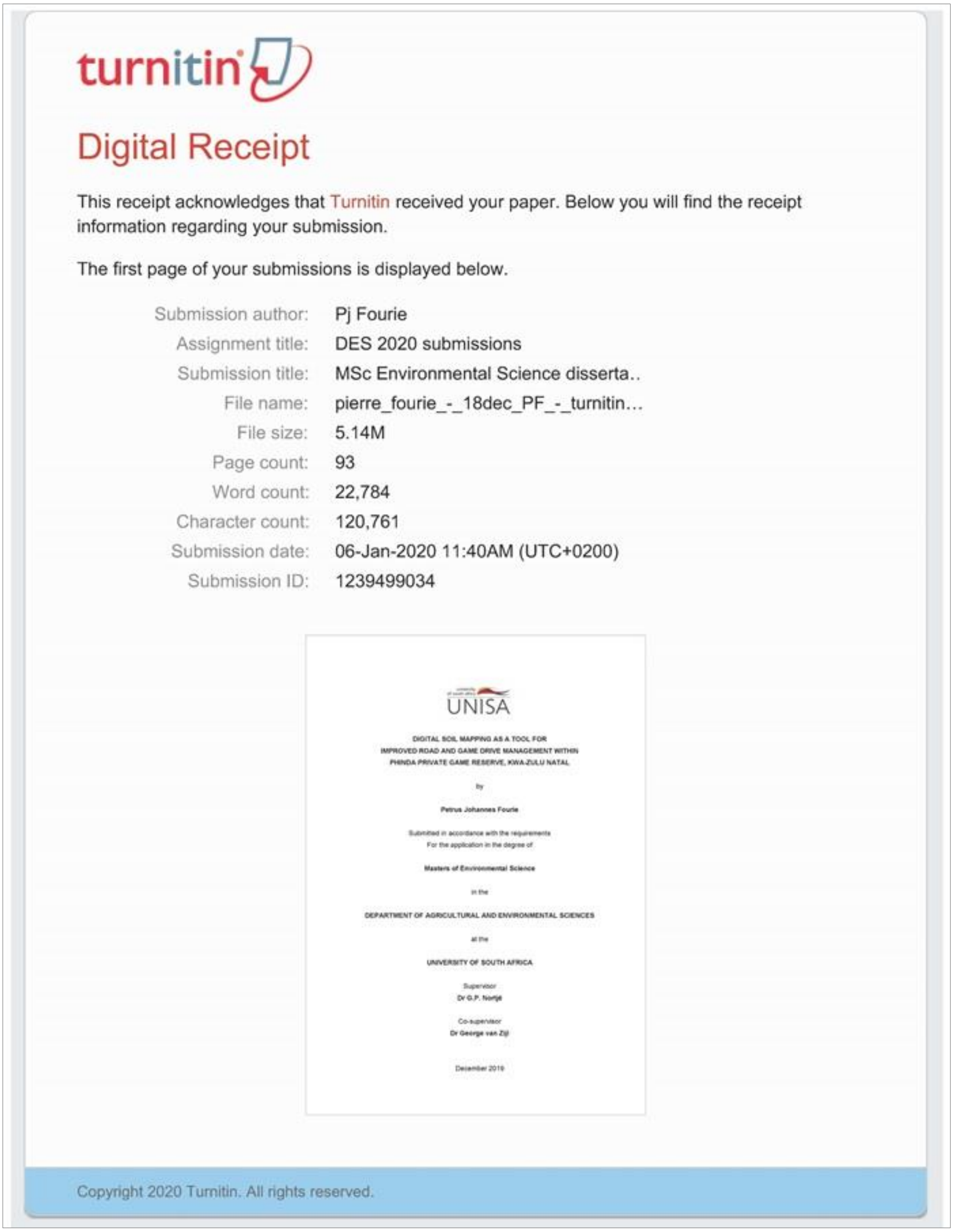
APPENDICES

Appendix A: Turnitin Digital Receipt



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UNISA

DIGITAL SOIL MAPPING AS A TOOL FOR
IMPROVED ROAD AND GAME DRIVE MANAGEMENT WITHIN
PHINDA PRIVATE GAME RESERVE, KWA-ZULU NATAL

by

Petrus Johannes Fourie

Submitted in accordance with the requirements
For the application in the degree of

Masters of Environmental Science

in the

DEPARTMENT OF AGRICULTURAL AND ENVIRONMENTAL SCIENCES

at the

UNIVERSITY OF SOUTH AFRICA

Supervisor
Dr G.P. Nortjé

Co-supervisor
Dr George van Zijl

December 2019

Figure A.1: Turnitin digital receipt

Appendix B: Ethical clearance

UNISA university of south africa

CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 18/02/2019

NHREC Registration # : REC-170616-051
REC Reference # : 2019/CAES/028
Name : Mr PJ Fourie
Student #: 45943737

Dear Mr Fourie

Decision: Ethics Approval from 14/02/2019 to 28/02/2020

Researcher(s): Mr PJ Fourie
45943737@mylife.unisa.ac.za

Supervisor (s): Dr GP Nortje
nortjgp@unisa.ac.za; 011-471-2286

Working title of research:

Predictive soil mapping in Phinda Private Game Reserve

Qualification: MSc Environmental Science

Thank you for the application for research ethics clearance by the CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is granted for a one-year period. After one year the researcher is required to submit a progress report, upon which the ethics clearance may be renewed for another year.

Due date for progress report: 28 February 2020

Please note the points below for further action:

1. What will be done with the soil samples? What will they be tested /investigated for? Is it only to identify the horizons in the soil or will other analysis be done as well?
2. How will the interpolation between the various sampling points be done?
3. What is a sensitive soil? There is an index that is used to classify soil, and this information should be included in the research proposal.
4. The problem statement needs to be strengthened and referenced where possible. The revised proposal will be circulated to the committee once received.

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Figure B.1a: Ethical clearance, first page

*The **low risk application** was **reviewed** by the CAES Health Research Ethics Committee on 14 February 2019 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.
2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
6. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
7. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:
*The reference number **2019/CAES/028** should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

URERC 25.04.17 - Decision template (V2) - Approve

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Figure B.1b: Ethical clearance, second page

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Figure B.1c: Ethical clearance, third page