GRASSLAND REHABILITATION AFTER ALIEN INVASIVE TREE ERADICATION: LANDSCAPE DEGRADATION AND SUSTAINABILITY IN RURAL EASTERN CAPE

by
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DECLARATION

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ABSTRACT

Rehabilitating grassland, a threatened biome, requires a comprehensive management approach that integrates the environmental, economic and social matters in sustaining this system. In the Eastern Cape of South Africa, three Quaternary catchments (QCs) (T35B, T12A & S50E) have been severely invaded by Invasive Alien Plants (IAPs) as well as altered by agrarian intensification and human development. Working for Water (WfW) Alien Plant Clearing Programme have been clearing IAPs in these catchments for the past twelve years. The current research aimed at establishing various degradation gradients occurring in the QCs. This was done by conducting land cover classification and change analysis over time, evaluating soil quality and assessing the success of the WfW program by quantifying the net primary production (NPP) and evapotranspiration (ET) trends on the cleared areas. A novel management scheme for decision makers, driver-pressure-state-impact-response (DPSIR) framework, was therefore suggested for managing these QCs sustainably.

The soil analysis showed that phosphorus (P) levels are significantly different ($P<0.05$) between invaded, cleared and natural sites. High nitrogen (N) and pH were associated with *Acacia* proliferation in acidic soils. Object based image analysis (GEOBIA) was used for the land use land cover (LULC) classification using Landsat 8 OLI & TIRS imagery. LULC change analyses were carried out on two reference bases [National land cover (NLC) 2000 & Edited NLC (ENLC) 2000]. Land cover change analysis was facilitated by using a framework introducing labels to describe land cover change. Annual MODIS ET (MOD16)/NPP (MOD17) data were used to evaluate the rehabilitation progress in T12A using WfW clearing data. A DPSIR management framework, structuring the sustainable indicators at the QCs in a logical manner, was developed for decision and policy makers for dealing with management issues related to land use, water resources and soil quality management.

The present research recommends that additional soil samples need to be collected for validation of soil nutrients status. Medium resolution Landsat imagery used for the LULC mapping provided accuracies of greater than 80%, but could not differentiate between invasive and indigenous trees. Hyperspectral or higher resolution imagery should be explored for mapping and delineating IAPs. Using coarse resolution MODIS products to model ET/NPP did not provide adequate detail of the cleared patches to describe the actual status of WfW clearings and their rehabilitation progress.

KEY WORDS

Grassland rehabilitation, landscape degradation, invasive alien plants (IAPs), management practices, soil nutrients, remote sensing, object based image analysis (OBIA), land use land cover (LULC), change detection, DPSIR, sustainability.

OPSOMMING

Rehabilitasie van grasvelde, ‘n bedreigde bioom, vereis 'n omvattende benadering wat die omgewing, ekonomiese en sosiale aangeleenthede in die handhawing van 'n stelsel integreer. In die Oos-Kaap provinsie van Suid Afrika is drie kwaternêre opvanggebiede (QCs) (T35B, T12A S50E) erg deur indringerplante (IAPs) asook verandering deur landbou intensifisering en menslike ontwikkeling ge-affekteer. Die Working for Water (WfW) se uitheemse plant program roei alreeds vir die afgelope twaalf jaar IAPs in hierdie opvanggebiede uit. Hierdie navorsing is daarop gemik om verskeie agteruitgangsgradiënte wat in die QCs voorkom te bepaal deur die evaluering van grondkwaliteit, uitvoer van landbedekking klassifikasie en veranderingsontleding asook. Die WfW rehabilitasie pogings van die afgelope twaalf jaar is deur kwantifisering van die Netto primêre produksie (NPP) en evapotranspirasie (ET) tendense vir die skoongemaakte gebiede beoordeel. ‘n Nuwe bestuurskema, gebaseer op die drywer-druk-stand-impak-reaksie (DPSIR) raamwerk, word ter bevordering van volhoubaarheid in die QCs vir besluitnemers aanbeveel.

Die analise van grondvoedingstowwe het getoon dat fosfor (P) beduidend ($P<0.05$) tussen indringer, skoongemaakte en natuurlike terreine verskil. Hoë stikstof (N) en pH hou verband met *Acacia* teenwoordigheid in suur gronde. Objekgerigte beeldanalise (GEOBIA) is gebruik vir die grondgebruik grondbedekking (LULC) klassifikasie met behulp van Landsat 8 OLI & TIRS beelde. LULC veranderingsanalise is op twee verwysingsbasisse [National land cover (NLC) 2000 en gewysigde NLC (ENLC) 2000] uitgevoer. Grondbedekkingsveranderingsanalise is deur ‘n raamwerk gefasiliteer wat gebruik maak van etikette om verandering te beskryf. Jaarlikse MODIS ET (MOD16) / NPP (MOD17) data is gebruik om die rehabilitasie vordering met behulp van WfW skoonmaakdata in T12A te evalueer. ‘n DPSIR bestuursraamwerk, wat die strukturering van die volhoubaarheidaanwysers vir die QCs op 'n logiese manier organiseer, is ontwikkel om besluitneming in die hantering van bestuurskwessies met betrekking tot grondgebruik, waterbronne en grondkwaliteitsbestuur te ondersteun.

Hierdie navorsing beveel aan dat bykomende grondmonsters versamel moet word om die grondvoedingstofstatus te bevestig. Medium resolusie Landsat beelde wat vir die LULC kartering gebruik is het akkuraathede van meer as 80% verskaf, maar kon nie tussen indringer en inheemse bome onderskei nie. Hiperspektrale of hoër resolusie beelde moet vir kartering van IAPs ondersoek word. Die gebruik van growwe resolusie MODIS produkte om ET / NPP te modelleer het nie voldoende detail vir die skoongemaakte areas verskaf om die werklike status van WfW uitroei en rehabilitasie vordering te beskryf nie.

SLEUTELWOORDE

Grasveld rehabilitasie, landskapagteruitgang, indringerplante, grondvoedingstowwe, afstandswaarneming, objekgerigte beeldanalise (OBIA), grondgebruik grondbedekking (LULC), veranderingsanalise, DPSIR, volhoubaarheid.

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ACRONYMS AND ABBREVIATIONS

AI	Artificial intelligence
ANN	A neural network
ANOVA	Analysis of variance
ASTER	Advanced spaceborne thermal emission and reflection radiometer
ATCOR	Atmospheric correction
BGC	Biogeochemical cycles
BRS	Bare rock and soils
CART	Classification and regression trees
Cc	Correlation coefficient
CD: NGI	Chief directorate: National geo-spatial information
CEM	Climate envelope modelling
CGA	Centre for Geographical Analysis
CLs	Cultivated lands
CMAs	Catchment Management Agencies
CSIR	Council for scientific and industrial research
CT	Classification tree
CVA	Change vector analysis
DAAC	Distributed active archive centre
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DEM	Digital elevation model
DLC	Derived land cover
DN	Digital number
DPSIR	Deep pressure state impact response
DWAs	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EDTA	Ethylenediamine tetraacetic acid
EMS	Electromagnetic spectrum
ENLC	Edited national land cover
EROS	Earth resources observation and science
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration

ETM+	Enhanced thematic mapper plus
EVI	Enhanced vegetation indices
FAO	Food and agricultural organisation
FITBs	Forest indigenous, thickets
FPs	Forest plantations
GEOBIA	Geographical object based image analysis
GCOS	Global climate observing system
GCPs	Ground control points
GIS	Geographical information system
GPP	Gross primary productivity
IAPs	Invasive alien plants
ICM	Integrated catchment management
LAI	Leaf area index
LCC	Land cover change
LCCS	Land cover classification system
LDCM	Landsat data continuity mission
LUC	Land use change
LUE	Light use efficiency
LULC	Land use land cover
LULCC	Land use land cover change
LWP	Livestock water productivity
MAR	Mean annual rainfall
MLC	Maximum likelihood classifier
MODIS	Moderate resolution imaging spectroradiometer
MRT	Modis reprojection tool
NASA	National Aeronautics and Space Agency
NDVI	Normalised difference vegetation index
NDWI	Normalised difference water index
NIAPS	National invasive alien plant survey
NIR	Near infrared
NLC	National land cover
NPP	Net primary productivity
NTSG	Numerical terradynamics simulation group
OLI	Operational land imager

PCA	Principal component analysis
QCs	Quaternary catchments
RES	Reward for ecosystem services
RGB	Red, green, blue
RTM	Radiative transfer model
SAPIA	The southern African plant invaders
SAVI	Soil-adjusted vegetation index
SBC	Spot building count
SES	Socio-ecological system
SPOT	Satellite pour l'observation de la terre
Spp.	Species
STARFM	Spatial and temporal adaptive reflectance fusion model
SUDEM	Stellenbosch university digital elevation model
TIRS	Thermal infrared
TM	Thematic mapper
ToA	Top of atmosphere
UG	Unimproved grassland
UrBu	Urban/built-up
USBC	United States Bureau of the Census
USGS	United States Geological Survey
UTM	Universal transverse mercator
VIs	Vegetation indices
Wb	Waterbodies
WDRVI	Wide dynamic range vegetation index
WfW	Working for water
Wl	Wetlands
WMA	Water management areas
WRC	Water Research Commission
WUE	Water use efficiency

CHAPTER 1: **RESTORATION: TOWARDS LAND USE LAND COVER CHANGE**

After direct habitat destruction, invasive alien plants (IAPs) are the second most important threat to biodiversity globally (Driver et al. 2012). Large areas have been transformed as a result of these invasions and many negative impacts on the economy in sectors such as health, agriculture, water supply and tourism have resulted (Pysek et al. 2012). In South Africa, grassland is the second largest biome found chiefly on the high central plateau of South Africa and the inland regions of Kwazulu-Natal and the Eastern Cape. It has been documented to be severely affected by alien invasions with these aliens exerting tremendous impacts on the ecological and social development of the ecosystem (Lenda et al. 2013; García-LLorente et al. 2011). Between 60 to 80% of South Africa's grassland veld types (Acocks 1975) have been irreversibly transformed and less than 2% are formally conserved (Carbutt & Martindale 2014; Carbutt et al. 2011).

Land cover dynamics as a result of natural or anthropogenic factors influence the natural state of pre-existing land cover at differing spatio-temporal scales. Natural disturbances, other than alien invasion, operate based on some infringing factors and time scales, and may include drastic responses to volcanic eruptions, earthquakes or vegetation shifts in response to climatic and evolutionary processes (Lambin, Geist & Lepers 2003). Anthropogenic land cover change often occurs as a consequence of landscape modification to sustain socio-economic development targeted at supporting the increasing growth and demand of human population. However, these two land cover change drivers can coherently co-exist in grassland biomes as well as other natural biomes.

The occurrences and mechanisms of these land-change processes may be difficult to analyse due to the wavering interactive variables driving these changes (Nagendra, Munroe & Southworth 2004). Studies have shown time-serial changes through change analysis of either natural or anthropogenic land-change factors using GIS and remote sensing techniques (Olexa & Lawrence 2014; Yang, Weisberg & Bristow 2012; Reis 2008). These long-term mapping and classification techniques aid in empirically amplifying the definite time-serial changes to match its varying cumulative effects on biodiversity.

Individual species have shown to affect specific components of the ecosystem such as nutrient cycling rates including above and belowground nutrient pools, plant growth rates, mineralization rates, rates of litter fall and chemical quality (Chapin et al. 2000; Hector et al. 1999; Hooper & Vitousek 1998). Novel strategies used by IAPs may allow them to exploit resources that are unavailable to resident plants (Ehrenfeld, Kourtev & Huang 2001; Ehrenfeld & Scott 2001) by altering the microbial community composition and nutrient availability patterns. Invasive alien species have the ability to disrupt existing plant-environment interactions. This body of evidence strongly suggests that when the species composition of a community changes due to invasion and spread of exotic plants (alien plants), there are likely to be consequent changes in nutrient cycling processes.

Individual plant characteristics such as phenology, nutrient uptake, litter fall, tissue chemical composition, and microbial symbiosm can have significant effects on soil nutrient cycles (Angers & Caron 1998; Berendse 1998; Binkley & Giardina 1998) which may, in turn, alter the growth and survival of the species that drive these effects. Because they are novel and may have different biochemical constituents (Vivanco et al. 2004), and are often dominant components of plant communities, IAPs can have unusually strong effects on soil nutrient cycles (Ehrenfeld, Kourtev & Huang 2001; Ehrenfeld & Scott 2001). The potential of IAPs to alter soil nutrient accessibility may be much greater than these summaries suggest. Therefore, there are extensive data from natural communities and experimental systems to show the connection between plant species composition and these ecosystem processes (Ehrenfeld 2003).

However, managing ecosystems invaded by alien plants is an increasingly complex problem globally (Roura-pascual et al. 2009). Most restoration programmes use passive approaches for restoring aspects of functionality in degraded ecosystems, with the aim of enhancing the recovery of native species by simply removing existing invasive species (Gaertner et al. 2012, Le Maître et al. 2011). This approach often fails due to secondary invasions of the same invader or other invasive species (Loo et al. 2009; Zavaleta, Hobbs & Mooney 2001). Consequently, it has been argued that active restoration (i.e. additional restoration activities beyond removal of the invader) is critical when dealing with alien invasions (Reid et al. 2009; Esler et al. 2008). Such an active approach was carried out by Souza-Alonso et al. (2013) by directly applying herbicide (triclopyr) after the cutting of *Acacia dealbata* that promoted native species biomass after one year of the last herbicide application. The ecological and financial feasibility of active restoration might seem difficult, but the financial analysis from flower harvesting following active restoration consistently outweighs income following passive restoration. Therefore, the associated increase in income does not always justify the higher costs (Gaertner et al. 2012).

Many studies have been carried out on IAPs in various biomes (Nyoka 2003). Other studies analysed various GIS and remote sensing tools and models for mapping land cover and land cover change (Olexa & Lawrence 2014; Yang, Weisberg & Bristow 2012; Reis 2008). Others evaluated IAPs alteration of soil community and plant-soil feedback (Ehrenfeld, Kourtev & Huang 2001; Ehrenfeld & Scott 2001; Chen & Stark 2000). While other studies assessed the restoration and management approaches for degraded ecosystems (Gaertner et al. 2012; Souza-Alonso et al. 2009; Mason & French 2007).

Collectively, this study will examine two land tenure systems (freehold and leasehold) where active alien clearing has been done, in order to evaluate the long-term impact of land cover alterations and rehabilitation progress after clearing. The net primary productivity (NPP) and evapotranspiration (ET) trends over time at three selected quaternary catchments (QCs) in the rural regions of the Eastern Cape will also be examined. Additionally, to proffer restoration activities that precedes the soil nutrients analysis to facilitate active and sustainable restoration. Furthermore, the study will investigate the impact of natural and anthropogenic land cover change characteristics on the stakeholders using a driver-pressure-state-impact-response (DPSIR) framework. The DPSIR framework will optimize appropriate measures towards setting the desired equilibrium between the social and ecological differences of the landscapes.

1.1 DPSIR FRAMEWORK: GAUGING SOCIO-ECOLOGICAL INTERACTION

The DPSIR framework is an integrated approach that effectively manages resources by uniting ecological and socio-economic factors in attaining sustainable benefits for future use. The indicator-based framework was developed by the Organisation for Economic Co-operation and Development (OECD 1993). It has been valuable for recognising and establishing indicators for sustainable resource management at the catchment level (Walmsley 2002). The indicators have been useful in communicating information to the decision and policy-makers for effective resource management (Hammond et al. 1995). This framework, that gauges the human-environment interaction, tends to be systematically useful in categorising physical data from several fields and sources (Alfieri, Hassan & Lange 2004).

As summarised by Walmsley (2002), ‘driving forces’ at catchment level stemmed from the natural states and levels of economic development due to human needs. ‘Pressure’ indicators are generally the natural events or human intensification of resources either deliberately or unpremeditated. Indicators for ecosystem ‘state’ (biotic and abiotic conditions of the ecosystem) can be quantitatively and qualitatively categorised into factors that physically impact on the ecosystem and utility value of the resources. Relatively, ‘impact’ indicators can delimit factors affecting the ecosystem directly from those impacting on the utility value of the resources. Policy-makers therefore decide in 'response' to the ecosystem-service impact or their perceived relevant value.

The DPSIR framework has been applied to various approaches to derive sustainability 'indicators' for monitoring programmes. This framework also categorically reviews information from several sources and develops decision models or tools for comparing decision outcomes. Studies have evaluated this framework as source-specific indicators towards effective management and sustainability (Mattas, Voudouris & Panagopoulos 2014; Benini et al. 2010). Wei et al. (2007) identified key indicators using this DPSIR framework for evaluating giant panda sustainability in sanctuaries. Odermatt (2004) demonstrated the possibility of global application of mountain development and sustainability model using this framework. Benini et al. (2010) adopted DPSIR as a reference framework to ascertain indicators allied with the reduction of river volume and landscape modification in Lamone River basin. Another assessment using this framework integrated the driving forces of land use change in the coastal regions of Eastern Cape (Palmer et al. 2011).

1.2 REAL WORLD PROBLEM

Water is the most important limiting natural resource due to the low annual rainfall experienced in South Africa (DWAF & WRC 1996). A preliminary assessment confirmed IAPs impact on the total water use in the Eastern Cape (Le Maître, Versfeld & Chapman 2000). The current rate of the spread of invasive pines in South Africa seems to predict water shortages in many towns, cities and rural areas in the near future (Hoffmann, Moran & Van Wilgen 2011; Van Wilgen et al. 2008). It was however, predicted that climate change would compound the threat of alien plants on the country's water resources by accelerating the alien plant spread within the current invaded area at an increase rate of more than 5% annually (Richardson & Van Wilgen 2004; Le Maître, Versfeld & Chapman 2000). Similarly, a predicted increase in atmospheric evaporative demand in the western parts of the country due to climate change (DWAs 2010) that intensified the IAPs transpiration rate was also established.

The allelopathic activity of *Ludwigia spp*. was identified as a competitive factor that negatively influenced the vulnerable native species' survival and altered the standard quality of water resources (Dandelot et al. 2008). Few studies have argued of IAP's impact on water resources encroaching on the delivery of ecosystem services (Dandelot et al. 2008; Richardson & Van Wilgen 2004). Over the past 15 years, considerable sums (of more than R3.2 billion) have been allocated by the South African government to control IAPs and increase water yield and supply across the country (Currie, Milton & Steenkamp 2009). Gorgens and Van Wilgen (2004) confirmed the current knowledge of the impact of IAPs on water availability.

Primary productivity of the natural velds in South Africa for livestock farming needs predictions on the degrading gradients of rangelands, in order to strategize for proper interventions and reclamation processes. In South Africa, besides plant invasions, other factors that affect veld productivity include fire outbreaks, droughts, land use approaches and livestock population (overgrazing) and management. Recent literature has, however, highlighted the inducing forces on natural velds as both anthropogenic and natural sources (Lambin et al. 2007; Musil, Milton & Davis 2005).

As in other parts of the world, impacts of plant invasions in South Africa have been measured in numerous ways, such as making comparisons between biomes, or with other regions or countries (Van Wilgen et al. 2011). Nevertheless, both IAPs and other land use approaches generally contribute to land degradation, reduction of water resources and other available resources to native species and rural inhabitants. Veld degradation therefore requires empirical ecological and geospatial data for evaluation, reversion and reclamation.

1.3 OVERARCHING WATER RESEARCH COMMISSION PROJECT

Before proceeding to an in-depth discussion of the context of this study, it is important to bring to light the participating external bodies involved in this study. The Water Research Commission (WRC), a South African research programme, is an organisation that provides knowledge base of the prevalent water conditions in South Africa. This is done by funding water-related research that builds on the scientific database for distribution of information to relevant stakeholders. Despite addressing and improving challenges relating to water resources, technologies and legislation, WRC funds research related to aquatic ecosystems, waste management, natural vegetation, climate change and water use in agriculture. Nonetheless, this particular study is a part of a ‘larger project’ contracted by the WRC to various universities and professional organisations. This overarching project is to investigate the possibility of rehabilitating grassland after eradication of alien trees in the Eastern Cape. Among the organisations involved are Rhodes University, Agricultural Research Council (ARC), Stellenbosch University, Joe Gqabi District Municipality, CapeNature and University of Fort Hare.

The contextualisation of the overarching project aims to address issues in areas related to:

- Sustainable development solutions including applicability of reward for ecosystem services (RES) to sustainable management of grasslands.
- Improved models that provide better estimates for evapotranspiration (ET), water use efficiency (WUE) and livestock water productivity (LWP).
- Empowerment of communities, such as sustainable management by rural communities where livestock farming plays a crucial role in livelihood strategies.
- Optimizing the land use options available to graziers using the WUE and LWP concepts.
- Policy and decision-making that will provide evidence-based scientific input into the policies of Working for Water (WfW), Department of Water Affairs (DWAs) and Department of Agriculture, Forestry and Fisheries (DAFF).
- Human capital development in the water sector and training of post-graduate students in ET modelling and hydrology.

The aim of the overarching project is reflected in the research title, which is 'Rehabilitation of grassland after eradication of alien invasive plants in rural Eastern Cape'. The broad **objectives** include:

- Mapping land use land cover (LULC), classification and determining the historical time-serial dynamism using earth satellite imagery.
- Parameterize, evaluate and modify suitable models for ET, LWP and NPP estimates for IAPs and grasslands.
- Explore and compare ET, LWP and NPP among catchments with contrasting land tenure systems, comprising diverse biomass and condition states for grassland and IAPs.
- Apply selected models for predicting ET, LWP and NPP to these catchments.
- Sample and determine soil nutrient status to adjust the optimal soil condition necessary for regeneration or agricultural practices (restoration).
- Examine the possibility of using a RES system in rural rangelands as a possible solution to degradation and water issues (quantity and quality).

This research was funded by the Water Research Commission (project no. K5/2400/4 titled 'Rehabilitation of grasslands after eradication of alien invasive trees') under the guidance of Dr Gerhard Backeberg and Dr Sylvester Mpandeli. As a component of this overarching project, this study will focus on the following research questions: Is there a difference in the nutrient status of soils prior to and post-clearing of IAPs? Can land cover classification and change analysis be used to define change trajectories and evaluate degradation gradients? Can the effects of WfW clearing be measured using satellite data? Is the DPSIR framework suitable to use in this environment?

1.4 RESEARCH AIM AND OBJECTIVES

This study will therefore focus on carrying out some aspects in support of the overarching project. The **aim** of the present study is to investigate degradation gradients by natural and anthropogenic factors at landscape scale and associated rehabilitation progress. The **objectives** associated with this study are to:

1. measure the nutrient status of soils within the catchments, prior to and post clearing of IAPs and evaluating the optimal soil nutrient pools towards rehabilitation and land use options;
2. determine the extent of degradation through land cover classification and change analysis;
3. develop a novel framework for land cover change evaluation;
4. quantify the trends in NPP and ET prior and after clearing;
5. investigate and suggest alternative restoration interventions for landscape sustainability;
6. use the DPSIR framework to consolidate and report the landscape effects and solutions to decision makers.

1.5 RATIONALE AND SIGNIFICANCE

Quaternary catchments (QCs) in the Eastern Cape of South Africa are highly regenerative ecological systems sustaining socio-economic and political platforms that have been severely invaded by IAPs and altered by human factors. Limited options for new reservoir and other water schemes for the future prompted a sustainable approach towards increasing and conserving water supplies in rural areas in proximity to these catchments. Consequently, Chris Hani District Municipality and Working for Water (WfW) Alien Plant Clearing Programme, have been clearing IAPs in these catchments for the past twelve years with the primary motivation of water saving (Dye et al. 2008). Successful clearing of these often aggressive woody trees and shrubs requires careful regeneration of effective indigenous vegetation cover after the physical clear-felling and removal of IAPs (Palmer 2014). However, clearing of IAPs on their own is not a sufficient motivation to proceed with Municipal and WfW programmes. Therefore, there is a need to consider sustainability of the landscape when the activities of these programmes are completed (Palmer 2014).

The socio-ecological system (henceforth SES) existing in the rural landscape practices two different types of land tenure (land use) systems. Such land use includes freehold farms and communal/leasehold areas (with diametrically opposing landscape management approaches), coupled with diverse land cover types inter alia areas of irrigation agriculture, dryland cultivation, residential, extensive rangeland and forest. Each component of the SES depends on resources from carbon capture processes for building dwellings using forest woods; livestock feeding on the grassland NNP; annual crops/foods for households and forest fuel (wood) (Palmer 2014). As a result, strong consideration is given on the connectivity between the control of undesirable woody plants and derived benefits of humans living in the catchments. Carbon capture, as the primary driver of livestock and food production in this human-dominated SES, requires the evaluation of the relationship between the total economic value and water use efficiency (WUE) for the assessment of the water cycle.

Currently, the major users of water and carbon in this SES are livestock and alien trees. Therefore, changing the landscape water use of alien trees to increase water flow into dams and river systems will enable sustainability and achieving both end–user requirements (such as farming). Based on communal ownership, rangeland management approaches that were previously applied proved ineffective as the livestock owners over-exploited the rangeland because it was free (Palmer 2014). Besides parameterising LWP or WUE, ET and carbon capture (NPP), scenarios to influence land use behaviour/land–use pattern will be developed to evaluate the consequences the land tenure systems.

1.6 DESCRIPTION AND CHARACTERISTISATION OF STUDY SITES

Vegetation types

The study areas (three QCs), situated in the Mzimvubu to Keiskamma Water Management Areas (WMA), are bounded by the Great Kei River, the Great Fish River, the Orange River and the Mbashe River catchments (DWAF 2004). The catchments comprise areas of the former Transkei and Ciskei. The vegetation can best be described in relation to natural vegetation, formal afforestation and IAPs vegetation. However, grassland is dominant in the plateau areas with the invasion degree of Acacia Karoo Thornveld as well as moderate patches of semi-arid thorn bushveld and Afromontane forests. The vegetation diversity and richness have been degraded by IAPs, overgrazing, burning, wood-felling and poor farming practices.

Geological characteristics

The geological characteristics of the soil include the Beaufort series of the Karoo Supergroup (consisting of sandstone, mudstone and shale) and the Adelaide and Tarkastad subgroups (comprising mudstone and sandstone) dominate the catchments. In addition, the Molteno formation (containing siltstones, gritty sandstones, grey mudstones and shale) and the Elliot Formation (red and purple mudstone and medium-grained yellowish-white and red sandstone) were found to occur along the Tsomo and Northern boundaries (DWAF 2009; 2004). The soil compositions are mostly deep clayey loams to rocky soils, that stretches from Thomas river to the Tsomo river sub-catchments (DWAF 2009).

Land tenure system

The land tenure characterised in these areas ranges from private ownership to five different tenure systems including institutional (e.g. church), municipal, state, freehold and tribal land tenure systems. Freehold land tenure assumes the highest held land title by individuals and agricultural syndicates. Attempts have been made to annul the communal or tribal land tenure system due to irresponsible practice of land use such as overgrazing, but this has not yet yielded much success (DWAF 2004). Land use and settlement patterns are characterised by non-clustered rural and urban settlements as well as grazing and communal (subsistence) farming. Other land use activities include game farming and commercial farming (highly irrigated).

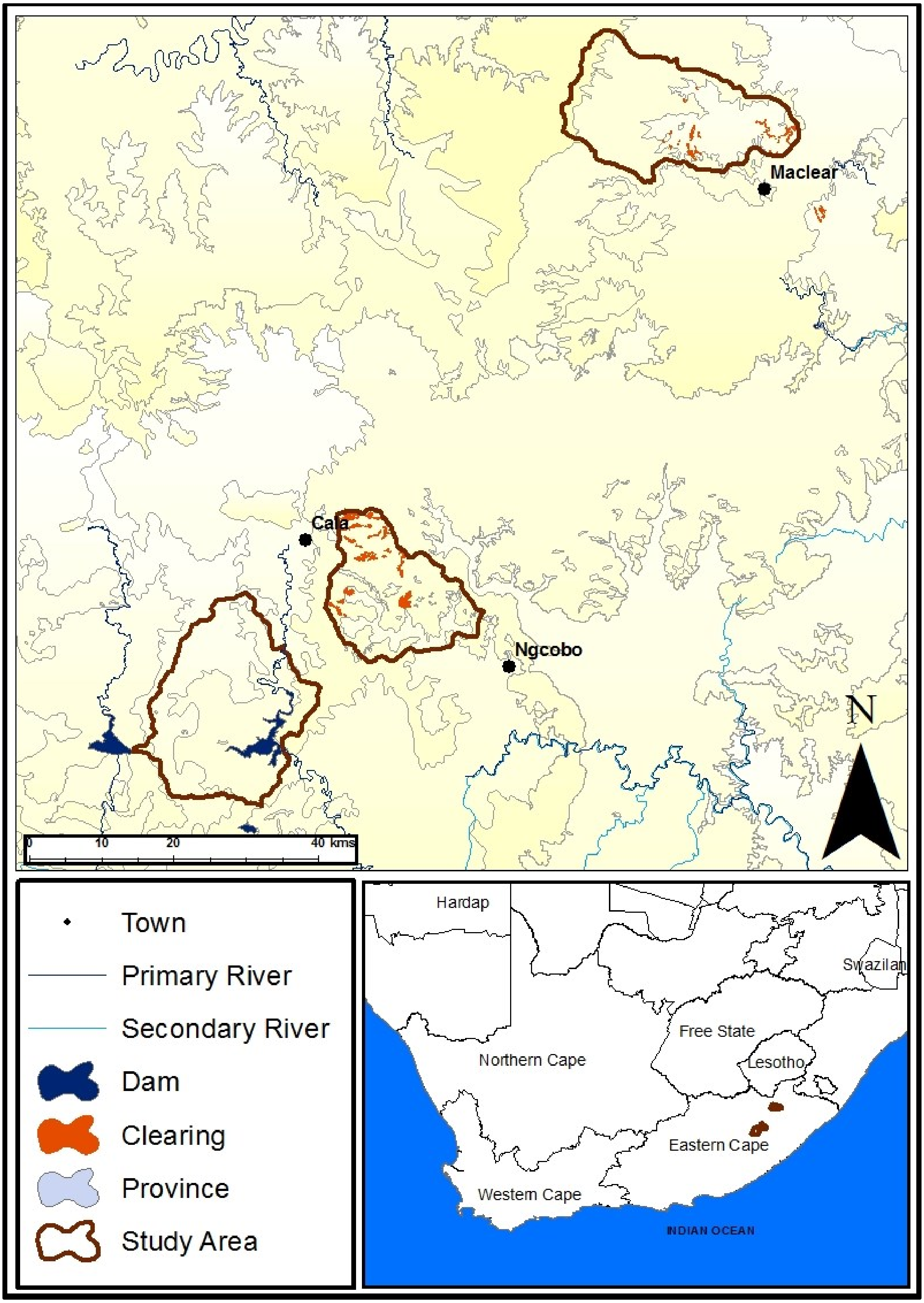


Figure 1.1 Three study sites (QC S50E, T12A and T35B) in relation to types, primary and secondary rivers, clearings, major towns and roads.

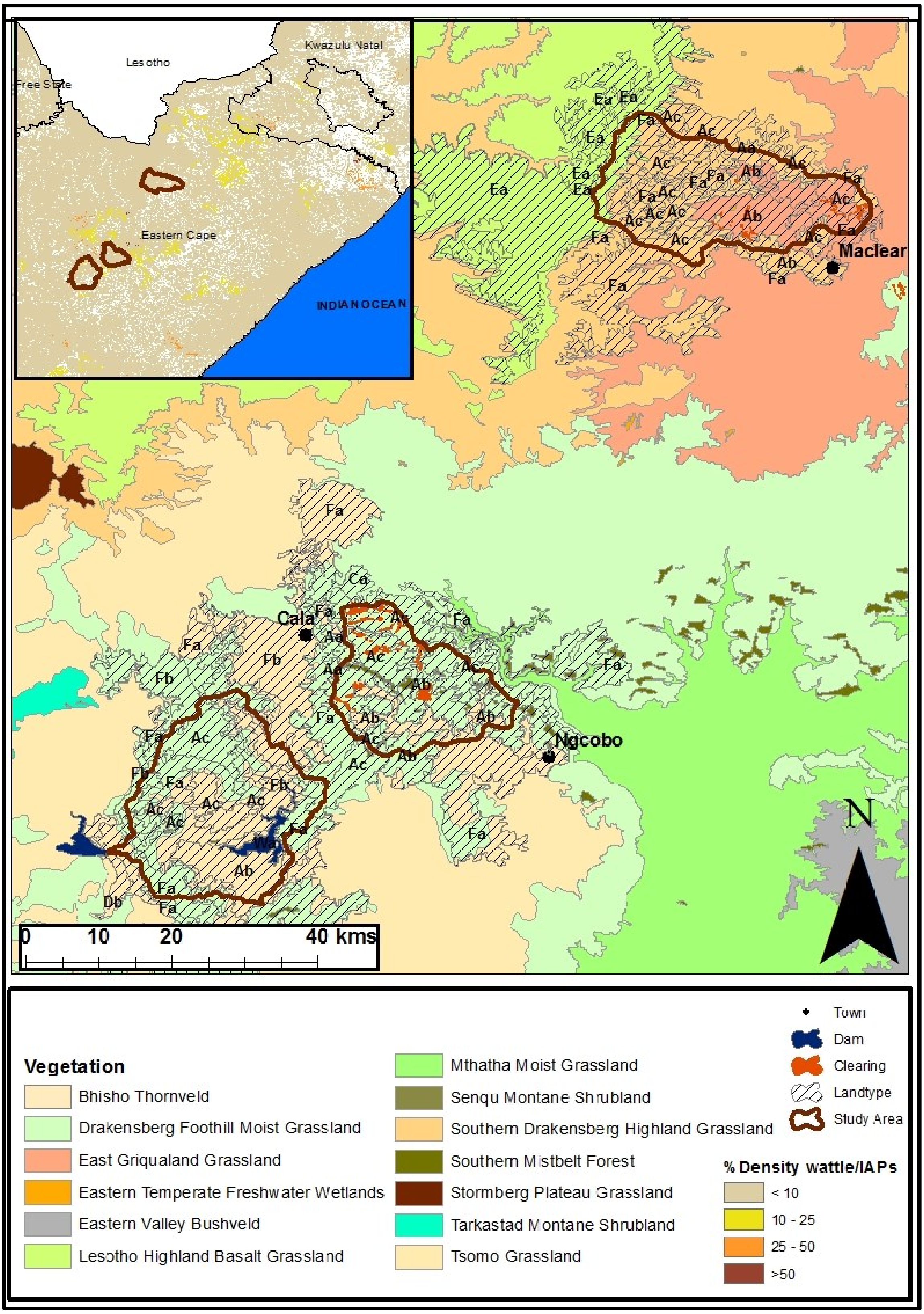


Figure 1.2 Study areas in relation to land types, with different vegetation types and dams.

Note: Landtypes Ab, Ac, Fa, and Fb in QC S50E and T12A composed of Elliot formation, Beaufort formation and Molteno formation of Karoo sequence (gabbro, alluvium and dolerite). Landtypes Ac, Ab, Fa, Ea in T35B composed of Elliot formation, Burgendorp formation, Molteno Formation and Drakensberg formation (dolerite and gabbro) of Tarkastad Subgroup. Terrain types: Thin humic A-horizons.

The QC S50E, having a landmass of 447.60 km^2 and stretching from the middle reaches of Kei River, represents an area where IAPs are a known threat, with high grazing potential and some clearings by WfW (Figure 1.1). The land types (Ab, Ac, Fa, Fb as shown in Figure 1.2) found in the catchment are mostly characterised by the Elliot formation, Beaufort group (Burgersdorp Formation), Molten formation of Karoo sequence as well as some gabbro, alluvium and dolerite intrusions. The terrain type is mostly of thin humic A- horizons of 300 – 400 depth. The soil texture characterises of fine sandy loam and sandy-clayey loam. The primary river in the catchment is the Tsomo River (Figure 1.1). The catchment is exclusively under communal tenure. S50E is located near Tsomo and contains the Emalahleni and Sakhisizwe Local Municipalities (Chris Hani District Municipality). This catchment supplies the Ncora Dam on the Tsomo River.

The QC T12A has an area of 278.66 km^2 and is situated east of Cala. Because it is in close proximity to S50E, it has similar vegetation types. These include Drakensberg foothill moist grassland and Tsomo grassland. In addition it has small patches of southern Misbelt forest (Figure 1.2). The Ab and Ac land types of this catchment contain similar formations to S50E with similar soil texture characteristics but these are found on different slope and terrain types (Figure 1.2). There is no dam or primary river cutting across this catchment. However, two secondary rivers, Nkwekwezi and Mgwali feed into Qumanco primary river south-west of the catchment. The catchment is under communal tenure and it has a good history of IAPs clearings done by WfW.

The QC T35B, 395.48 km^2, falls in the Mzimvubu catchment and contains examples of recent commercial afforestation, commercial rangelands and the SES associated with communal tenure. T35B, which forms part of the Elundini Local Municipality and Joe Gqabi District Municipality, is located near Ugie and Maclear where there has been increased afforestation over the last 20 years. There is no large dam in this catchment, but commercial rangelands without cultivation provide the opportunity to evaluate the effect of contrasting land tenure regimes on the evapotranspiration of grasslands. (Palmer 2014). The soil characteristics of T35B consist of land types (Ab, Ac, Fa, Ea) of the Burgendorp Formation (brownish-red and sandstone), the Molteno Formation, the Elliot Formation, the Tarkastad Subgroup with dolerite and gabbro of the Drakensberg Formation (Figure 1.2) which consists mainly of sandy-clayey, sandy-loamy and clay-loamy soils. The Mooi River at the western part of the catchment has its tributaries, Little Pot and Pot Rivers cutting into the catchment and some IAPs clearings have also been carried out by WFW in these areas.

1.7 RESEARCH DESIGN AND REPORT STRUCTURE.

The methodologies adopted for this project ranged from empirical to non-empirical strategies. The research approach adopted experimental, model building and empirical approaches, while the type of data to be used comprised predominantly of quantitative data. Primary data were collected through field sampling. Satellite imagery was acquired from source while secondary data were obtained from various institutions such as WfW for further analysis. The research design, shown in Figure 1.3, describes the salient steps and approaches that were undertaken for this project related to the particular objective addressed.

Agricultural practices intensify the impacts of IAPs as stipulated by Vitousek (1990) on the ecological ecosystem. These impacts include flow alteration (Mack & D'Antonio 1998) and resource reduction (Coutts-Smith & Downey 2006) within biogeochemical cycles and food webs (Gerber et al. 2008; Standish et al. 2004). Evaluating the change over time caused by these forces requires classification and change-detection analysis (Figure 1.3). Rehabilitating the degraded rangelands to suit the best land use options and end-user requirement will demand empirical ecological data analysis (soil analysis) as narrated in Figure 1.3. Investigating the best management strategy with a DPSIR framework for decision makers is also covered (Figure 1.3).

This chapter includes the introductory section that discussed the key issues of the present study: external bodies involved; contextualisation focus; and aims and objectives of the overarching research of which this research is a part of. The research aim and objectives of this study and the characteristics of study areas were discussed. The research design is provided in Figure 1.3. The main features that make up the design of this study will include mapping, change analysis, NPP and ET rate (e.g. IAPs, other vegetation), IAPs impact on soil nutrients and rehabilitation model. Outcomes of these features will be disseminated for decision makers using DPSIR framework.

The next two chapters (2 and 3) will evaluate and discuss some published scholarly works related to the study and highlight some neglected aspects in previous research, thus providing a detailed description of issues and potential research pathways for the current study and future research. Chapter 2 is a detailed literature review of the on IAPs in the context of alien invasion and loss of biodiversity and ecosystem services. It intends to distinguish between the inter-changeable definitions of land use and land cover. Progressively, understanding the susceptibility of grassland to invasion and related researches - coupled with the distribution of invasion across South Africa - are well-. Moreover, the impact-focus of IAPs on the SES is also detailed. Chapter 2 will conclude by discussing effective restoration practices for sustainable control and restoration (reclamation) of degraded rangelands.

Chapter 3 reviews literature on earth observation and of land cover assessment. It includes various mapping and classification procedures and tools such as unsupervised, supervised, OBIA and limitations of remotely sensed imagery to be adopted in the present study. Basic ancillary data (particularly vegetation indices) for rangeland mapping and classification errors are also reviewed. Lastly, accuracy validation and change detection techniques are discussed.

Chapter 4 focuses on the methods used in analysing soil nutrients including the sampling protocol and laboratory procedures, with these procedures being targeted at addressing objectives 1 and 5 of this study (Figure 1.3). The outcome of the analysis is statistically extrapolated and analysed. Chapter 4 also presents the results of the soil analysis directed at proffering a rehabilitation scheme suitable for soil remediation of the study areas. Discussion of the result and recommendations are also presented in this chapter.

Chapter 5 covers the methods used for land cover mapping as well as NPP and ET quantification trends (Figure 1.3). It provides the explanatory base of the framework adopted for land cover mapping, change detection analysis and accuracy assessment. The NPP and ET estimation techniques and the selected cover classes modelled are then discussed. The results and discussion addressing objectives 2 to 4 of the current study are included chapter 5 under various subheadings.

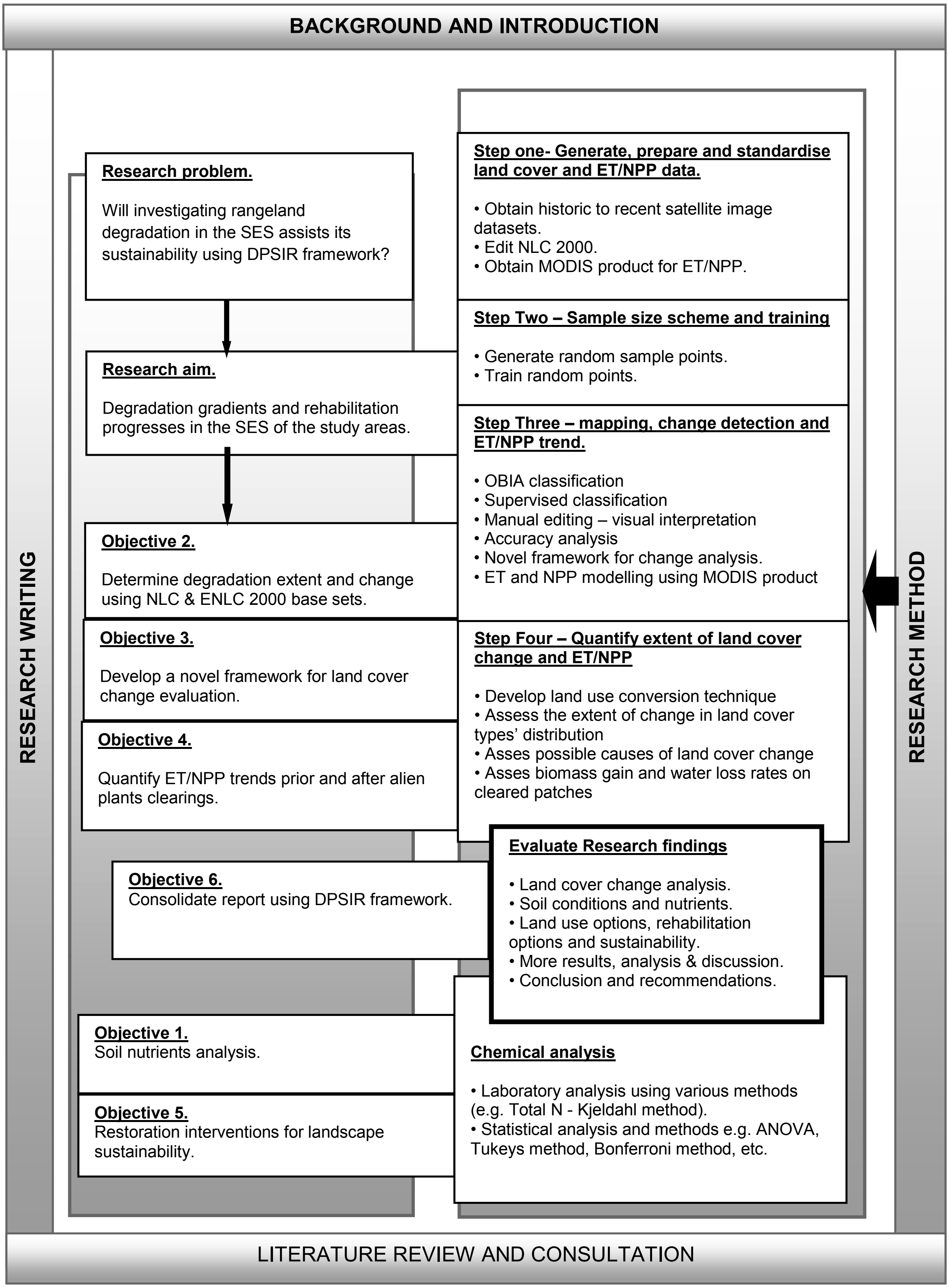


Figure 1.3 Sequential steps and procedures describing the methodology designed for attaining the objectives and aim of the study.

Chapter 6 discusses the overall issues towards the rehabilitation of the QCs identified by reflecting on the various generated results. It includes a presentation of the links between the objectives and the achievement of the major aims (of both the overarching project and this study) using the DPSIR framework. The DPSIR framework is used to address and discuss objective 6 of this study (Figure 1.3). This discussion is followed by an overview of a consolidated management scheme based on the DPSIR framework is which can provide policy-makers with improved land reform and land use options. In this chapter, the study will model the DPSIR framework to summarise various elements acting on the natural systems in the study areas. It will further establish the interaction between social and ecological impacts on the socio-ecological system (SES) existing at the QCs. This would enable decision makers in developing the management schemes suitable for the landscapes. Chapter 6 will close with salient concluding remarks on the research problem and critical reflection emanating from the aims, and the objectives in the light of the future sustainability strategies.

CHAPTER 2: **ALIEN PLANTS, IMPACTS AND RECLAMATION**

An in-depth review of related literature and current research through systematic discussion, debate, comparison and evaluation of previous findings will aid in the realisation of the objectives and address uncertainties for the present study. The literature review that is both directly and indirectly related to the present study will aid in the identification of the weaknesses and strengths of the methodologies to be adopted. This research utilises a multi-disciplinary approach including ecology, soil science, geography (GIS and remote sensing) and social science. The reviewed literature is divided into two chapters (2 and 3).

The current chapter will encapsulate the contextual literature on alien plants, invasion, distribution, impact, control, grasslands invasibility and reclamation within several analytical platforms. For the purpose of clarity, each component is subdivided into individual sections namely:

- Alien invasion, biodiversity and ecosystem services;
- Definitions and drivers of land use land cover change;
- Invasibility of grassland biome;
- Invasion distribution in South Africa;
- Impacts of alien invasive plants; and
- Control of IAPs and restoration of degraded ecosystem (rangelands).

2.1 **ALIEN INVASION, BIODIVERSITY AND ECOSYSTEM SERVICES**

Globally recognized as the second largest threat to biodiversity (Driver et al. 2012; Diaz et al. 2006) and ecosystem functioning (Mack et al. 2000; Riuz, Fofonoff, & Hines 1999; Crooks & Khim 1999) after habitat destruction, IAPs compromise ecosystem processes that transform into essential supplies for human and ecosystem survival. Alien plant invasion has been identified as a growing threat to effective delivery of ecosystem services such as the provision of food, game animals, pharmaceuticals, water, timber; regulating climate, flood, disease, pollination and purification of water/air; detoxifying and decomposing waste and culturally as recreation, aesthetics, tourism and spirituality (Millennium Ecosystem Assessment 2005). This collection of ecosystem services operates across a wide range of spatial and temporal scales (Daily et al. 1997). Should the current trend of alien invasion persist, the impacts could limit accessibility to secure livelihoods, good health and social relations, security and freedom (Mooney 2005) and the disruption of the delivery of goods and services (Pejchar & Mooney 2009; Daily et al. 1997). Invariably, reduction in biodiversity (Diaz et al. 2006; Loreau et al. 2001) heightens the ecosystem susceptibility to biological invasions that, in turn, erodes ecosystem services (Diaz et al. 2006).

Biodiversity, along with other natural resources, has been altered due to natural or anthropogenic factors that influence land cover distribution. Ecological degradation stemming from myriads of human development and natural disasters has resulted in significant land cover change over the past hundred years, with detectable biodiversity loss and habitat fragmentation (Biggs & Scholes 2002). Diverse land use patterns, resulting from varying land user attitudes towards land exploitation and management, often lead to ecological destruction, biodiversity loss and high water abstraction (Foley et al. 2005).

As a significant property of ecology, biodiversity is constantly threatened by alien invasion which impacts on ecological processes such as plant-soil interrelationship, soil nutrient cycling, as well as system resistance and stability (De Villiers et al. 2005; Mannion 2002). When biodiversity is reduced, greater loss of soil nutrients through leaching will occur, which eventually lowers soil fertility vis-a-vis plant productivity (Tilman et al. 1997). Land cover change caused by IAPs further alters soil moisture and hydrological cycles, consequently leading to ecosystem pollution, water system contamination and shortage (Dandelot et al. 2008; Richardson & Van Wilgen 2004). However, a need to balance the generic empirical properties of soil nutrient cycling to promote productivity, vis-a-vis enabling active restoration is required, as alien impacts often appear to be species-site-specific.

2.2 LAND USE AND LAND COVER CHANGE DEFINITIONS

Scientific literature often misconstrues the true meaning and usage of land cover and land use, using both terms as either separate entities sharing one meaning or interchangeable wordings of either terms. In order to maintain consistency, these two terms will be specified as ‘land cover’ and ‘land use’ rather than ‘land-cover’ and ‘land-use’, when used as adjectives. Although there are significant overlaps between land cover and land use classification, the current misrepresentation possibly emerged from inter-relatedness of both terms in human settlement regions (Stuckenberg 2012). For instance, a cropland or IAPs can be classified as a land cover class as well as a land use pattern due to their economic relevance.

In order to clarify the similarities and differences between these two terminologies and for the purpose of this research, the term ‘land cover’ describes the physical and biological features covering the earth surface. The more complicated term, 'land use', attracted diverse definitions as natural scientists view land use as anthropogenic activities (agriculture, construction, forestry etc.) that alter earth surface processes such as biodiversity, hydrology and biogeochemical processes (Ellis 2013). However, social researchers (land managers) included socio-economic context and purpose of land management in the definition of land use. For the purpose of this research, IAPs will be categorised as land cover change (LCC) in relation to their ecological impact, also as land use change (LUC) from a socio-economic impact perspective. Land use land cover change (LULCC) (also referred to as 'land change') can be simply defined as land modification pattern by human activities for subsistence and commercial as well as natural factors that generally influence natural ecosystem processes.

Land cover can be directly (in situ field observation) and indirectly (earth observation) monitored but evaluation of land use and land use change requires consolidation of social (interviews with stakeholders) and scientific approaches to determine the impacts of various human activities at different regions in the landscape; especially when such areas appear unperturbed. For instance, as woody vegetation may appear as a functional shrubland, or as a commercial plantation undergoing re-growth after harvesting. This confirms the importance of LULCC to be tackled from an interdisciplinary stance by unifying both scientific approaches (social and natural contexts) (Ellis 2013). Monitoring and curbing the resultant impacts of LULCC in order to sustain land resources has become the primary responsibility of policy-makers, land managers and researchers. Broad impacts of LULCC, methods of control and measurement as well as restoration protocols are further detailed in this chapter.

2.3 INVASION DISTRIBUTION IN SOUTH AFRICA

As the name implies, 'alien' or exotic plants comprise plant species not recognised as indigenous or dominating species within a particular vegetation class. Alien plants are mostly introduced from a different location into 'natural vegetation' of rich biodiversity and functional ecosystem. Following their introduction, alien plants become invasive by establishing their basal cover and expanding rapidly beyond current habitat boundaries (Lodge 1993). Alien species introduction are mostly products of direct continuous human re-distribution of species to support agriculture, aquaculture and recreation; indirectly through ballast water discharge, attachment to ships' hulls and creation of new links between oceans. Approximately, 50 000 foreign species (non-native species) were introduced in the United States as a result of human population growth, rapid movement of people and alteration of the environment (Pimentel, Zuniga & Morrison 2005). There is an increase in international trade of goods and materials among nations, and this trade patterns create opportunities for unintentional introductions (USBC 2001). Due to development and commercial activities, deliberate introductions of alien plants exist in most countries. In other words, introduction of alien species could either be accidental or deliberate; many efforts to decipher the properties that code them into becoming invasive have been attempted (Gurvich, Tecco & Díaz 2005).

In the 17th century, alien species were accidentally introduced in South Africa by the European ships that stopped at Cape of Good Hope for overhauling; but were also cultivated deliberately for commercial afforestation due to predominant slow growing indigenous trees (Beater 2006). In order to meet the increasing demand for timber, tannins, oils, firewood, wind breakers, ornamentals, charcoal etc., fast growing tree species were introduced (Nyoka 2003). One hundred and sixty-one out of about 8 750 trees introduced into South Africa (Van Wilgen et al. 2001) are regarded as invasive with 110 of the invasive species being classified as woody trees (Nyoka 2003). The introduction and purpose of early invaders is detailed by Van Wilgen et al. (2001), while emerging invaders are highlighted by Mgidi et al. (2007) and Nel et al. (2004).

Recently, growing concerns on safeguarding the socio-ecological benefits of ecosystems have overridden the initial celebration of plant transfers (Cronk & Fuller 1995); as condensed from the large body of literature pummelling on the disruptive effects of IAPs (Ehrenfeld, Kourtev & Huang 2001; Le Maître Versfeld & Chapman 2000; Dye & Poulter 1995). Plant transfers seem to be categorised as good and bad scenarios (Kull & Rangan 2008) or conflict of interest between the two, but do-nothing scenario is not sustainable because the benefit – cost ratio is not always justified (see De Wit, Crookes & Van Wilgen 2001).

Several estimates have been made (Nyoka 2003) using different methods, including concentrating on a particular specie or area, to analyse the spatial extent of alien plant invasions in South Africa (Van Wilgen, Forsyth & Le Maître 2008; Van Wilgen et al. 2001; Le Maître, Versfeld & Chapman 2000). Estimates on the range and abundance of alien plant invasions in South Africa have been made using several methods and analyses (Kotze et al. 2010; Van Wilgen, Forsyth & Le Maître 2008; Nyoka 2003). With mapped areas of 18 million hectares of IAPs in 2010 (Kotze et al. 2010), this figure has significantly increased from the rough estimates made by Le Maître, Versfeld & Chapman (2000) of only 10 million hectares in 1996 / 1997. The Southern African Plant Invaders (SAPIA) database, however, harbours IAPs data distribution records in South Africa (Lesotho) and Swaziland with a record span of 31-year period (Henderson 2010). This information database is best used for broad-scale study (national or regional scale) for evaluation of invasion potential, degree and impacts as well as the distribution of contemporary emerging alien plants (Van Wilgen, Nel & Rouget 2007; Van Wilgen et al. 2004; Richardson & Van Wilgen 2004).

The 'invasion paradox' (Fridley et al. 2007) describes the successful invasion and co-existence of alien species in non-native habitat through niche differentiation (Catford et al. 2012; Lambdon Lloret & Hulme 2008) and habitat filtering (Keddy 1992). The former remarked on the unique traits of alien species over native species that promote alien invasion and dominance at different niches. Such unique traits include possession of leaves and branches (e.g. *Acacia mearnsii*, *Lantana camara*) that contains chemical inhibition of growth and seed germination of other plants (allelopathic properties) and fire-tolerance features (e.g. *Cytisus spp*., *Brassica spp*) (Richardson & Van Wilgen 2004); while the habitat filtering points out that alien species possess specific traits to pre-adapt to new habitat, probably sharing similar traits with native species. In plain terms, successful alien species invasion is dependent on alien invasiveness and community invasibility, where the capacity of alien species to invade varies significantly with ecosystem's susceptibility. Such habitat susceptibility, for instance, accelerated the invasion of *Bromus tectorum* in the Great Basin Sagebrush ecosystem (Chambers et al. 2007).

Gurvich, Tecco & Díaz (2005) meta-analysed certain vegetative attributes, termed triggering attributes, from the literature to demonstrate uniqueness in trait distribution as attributes of dominance in an ecosystem. Chapin et al. (1996) proposed that the invasion of any specific species was relative to these peculiar attributes that bridged the trait distribution in a community. Such adaptive invasion by alien species through evolution was illustrated by Prentis et al. (2008). Generally, invasive intensity highly depends on the invasion history and reproduction rate of invading species (Kolar & Lodge 2001).

Conversely, Vitousek (1986) argued that the impact on biodiversity and ecosystem function was dramatically higher when an entirely new life form invaded an ecosystem. Fridley et al. (2007) confirmed the probability that rich native ecosystems serve as hotspots for alien species with associated reduction in biodiversity. Moreover, Mgidi et al. (2007) established the invasion potential of emerging invaders along with Nel et al. (2004) using climate envelope modelling (CEM). While updating the protocol for the SAPIA database, new and emerging alien plants invasions were discovered in various provinces in South Africa (Henderson 2010). For instances *Senecio inaequidens* and *S. pterophorus,* two alien plants from South Africa that invaded protected areas in Spain, were shown to establish a higher invasion rate in grassland and shrubland than in forests between seasonal disturbances in Mediterranean plant communities (Caño, Escarré & Sans 2007).

The multivariate analysis conducted by De Gruchy, Reader & Larson (2005) strongly affirmed that the alien and native species compositions relied heavily on disturbance type, species composition and nutrient level (see also Chambers et al. 2007). Fire and grazing impacts also create favourable gradients for successful displacement of native species by alien plants in blue oaks savannah, chaparral and coniferous forests (Keeley, Lubin & Fotheringham 2003). A sub-sequential decadal mapping of fire history and invasion in Banskia woodland was found to reduce species richness and changed resource use patterns with increased level of invasion (Fisher et al. 2009). Fire, with removal of perennial herbs across elevation gradients, increases the potential for invasion and resource availability (soil water and nitrate) in sagebrush ecosystem that favour the invasiveness of *Bromus tectorum* (Chambers et al. 2007). Sanders et al. (2007) suggested insects as mediators in invasion dynamics.

Invader-community interaction determines the rate of displacement of native plants by alien plants (Lambrinos 2002; Troumbis, Galanidis & Kokkoris 2002) as the biotic and abiotic characteristics of a habitat can act as barriers to invasion (Levine, Adler & Yelenik 2004). There are various factors and attributes that have allowed IAPs to gain dominance in non-native habitats (e.g. Gurvich, Paula & Sandra 2005; Lambrinos 2002; Davis et al. 2000). These include the eco-physiological characteristics of invasion and invasibility (e.g. Rejmánek 1996; Roy 1990) inter alia climate change, fire regime, land use, grazing and spread vectors that interactively promote the invasion of alien invasive species (Crowl et al. 2008).

General review on invasiveness tends to greatly concur with the evidence pertaining to target-community susceptibility as compared to the attributes of alien plants (Shea & Chesson 2002). However, other factors influence invasiveness and community invasibility as found in invading species and community characteristics and dynamics (Hobbs & Humphries 1995). Such other factors include taxonomic position, seed dormancy, edge effects, resource availability and mode of reproduction (Beater, Garner & Witkowski 2008).

Grasslands, as well as savannah biomes, are noted to be extensively invaded by *Acacia spp, Pinus spp, Eucalyptus spp, Salix fragilis Melia azedarach* and *Jacaranda mimosifolia* both at riparian and non-riparian zones (Nyoka 2003). However, grasslands of the Drakensberg escarpment, moister regions of savannah biome along the lower escarpment and the KwaZulu-Natal midlands and coastal belt seem to be worst affected (Van Wilgen et al. 2001).

Globally, most temperate grasslands are heavily impacted by agricultural reinforcement with the recent aftermath of invasion intensification. Roadside grasslands dominated by grazers and serpentine soil reveal the reverse, but contradictory effects of alien invasion as non-grazed patches close to the roadside show higher density of exotic plants than grazed patches away from the roadside (Safford & Harrison 2001). Despite the anthropogenic activities and grazing potential, there are still predispositions of fescue grasslands invasion by IAPs (Tyser & Worley 1992). For instance, *Phledimus stoloniferus*, an aggressive alien species, was seen to displace native species and affected agricultural activities in the invaded grasslands (Huguenin-Elie n.d).

High density stands of alien conifers were shown to reduce nearly 29 000 grassland invertebrates (composition of beetle species) at low tree density (400 trees per ha) (Pawson et al. 2010). Coleoptera diversity in Drakensberg grasslands experienced greater reduction in size in grasslands invaded by *Acacia dealbata* (Coetzee, Rensburg & Robertson 2007). In addition, reduced grassland ant richness and colony size was prominent in *Solidago spp* invaded grasslands compared to non-invaded grasslands by as it increased the workers' foraging activities (Lenda et al. 2013). *Chromoelana odorata* invasion further reduced endemic fauna (spider colony) in a grassland community with high grazing intensities (Mgobozi, Somers & Dippenaar-Schoeman 2008).

Grassland invasibility might be promoted by grazing intensity, roadside deposition, resource availability and community composition (Renne, Tracy & Colonna 2006). The biotic and abiotic assemblages of grassland communities seem to be affected as a result of natural and anthropogenic tendencies (Pawson et al. 2010; Safford & Harrison 2001). Nonetheless, grassland invasibility and its associated impacts appear to be well researched and documented (Pawson et al. 2010; Lenda et al. 2013).

2.4 IMPACTS OF INVASIVE ALIEN PLANTS

The impacts of IAPs can be described as the alteration of entire ecosystem processes (Mack et al. 2000). The impact of IAPs is apparent in the distortion of habitat structure through fragmentation, alteration, destruction or replacement. These impacts have rippling effects through reduction in biodiversity to disruption of ecosystem functions and services. For example, the removal of hemlock woolly adelgid (a small, aphid-like insect), had direct impacts on the structure, composition and ecosystem function (Kizlinski et al. 2002), as well as indirectly affecting the composition and distribution, of bird populations in the community (Tingley et al. 2002). Description of IAPs impacts can be either theoretical or anecdotal. It can also be explained in various forms. For the present study, it has been narrowed to the ecological systems pertaining to this study.

As compared to indigenous trees, alien plants are known to extend their basal roots deeper into the soil, sucking out comparatively larger volumes of water and out-competing indigenous plants. In riparian zones, run-off and stream flows have been obstructed by self-established alien invasive stands due to increased evapotranspiration (ET) rates. For example, changes in stream flow voluminously increased in a fynbos catchment (mountainous) after clearing of riparian vegetation invaded by *Acacia spp*. in the Western Cape (Prinsloo & Scott 1999). Diurnal transpiration of IAPs causes stream flow fluctuations but with a cloudy moist climate, evapotranspiration decreases as evaporative air demand is lessened (Dye & Poulter 1995). Difficulties exist in establishing IAPs' impacts on water use or water resources, consequently few studies have attempted such impact quantification of IAPs on water resources (Dye et al. 2001; Le Maître, Versfeld & Chapman 2000; Prinsloo & Scott 1999).

Alien plants' novel strategies competitively absorb soil nutrients and moisture and alter the accessibility, timing, abundance of these resources to resident species (Ehrenfeld & Scott 2001). Because of their novelty, in terms of their biochemical and physiological composition, alien plant invasion of any plant community predispose their strong influence on soil nutrients and cycles (Ehrenfeld 2003; Ehrenfeld, Kourtev & Huang 2001; Ehrenfeld & Scott 2001). For example, C4 alien grass (*Microstegium vimineum*) litter and *Bromus tectorum* immobilised Nitrogen (N) with high carbon and nitrogen concentration at low decomposition rates (Thorpe & Callaway 2005; Ehrenfeld, Kourtev & Huang 2001).

Myrica faya promoted invasion of other exotic earthworms that depleted soil-stored nitrogen, altering the natural nutrient cycling through its elevated increase of soil nitrogen (Thorpe & Callaway 2005). Non-nitrogen fixing IAPs' litter quality might influence the populations and activities of nitrogen-fixing bacteria with no symbiotic relationship, thus altering nitrogen input in the soil (Thorpe & Callaway 2005). For example, altering of nutrient cycles by alien plants (*Centaurea maculosa*) through root exudates (polyphenol) impacted strongly on some groups of bacteria and some processes of the nitrogen cycle of the soil (Bais et al. 2003). *Bromus tectorum* dramatically altered phosphorus cycling through its novel accessibility to recalcitrant phosphorus unavailable to native plants, thereby increasing its dominance over the natives (Thorpe & Callaway 2005). Conclusively, IAPs exhibit novel schemes that can alter soil community, nutrient availability, nutrient cycling and existing plant-soil interaction, as well as water resource availability, that will proportionately affect ecosystem function and productivity.

A considerable amount of literature has captured the magnitude of IAPs impact on ecological, economic and social structures using various cumulative, systematic and empirical methods of assessment and evaluation (Pysek et al. 2012; Vila et al. 2011). The effects of IAPs on the delivery of ecosystem services from which all life forms are sustained is often excluded (Hulme et al. 2013). However, the global overview of significant ecological impacts of IAPs in literature provided highlights the complex interaction existing between the characteristics of IAPs and the susceptible environment (Pysek et al. 2012). Synthesising 199 articles to describe impacts of 135 alien plants taxa on ecosystem and surrounding on a global scale, it was found that of the 24 different impact types studied, 11 were noted to be significantly affected by alien plants, although the magnitude and direction differed within and between various impact types (Vila et al. 2011). Pysek et al. (2012), however, argued that there was no global measure of alien impact and that impact measurement solely depended on the existing context. Ehrenfeld (2003) conducted a similar meta-analysis on the effects of invasive alien species on soil nutrient cycling processes by reviewing literature on soil-related processes, soil moisture and comparison between exotic and native species in terms of co-occurrence and displacement. It was found that the spatial and temporal alien species impacts were not significantly varied among ecosystem types, but that the impacts to heterogeneity and consistency varies within an impact type. However, Simberloff (2014) found that ten percent of invading species have specific and obvious impacts on different components of the natural ecosystems. Nonetheless, the biases in various syntheses and individual impact assessments stemmed from the neglect on the biogeography of the study species and impact extent, that has no direct translation to ecosystem service reduction (Hulme et al. 2013), not until recently (see Petz, Glenday & Alkemade 2014).

The measurement of specie-impact assessment is often impractical and difficult due to high variability of biodiversity in an ecosystem (O'Connor & Kuyler 2009) and scarce knowledge and understanding of the ecosystem vulnerability to degradation and biodiversity loss (Cowling & Heijnis 2001; Holmes & Richardson 1999). Habitat destruction varies between species, often making it impossible to quantify the impacts at measurement scale, since the degradation threshold of an ecosystem which could lead to biodiversity extermination are not clearly established (Didham et al. 2007; Cowling & Heijnis 2001). Commonly, biodiversity measurement is factored into spatial evolutionary and ecological processes that are difficult to quantify, but often easy to input into spatial analysis methods (Cowling & Heijnis 2001). No acceptable standards for impact measurement of land-change exist to fully quantify the devastating impacts of LULCC (Reyers et al. 2001).

2.5 KEY INVASIVE ALIEN PLANTS IN SOUTH AFRICA

About 1 300 species of trees and shrubs of *Acacia* species originating from Australia and Tasmania (Maslin 2001) are the most threatening IAPs worldwide. *Acacia mearnsii* De Wild (also called black wattle) and *Acacia dealbata* Link (also known as silver wattle) are one of the key invasive tree species in South Africa, occurring mostly at the Drakensberg Escarpment of the Eastern Cape and KwaZulu-Natal provinces (Pieterse & Boucher 1997). These fast-growing, nitrogen-fixing trees introduced in the 19th century as a commercial source of tannin, timber, ornaments and as a source of fuel wood for local communities (Matthews & Brand 2004) invade about 2 500 000 ha in South Africa. Although these species seem unable to produce viable seed at lower altitudes, they occur as the most prolific plant invaders in disturbed areas, riparian habitats, roadsides and veld, rangelands and grasslands, forest edges and woodlands, urban areas and water courses. *Acacia mearnsii* and *Acacia dealbata* rate as the number eleven invaders in the fynbos biome, fifth in Natal and sixth in Transvaal (Pieterse & Boucher 1997). Known for their high water utilisation capacity, these fast-growing dominating species have created socio-economic concerns as well as ecological unsustainability relating to displacement and encroachment on native vegetated grassland and arable lands.

The invasiveness of these species may be attributed to their phenotypic features, vegetative regeneration, allelopathic properties as well as their positive plant-disturbance relationship (Fuentes-Ramírez et al. 2011). The dual effects of *Acacia spp* in terms of its source of livelihood for rural population and high water consumption agree strongly with the aforementioned ‘conflict of interest’ argued by De Wit, Crookes & Van Wilgen (2001) and further debated by De Neergaard et al. (2005). Black and silver wattle rank topmost in water use among other invading species, reducing Mean Annual Runoff (MAR) by an estimated 7 % (Le Maître, Versfeld & Chapman 2000) and averagely 200mm yr^{-1} of long periodic mean annual rainfall (De Neergaard et al. 2005). Other socio-ecological impacts caused by these species include decreasing diversity of invertebrates, reducing stream flow, destabilizing stream banks, increasing erosion and altering soil community (Prinsloo & Scott 1999).

2.6 CONTROLLING INVASIVE ALIEN PLANTS

Three practical approaches – mechanical, chemical and biological – are used in controlling IAPs, but often prove ineffective once alien invasion has gained maturity. Mechanical or manual clearing of alien plants has been identified as the eco-friendliest and frequently used method, but is labour intensive (Mack et al. 2000). Other mechanical approaches include manual-pulling, hand-cutting and fire-burning, but such methods are also limited by their small-scale application.

In agriculture, chemical methods are most commonly used in combating weed population, but this is limited for broad-scale application due to its cost. Adverse effects on human health and non-target crops also hinders its usage; however contemporary herbicides tend to be user- and environmentally- friendly in terms of toxicity, residence time and specificity (Hobbs & Humphries 1995). Biological control methods have emerged due to the limitations of chemical and mechanical control methods when immediate intervention and remediation are required. Reducing the impact by removal of alien plants through skilful introduction of specialist natural enemies such as bio-control agents can replace chemical and mechanical methods (Olckers, Zimmermann & Hoffman 1998). However, non-specificity of bio-control agents to the target host can cause extinction of non-target species (Simberloff & Stiling 1996; Howarth 1991), this being the major pitfall of this method. However, the parsimonious costs of operation, safety operation, extensive natural dispersal, easy integration with other management approaches and self-sustaining of biological control methods has outweighed the criticisms against this method.

Strategizing for sustainability and conservation, the national Working for Water programme (WfW) was established to bridge the gap between socio-economic development and ecological health. WfW, administered previously through the Department of Water Affairs and Forestry and now the Department of Environmental Affairs, was established in 1995 with initial allocation of R25 million for development (Macdonald 2004). The WfW programme attempts to maximise the sustainability of natural, ecological, social, economic and political activities between man and natural resources, plainly stated, managing and saving water resources and ecosystem services from IAPs (Macdonald 2004). Since the inception of WfW, large area masses of riparian zones invaded by mostly woody plants have undergone clearing and follow-up treatment. For instance, Sabie River and Kei River catchments have been frequently cleared (Levendal et al. 2008) and documentation of the clearing history of both catchments have been kept.

Many studies focus on control approaches such as removal of IAPs, while recovery of invaded habitats to pristine states are carried out through processes of natural attenuation without further management procedures (Reid et al. 2009). Although vegetation regeneration will occur, it is often impaired by the re-sprouting of removed plant species. Such passive restorations may defeat the purpose of the initial control measures applied, exacerbate the invasion degree and alter the already designed management strategy. In order to avoid greater habitat loss and degradation, active ecosystem restoration is a highly valuable tool in achieving conservation and eco-sustainability (Cairns 2002; Hobbs & Harris 2001).

Objectively, ecosystem restoration aims at returning a degenerated habitat to its natural condition prior to degradation, as well as restoring the functionality and self-regulatory ecosystem processes. This theoretical restoration goal was readily broadened to inculcate 'recovery assistance and ecological management' as the most crucial but critical processes in achieving active ecosystem restoration (Society for Ecological Restoration 1996). However, it may be extremely difficult to return a degraded habitat to its pristine state after a disturbance regime, as evolved discontinuity in resident pools, dominance shifts, trophic connectivity and biogeochemical processes during invasion may impair the restoration strategy and efforts (Suding et al. 2004). Physical, chemical and biological phases of an ecosystem often limit ecosystem repair, therefore it is imperative to understand the re-vegetation process, reinvasion impact on regeneration, key species that drive regeneration coupled with vegetation structure and restoration process (Beater 2006).

Exclosures are, a commonly used rehabilitation approach in arid and semi-arid zones, to prevent livestock grazing in degraded sites. The term 'exclosures' refer to protected land units from a particular class of animals using barriers, quite opposite of 'enclosures' but often interchangeably used in literature (Aerts, Nyssen & Haile 2009). This is to allow for regeneration of native species in order to increase water infiltration and woody biomass as well as to reduce soil disturbance and erosion. Many studies have proven the effectiveness of exclosures in rejuvenating degraded soils that occur as a result of overgrazing (Mekuria et al 2007), in addition to the restoration of native vegetation in communal grazing lands (Yayneshet, Eik & Moe 2009) and the recovery of woody vegetation in a degraded dryland (Mengistu et al. 2005). Exclosures have also been established to be effective in recovering native plant species community, richness, diversity and general vegetation cover and structure in degraded rangelands (Yayneshet, Eik & Moe 2009).

Visser, Botha & Hardy (2004) evaluated various rehabilitation methods and treatment procedures (mosaic of seeding, tilling and branches) to re-vegetate bare patches of degraded rangeland as a result of overgrazing in Nama Karoo. A combination of different restoration techniques such as brush packing, ripping over sowing and organic matter addition were used as a trial test on a farm denuded with brackish soil and was confirmed as an effective restoration treatment if applied in degraded rangelands (Van den Berg & Kellner 2005). A different set of restoration methods was employed by Snyman (2003).in a semi-arid rangeland, over sowing and mechanical inputs. Successful re-establishing of some species were recorded after 10 years, but slow restoration in semi-arid rangelands were registered as a result of unreliable rainfall.

As discussed in Chapter 1, passive approaches for restoring functionality in degraded ecosystems (Gaertner et al. 2012; Le Maître et al. 2011) often fail due to reinvasion of the removed invader or another invader (Loo et al. 2009; Zavaleta et al. 2001). Active restoration, including additional restoration protocols after IAPs removal, has proven to be effective when restoring ecosystems degraded by alien invasion (Van den Berg & Kellner 2005; Visser, Botha & Hardy 2004). Therefore, the restoration protocol for this study is assumed to adopt similar rehabilitation programmes according to the outcome of the soil analysis to achieve active restoration and sustainability.

2.7 **CONCLUSION**

For several decades, land management and sustainability, often jeopardised by the consequences of pollution, biodiversity and climate change stemming from LULC changes, has been a growing concern at regional and global scales. Conservation of biodiversity requires policies and practises that will preserve natural reserves of high biodiversity from intensive agriculture and livestock grazing. Human overexploitation of natural resources has been the major drivers of land cover and land use change (Ellis 2013). Anthropogenic degradation renders the system permeable to other forms of natural and biological degradation such as IAPs and soil erosion. Although introduced for commercial forestry for economic development in the early era, alien plants have expanded beyond their cultivated boundaries and they are aiding in promoting LULCC and causing havoc in the socio-ecological sector.

Recently, research into IAPs has attempted to unravel the potentiality of alien species to colonise, persist and expand their ranges (Fridley et al. 2007; Lodge 1993), as well as the prevention and control of invasive species and potential ecological (Reid et al. 2009; Mack et al. 2000) and economic (Pimentel, Zuniga & Morrison 2005) impacts. Research into IAPs has been aimed at developing and improving the designs of control and management strategies (Van den Berg & Kellner 2005; Visser, Botha & Hardy 2004). While research is mostly centred on control strategies of various elementary physical, chemical and biological measures to abate IAPs invasion, these control approaches, also assumed as restoration methods, continued to be ineffective. As paramount as it is to understand the mechanism that facilitates or inhibits invasion, it is essential to assess threats and define control/restoration options for each invaded habitat and surrounding community (Valentine, Magierowski & Johnson 2007). The next chapter will review the literature on ET/NPP, land cover mapping and change analysis, related to various geospatial tools, as well as mapping and evaluation methods,

CHAPTER 3: **EARTH OBSERVATION AND LAND COVER MAPPING**

This chapter presents a theoretical review of earth observation and land cover mapping as well as ET/NPP modelling.

The review is structured into the following subsections:

- Earth observation, land cover mapping including supervised and unsupervised classification, decision trees and expert systems, and OBIA.
- Satellite imagery (Moderate resolution imaging spectroradiometer (MODIS) and LANDSAT imagery)
- Mapping rangeland degradation including various vegetation indices, algorithms and models; and
- Limitations of rangeland mapping using on coarse spatial resolution remotely sensed satellite data.

3.1 GEOSPATIAL TOOLS FOR MAPPING

It is noteworthy that satellite-based earth observation and GIS have been established as the best tools for observation, measurement and monitoring of land change (Kotze & Fairall 2006; Bolstad & Lillesand 1992). Remote sensing is a process of deriving information about the earth's land and water surfaces using satellite images acquired from overhead, by employing electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the earth's surface (Campbell 2007). Image analysis is a systematic method and a framework for examining these digital images in order to extract useful information. This method involves assigning pixels to classes, with each pixel evaluated as a discrete unit composed of values in several spectral bands (Campbell & Wynne 2011). The traditional pixel-based approach has recently been supplemented by OBIA, are widely used. Common image classification techniques include unsupervised and supervised classification (decision trees (DT) and expert systems).

Earth observation data provide large area coverage of features on the face of the earth at near real time. The historical archive of such imagery provides multi-temporal monitoring capability and is therefore well suited to generate land cover and quantify evapotranspiration. There are a number of satellites that can provide useful data in this regard, namely: MODIS, Landsat 8, Spot 5 and Spot 6.

The Moderate-resolution imaging spectroradiometer (MODIS) is located on board the Aqua and Terra satellites, launched by National Aeronautics and Space Agency (NASA) in 2002 and 1999, respectively. It is possible to obtain two MODIS images for each day of any area in the world. The difference between Terra and Aqua is the time of overpass. MODIS has a swath width of 2330 km, making it very useful to gather data for large areas. NASA offers readily available data products through the Distributed Active Archive Centres (DAACs).

The MODIS sensors have the capacity to capture data in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). It is also structurally designed to provide measurements in large-scale global dynamics including changes in earth cloud cover, radiation budget and processes occurring in the oceans, on land, and in lower atmosphere. The MODIS sensor provides the possibility to measure the normalised difference vegetation index (NDVI) at a resolution of 250 m, but also has five bands in the visible and near infrared region of the electromagnetic spectrum. These bands have a resolution of 500 m. Furthermore, the MODIS sensor has a large number of bands in the thermal infrared spectrum. Two of those, at 11 and 12 µm, can be used to calculate the surface temperature at a resolution of 1000 m.

Olexa & Lawrence (2014) affirmed the reliability of Terra MODIS on synthetic surface reflectance data and NDVI estimates to assess LULC of semi-arid rangeland by applying the spatial and temporal adaptive reflectance fusion model (STARFM) to five different Landsat TM and concurrent Terra MODIS scenes. Possible uses of the MODIS data using data products Gross primary productivity (GPP) and Net primary productivity (NPP) range from regional strategic planning, such as quantifying decadal harvest targets for large tracts of forest and when to move grazing animals among large pasture areas (Hunt et al. 2003).

The Landsat programme, a series of earth observation satellites termed which was originally instituted by NASA and the U.S Department of the Interior (Lillesand, Kiefer & Chipman 2004) and is the longest continuous spaceborne sensors jointly managed by NASA and the United States Geological Survey (USGS) (NASA 2011a). The area covered by a Landsat image is approximately 185x185 km and is skewed eastwards due to the earth's rotation (Lillesand, Kiefer & Chipman 2004). The data acquired for land and water resources from Landsat-8 has been an important asset to agriculturists and other public and private sectors. Thus far, NASA has celebrated one year of the success of landsat-8 launch without hitches and a rather rapidly increasing image database of USGS Earth Resources Observation and Science (EROS) at a 16-day repeat cycle.

Referred to as the LDCM (Landsat Data Continuity Mission), the Landsat 8 satellite expands on the 40 years of Landsat satellites recording information. The spacecraft carries multispectral and panchromatic sensors, as well as the Thermal Infrared (TIRS). Landsat 8 provides seven multispectral bands useful for vegetation studies (Table 3.1).

Table 3.1 Spatial and spectral resolutions of OLI and TIRS sensors.

Sensor	Spectral bands	Electromagnetic spectrum	Wavelength (µm)	Resolution (m)
OLI	Band 1	Costal aerosol	0.43 – 0.45	30
	Band 2	Blue	0.45 – 0.51	30
	Band 3	Green	0.53 – 0.59	30
	Band 4	Red	0.64 – 0.67	30
	Band 5	Near Infrared (NIR)	0.85 – 0.88	30
	Band 6	Short Wave Infrared Red (SWIR) 1	1.57 – 1.65	30
	Band 7	Short Wave infrared (SWIR) 2	2.11 – 2.29	30
	Band 8	Panchromatic	0.50 – 0.68	15
	Band 9	Cirrus	1.36 – 1.38	30
TIRS (resampled to 30 m)	Band 10	Thermal Infrared (TIR) 1	10.60 – 11.19	100
	Band 11	Thermal Infrared (TIR) 2	11.50 – 12.51	100

Landsat 5 (TM), Landsat 7 (ETM+) and ASTER are by far the most popular sensors for scientific purposes mainly because archival data from these sensors are available gratis over the Internet. Unfortunately, the scan-line corrector of ETM+ has been inoperative since 2003, rendering large areas of any image unusable. Landsat 4 and 5 carried on-board TM sensors consisting of seven spectral bands at resolution 30 m with thermal infrared band 6 resampled to 30 m from 120 m resolution using cubic convolution resampling method (Gibson 2000). Similar to Landsat TM with respect to resolution scale and band series with exception of the thermal band, Landsat 7 sensor was equipped with ETM+, the instrument which provided a 15 m high resolution panchromatic band 8. Moreover, Landsat 8 consists of two sensors; the Operational Land Imager (OLI) that captures image using nine spectral bands at 15 to 30 m resolution; and the Thermal Infrared Sensor (TIRS) for highly precise measurements of earth’s thermal energy to monitor land and water use. TIRS bands collected at 100 m resolution are resampled to 30 m (Table 3.1).

3.2 SUPERVISED AND UNSUPERVISED CLASSIFICATION

When using unsupervised classification, pixels are automatically classified into a user-specified number of image classes according to their spectral properties, after which the classes are manually labelled (Campbell 2007). The exploratory nature of this automated spectral delineation, allows repeated unsupervised area delineations with different parameters, enabling users to “get a feel” of which real-world classes are spectrally distinct and similar (Mather 2004). Unsupervised classification is extremely useful where a priori information regarding the study area or the classification structure is unavailable or not pre-determined (Campbell 2007).

On the other hand, supervised classification is defined by the application of a priori information of informational classes to determine the identity of unknown image elements. Data for informational classes are supplied to the classifier in the form of "training data". These externally sourced training data is used to obtain statistical information regarding the spectral properties of each class, which is then used by a classification algorithm to identify the class of unknown pixels (Campbell 2007; Mather 2004). Various classification algorithms are available, with the most used algorithm being the maximum likelihood classifier (MLC) (Tseng et al. 2008; Brown de Colstoun et al. 2003; Bolstad & Lillisand 1991). The classifier statistically compares the features of each of the known classes with those of an unknown pixel in geometric space, and assigns the pixel to a class based on the results of the comparison. Other classifiers such as artificial neural networks and support vector machines are gaining popularity. An overview of each of these classifiers can be found in Pauw (2012).

While supervised classification has some advantages and produce acceptable accuracies, supervised classification is only as accurate as the training data used. Training data must be therefore carefully prepared, which can be costly (Albert 2002). In addition, traditional supervised classifiers are often out-performed by more elaborate classification methods, such as artificial neural networks, expert systems and DT (Pal & Mather 2003).

A DT classifier recursively applies a set of decision rules to an input dataset, categorising the dataset into a set of target classes. A decision tree classifier is composed of a root node (the input dataset), internal nodes (splits) and terminal nodes (the target classes, known as leaves). Although each node in the tree can only have one parent node, there is the possibility of having two or more descendant nodes. Decision rules are applied at each non-terminal node, splitting the data into smaller subsets until the leaf nodes are reached and the data were classified (Chuvieco & Huete 2010; Friedl & Brodley 1997).

Various approaches have been proposed for the construction of a DT. Rules can sometimes be created manually based on the analyst's experience. According to Chuvieco & Huete (2010), such approaches can also be regarded as expert systems. However, supervised approaches where statistical procedures are used to infer the rules from training data, known as learning algorithms (Chuvieco & Huete 2010; Friedl & Brodley 1997), are commonly used.

Compared to other classifiers, DTs have the advantage of being able to accept a wide variety of input data, including both continuous and categorical data. Thus, ancillary data can easily be included. The simplicity of the structure of the classifier enables easy interpretation, straightforward testing as well as refinement when needed (Brown de Colstoun et al. 2003). Rogan, Franklin & Rogers (2002) found a DT to be significantly more accurate than a MLC in monitoring changes in forest vegetation in California. Similarly, Friedl & Brodley (1997) reported that DT provide significantly higher accuracies than MLC. Brown de Colstoun et al. (2003) also noted a higher accuracy for a decision tree classifier than that of traditional classifiers and comparable to that of a neural network (ANN).

The term "expert system" is used in many ways in remote sensing and can represent a number of different techniques. Tsatsoulis (1993) defines the categories of expert systems as user-assistance systems, classifiers, low-level processing systems, data fusion systems, and GIS applications. All pertain to different procedures in remote sensing analysis, but all are defined as "expert" in that they all employ artificial intelligence (AI) inference structures which use expert knowledge (Cohen & Shosheny 2002). For this reason, expert systems are also known in the literature as knowledge-based systems.

In contrast with traditional pixel-based classification approaches, object-based image analysis (OBIA) aims to delineate meaningful spatial units and classify them in an integrated way (Lang 2008), thereby making use of spatial concepts (Blaschke et al. 2000). In OBIA, each image object is aware of its context, neighbourhood and sub-objects so that geographical features can be characterised by their spatial, structural and hierarchical properties in addition to their spectral properties (Lang 2008; Bock et al. 2005). Furthermore, since objects offer additional spectral information including mean, median, minimum, maximum and variance values (Blaschke 2010), using objects as classification units rather than pixels reduces spectral variation within classes and removes the so-called "salt-and-pepper" effect (Liu & Xia 2011). In addition, OBIA is an iterative process which links to concepts of multi-scale analysis (Lang 2008; Blaschke 2010).

Several classifiers have been successfully applied to object-based classifications. Rule-based expert systems feature prominently in the literature on OBIA (Lang 2008). Expert systems attempt to model the complex network of knowledge and experience that humans use to understand the information in an image based on our perception of an image as a series of objects (Blaschke et al. 2000). Several studies report good results when using expert systems in object-based classification (Chen et al. 2009; Whiteside & Ahmad 2005).

For sparse, heterogeneous and largely non-photosynthetic material such as cleared land or newly restored patches, Steele et al. (2013) suggest using OBIA with decision-tree classification to provide a platform for classification that closely resembles human recognition of objects within a remotely sensed image, using the spatial context of the pixel and its relationship with its neighbours. However, Forsyth (2012) found that for single invasive species within a mountain landscape, pixel-based supervised classification performed better when compared to OBIA.

Segmentation is the initial step in object-based image classification where multiple pixels in an image are consolidated and segregated as discrete units (Kartikeyan, Sarkar & Majumder 1998). Segmentation algorithms basically amalgamate adjacent pixels iteratively into larger objects at certain homogeneity threshold defined by the user. Mostly selected according to the demands of a particular task, segmentation algorithms generally improve accuracy of classification process and can be optimised by varying the selected region, adjusting threshold of both merged regions and merging termination (Blaschke 2010; Walter 2004). They are often categorized as either unsupervised or supervised. While unsupervised approaches use spectral data to identify areas with common attributes which are then assigned to arbitrary land cover classes, supervised classification methods use expert system to place pixels or areas into predefined land cover classes (Lillesand, Kiefer & Chipman 2004).

Segmentation pitfalls such as of over- and under-segmentation have the potential to falsify the classification process and this occurs mostly as a result of radiometric noise and inelasticity of homogeneity variables (Baatz, Hofmann & Willhauck 2008). While under-segmentation incorporates surplus surroundings not in comparison with the selected segments into the output, over-segmentation erroneously omits certain variables from the output (Stuckenberg, Münch & Van Nierkerk 2013). However, these errors typically occur where multiple classes are consolidated into a unit feature in a segment; where features of a land cover are embedded in a more dominant land cover class; and where boundaries of segments are not corresponding to features on the ground. Although several techniques are available to diffuse the effects of these segmentation pitfalls, the occurrence of these aberrations are likely to manifest to varying degrees in any segmentation exercises (Stuckenberg, Münch & Van Nierkerk 2013).

3.3 HYPER/MULTISPECTRAL SENSORS AND VEGETATION INDICES

The subdivision of the electromagnetic spectral ranges of multispectral sensors into continuous wavelengths at intervals over a broad range of electromagnetic spectrum (EMS), allows the processing and recording of a series of images that can be combined in various ways (Lillesand, Kiefer & Chipman 2004). A frequently used arrangement involves the combination of red, green, blue (RGB) and near-infrared (NIR) bands of the EMS. The quality of multispectral imagery depends on the ability of the various selected bands to enhance the brightness and contrast of features, thus enabling identification (Keith et al. 2009; Lillesand, Kiefer & Chipman 2004). The application of these bands in vegetation analysis quantifies different vegetation characteristics in terms of chlorophyll absorption, biomass and moisture content that are mostly enhanced by the red and infrared bandwidths. Other applications of multispectral imagery can be used in bathymetric mapping for water-body penetration, forest mapping, anthropogenic and natural targets definitions as well as various thermal and rock types mapping. Multispectral data are readily available at a low cost, and do not require complex pre-processing and processing techniques. In addition, multispectral data have been used extensively for land cover classification e.g. South African NLC 2000 (Fairbanks et al. 2000) and Stuckenberg, Münch & Van Niekerk (2013).

The operational limitation of optical data, in terms of spatial resolution and mapping, still remains problematic. Spatial resolution is expressed by the size of an image pixel and is often coarser than the target objects. For example, a small target feature such as individual tree in a local or global land cover mapping may not be identified, as the feature of interest may occur beyond map scale or unit. Spatial resolution limits study details and is assumed as one of the sources of errors in classification, mostly in relation to problems associated with mixed pixels (Boyd & Foody 2001). Applying finer spatial resolution on relatively small target features will aid in the identification of small features in land cover mapping (Boyd & Foody 2011).

High-resolution hyperspectral data can provide significant enhancement of spectral measurement capabilities for investigating contiguous and narrow wavelengths (less than 10 nm) throughout the ultraviolet, visible and infrared portions of the electromagnetic spectrum (Mansour, Mutanga & Everson 2012; Thenkabail et al. 2004). These narrow spectral wavelengths allow identification of vegetation at species levels in different ecosystems (Thenkabail et al. 2004). A radiative transfer model (RTM) employed in a high-spatial hyperspectral ROSIS data (1m resolution) improved chlorophyll estimates in open canopies and repudiated the relationship between leaf biochemical constituents and hyperspectral optical indices that is usually found in a low-spatial hyperspectral imagery (Zarco-Tejada et al. 2004). Despite the great promise of detailed spectral information, mapping of vegetation species using hyperspectral remote sensing data remains a challenge due to data dimensionality, data processing, and cost of images (Mansour, Mutanga & Everson 2012; Metternicht, Blanco & Del Valle 2010).

Spectral vegetation indices (VIs) are useful tools for mapping and monitoring vegetation species especially in degraded areas (Sun et al. 2007). VIs are calculated based on either multispectral data or on hyperspectral data. The most widely used VIs are the NDVI, enhanced vegetation index (EVI), the simple ratio (SR) (Gitelson & Merzlyak 1993), and the transformed vegetation index (TVI), which respond to variation in the red and near-infrared spectra. Other VIs were developed to minimise the effects of soil background, atmospheric conditions, canopy geometry, and sun view angles (Gitelson et al. 2002) such as the soil-adjusted vegetation index (SAVI) (Huete 1988). The VIs evaluated the relationship between leaf area index and chlorophyll index of soybean and maize crops (Viña et al. 2011). NDVI and LAI has been connected to vegetation density relative to ET and photosynthetic mechanisms either through empirical field measurement analysis (Shippert et al. 1995) or theoretical RTM (Myneni, Nemani & Running 1997).

3.4 ACCURACY VALIDATION OF DERIVED LAND COVER MAPS

Accuracy assessments are used to determine the information quality of land cover maps derived from satellite imagery using field validation methods or reference data. Derived land cover maps are prone to uncertainties and imprecisions stemming from data acquisition, processing, analysis, conversion, error assessment as well as final product presentation (Congalton & Green 2009). This is further affected by limited data accessibility and resources, temporal and fiscal constraints and space-borne sensor sensitivity.

Conventionally, promoting accuracy and unbiased depiction of the land cover data is achieved by referencing the data with other data of higher precision or resolution scale. Common reference data are ground control points and higher resolution sensors with large objective data coverage. Cross-tabulating reference data with land cover maps using error matrixes detects misclassification or occurring change processes of a particular region. However, error matrix, also known as confusion matrix, is often used as a statistical approach that assesses the accuracy rate of the land cover maps derived from remotely sensed imagery (Foody 2002). The Kappa index of agreement is a standard component of accuracy assessment, which is used to compare two maps that show a set of categories (Pontius & Millones 2011; Congalton 1991) used to account for random chance in the accuracy assessment (Jensen 1996).

Ground based data or field data is fairly accurate for assessment of land cover map accuracy as it reveals areas beneath the regions covered by satellite imagery. As a result of the high resolution, aerial photography has become reliable reference data for land cover maps derived from coarse optical sensors. Errors nonetheless can occur from the interpreter or the ambiguity of the aerial photography. Therefore, Congalton & Green (2009) suggest the integration of field survey and aerial photography as well as experts' consultation in any area(s) of study.

Accuracy assessments are often cost-effective and consideration must be placed on the limitations posed by the study area, weather and sensor against statistical validation. However, selection of the sampling schemes must be dependent on the range of questions to be answered in a study and the kind of imagery to be analysed. Among the variety of sampling schemes, random sampling is commonly used and the reference plots of 50 per class as rule of thumb is suggested by Lillesand & Kiefer (1994).

3.5 LAND COVER CHANGE DETECTION

A range of methodologies for change detection, including image enhancement techniques, multi-date and post data classification, can be used for evaluating environmental changes (Mas 1999). The comparative approach of post data classification analysis generated independently at different times is the most commonly used change detection method (Mas 1999). Mas (1999) combined post-classification and image enhancement in order to minimise errors in change detection but found that post-classification analysis using supervised classification showed highest accuracy among many tested change detection techniques. Another detection approach analysed by Benini et al. (2010) used an indicator-based method by assigning LULC conversion labels to intersection of successive overlaid land cover maps that narrated the spatial distribution changes from the thematic representations.

Change modelling amasses a matrix of changes and extracts change density details among categories and periods (Benini et al. 2010; Tesfamariam 2000). Computer-based modelling is commonly used through software tools for different change procedures (ESRI 2009). The success of overlaying classified imagery to create detection tables for cross-tabulation (pivot tables) in Excel (Microsoft 2013) to detect temporal change has been shown by literature (Alphan, Doygun & Unlukaplan 2009). The intersect or combine tools in ArcMap can be used for intercepting change by combining two raster or raster-converted-vector-output land cover images and comparing them on a pixel by pixel basis (Münch 2015 Pers com; ESRI 2009).

3.6 CONCLUSION

Mapping vegetation in degraded or densely forested areas at species-level using multispectral data, such as Landsat imagery is challenging because of the low spectral resolution of sensors and spectral overlap between the vegetation species (Harvey & Hill 2001). The development of high-resolution multispectral sensors, such as WorldView, containing key spectral bands, has brought about unique opportunities for those wishing to classify vegetation at species level (Dlamini 2010; Omar 2010). Mohamed et al. (2011) used high-resolution QuickBird ortho-ready satellite imagery with success (2.4 m resolution) to study encroachment of woody Mesquite trees on rangelands. MLC algorithm was used along with regression analysis. Li et al. (2014) used high resolution imagery with object-based classification to determine land cover. Several studies have analysed image datasets from different satellites for mapping and classification of land cover using vegetation indices (Stuckenberg et al. 2013; Sun et al. 2007). Accuracy assessments of such sampled data are often verified using reference tools (maps, aerial photography) and management policies (Congalton & Green 2009).

Global scale observation and regional surveys of land cover are required to provide a broader understanding and monitoring of land cover change and also to enable the creation of strategic measures to mitigate the driving factors. Global/local modelling evaluating environmental processes using spatial analysis techniques forms the baseline of scientific decisions towards environmental management by the government, land managers or interested communities. Unlike global modelling that quantify large landmasses from a single unit analysis (Zhang, Ma & Guo 2009), local modelling specifies spatial heterogeneity of relationship and effect of change over time (Zhang Ma & Guo 2009; Fotheringham, Brunsdon & Charlton 2002). However, to determine the extent of degradation through land cover classification at local scales, a combination of some of the techniques discussed in this chapter, including knowledge-based OBIA classification, will be performed using Landsat data and this will be compared with the NLC 2000 data. In the next chapter, methods, results and discussion of the soil sampling and analysis will be discussed.

CHAPTER 4: **ASSESSING RANGELAND-SOIL DEGRADATION INDUCED BY WATTLES AND GRAZING**

The methodology adopted for the soil sampling concurs with Van der Waal (2009) & Yelenik, Stock & Richardson (2004). This approach is discussed in this chapter, addressing objectives 1 and 5 of the research, namely:

- To measure the nutrient status of soils within the catchments, prior to and post-clearing of IAPs and evaluating the optimal soil nutrient pools towards rehabilitation and land use options.
- To investigate and recommend alternative restoration interventions for landscape sustainability.

Based on the literature reviewed in Chapter 2, it was hypothesised that an alteration of soil nutrient pools takes place due to the invasion of IAPs (Thorpe & Callaway 2005; Ehrenfeld 2003). The soil analysis aims to address the following questions:

- How much do IAPs impact on soil quality prior and after eradication? Will measured nutrient pools indicate consistency or irregularities in quantity across different sampled treatments, depths and age classes/kinds of IAPs?
- If farming is selected as a land use option, will nutrient pools on natural grasslands, as the assumed control site, provide the standard nutrient requirements for rehabilitation?

In order to address these questions, this chapter provides an analysis of the key issues related to soil sampling and the analytical processes involved. It also provides a description of the following: soil sampling and nutrient management; the rationale behind soil sampling; characteristics and categories of sampled sites; sampling methods used; the laboratory and statistical analysis; soil sampling output and, finally, the soil sampling results.

4.1 **SOIL SAMPLING AND NUTRIENT MANAGEMENT**

Future challenges of alien invasion on soil quality will lead to adopting suitable land use options that will balance the production-economic yield with prevailing socio-ecological impacts. Selecting a land use scenario for an area is dependent on the soil nutrient account, which is critical in developing either a nutrient management plan for a cropland, or design a protocol(s) for other viable land use. IAPs are known to increase soil nitrogen content, deplete available resources for native plants and impact on the ecology and socio-economic ecosystem (Pysek et al. 2012; Vila et al. 2011).

Livestock grazing alters soil conditions as a result of dung deposition as well as hoof trampling that reduces/increases soil compactness, structure and viability (Röder et al. 2007). Improper cultivation further contributes to soil degradation that affects soil capacity to withstand adverse conditions (Röder et al. 2007). As a result, field sampling and soil testing become important tools for assessing soil fecundity for agricultural development (Motsara & Roy 2008). The next subsection will elaborate on the soil sampling perception at the study areas, sampling protocols and methods carried out.

Multivariate analysis can be used to evaluate IAPs impact at QC level. The sampling sites were identified on the basis of the degree of invasion by *Acacia dealbata* and *Acacia mearnsii*. Consequently, three degrees of invasion were identified, namely 'Invaded', 'Cleared' and 'Uninvaded' (Van der Waal 2009; Yelenik, Stock & Richardson 2004). These degrees of invasion (also referred to as 'treatments') were at a distance of ≥40 m (Gwate et al. 2015) from each other.

Invaded sites infested by either *A. mearnsii* or *A. dealbata* were sampled to evaluate *Acacia spp.* impact (allelopathy) in altering the soil nutrient pool and nitrogen upsurge (Pysek et al. 2012; Vila et al. 2011). Cleared soils will show the rates of nutrient refurbishment depending on variables acting on the system (Blanchard & Holmes 2008). Length of cleared dates (effect of time) is presumed to rejuvenate soil properties over time through natural attenuation. The pristine nature of rangeland prior to degradation is a primary tool for sampling uninvaded soils, primarily, as a control site that reviews the nutrient pools on invaded and cleared soils.

Clearing data for the QCs was obtained from WfW office in East London. Two out of the three study sites were selected for soil sampling due to availability of WfW clearing reports. The soil analysis and evaluation was independent of the characterisations of the study sites, rather dependent on the characteristics and degrees of invasion (treatments). The sampling was aimed at WfW cleared patches with documented history. This resulted in sampling outside the study area T35B at WRC8 as shown in Figure 4.1b and Figure 4.2b.

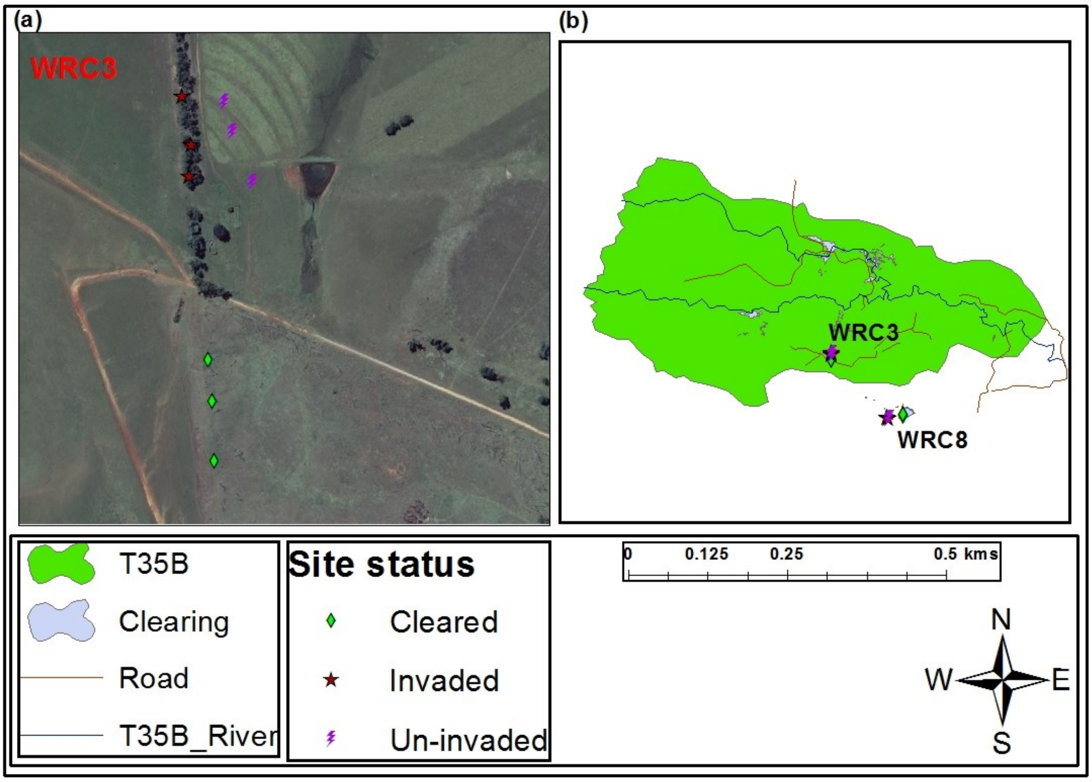


Figure 4.1(a) WRC3 aerial photographs and (b) map of QC T35B showing the WfW cleared patches, sampled sites and sampled points as well as road and river systems.

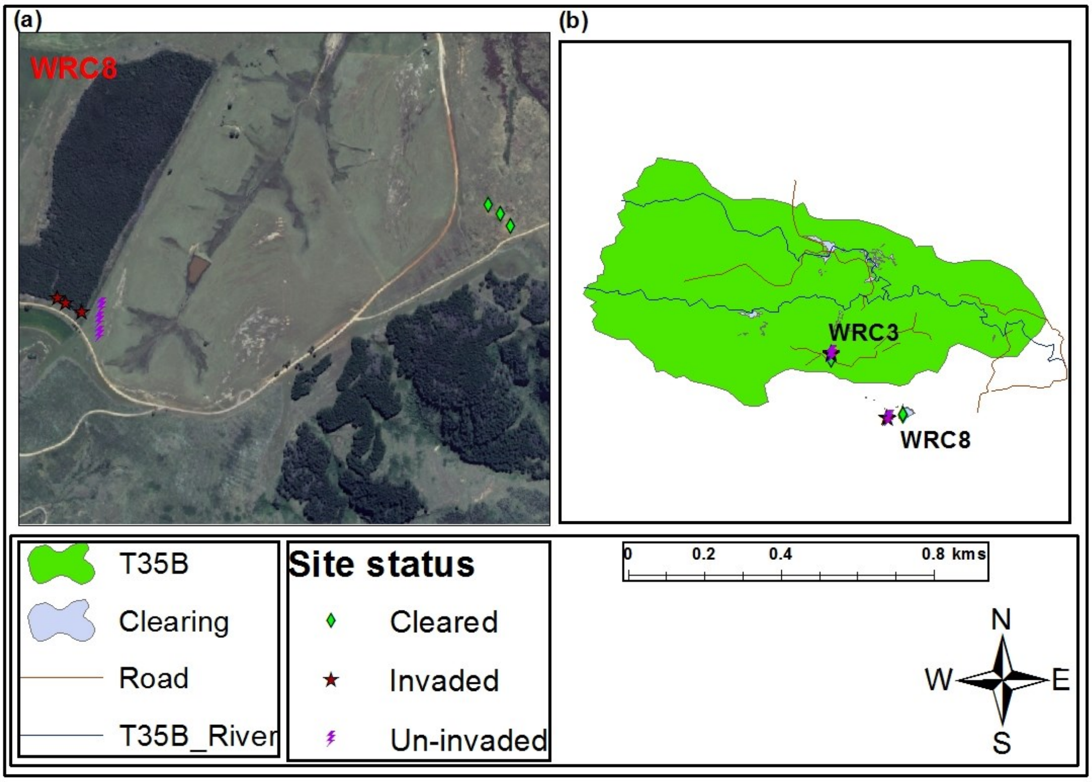


Figure 4.2(a) WRC8 Aerial photographs and (b) map of QC T35B showing the WfW cleared patches, sampled sites and sampled points as well as road and river systems.

Sampling at transect of 20cm (horizontally) apart were randomly done on 100 to 150 hectares of each treatment using comparative approaches in curbing soil type variability and landscape effects. Topographic sampling along landscape slopes was carried out on a single sampled site. This is known to offer better field variability and provide the most accurate soil sampling results (Franzen et al. 1998).

Two sample depths were used, cores at 10 cm depth were sampled to analyse macro and micronutrients during the winter season. Due to leaching properties of nutrients and nitrogen deposition below the soil horizon by IAPs' deep-penetrating roots (Matthews & Brand 2004), 20cm core depth were sampled to analyse below-ground nitrogen as well as other nutrients (Table 4.1).

Table 4.1 Soil sampling analogue analysing testing motive, nutrients to test, sampling depths and season of the sampling.

Purpose for testing	**Nutrients to test**	**Soil Depths**	**Season of the year**
Basic nutrients, fertility, acidity & soil conditions	• Macronutrients (N, P, K, Mg, Ca) • Micronutrient (Zn) • Others (total cations, pH, exchange acidity, acid saturation, sample density)	10 cm & 20 cm	Winter
Nitrogen	Nitrate (NO_3^--N) & Ammonium nitrate (NH_4^+-N)	20 cm	Winter

(a)

(b)

Figure 4.3 Team workers coring the soil surface with an auger in proximity to trees and stumps at QC T35B (WRC3) on (a) invaded and (b) cleared areas.

A soil 'auger' (Figure 4.4) was used to collect the soil samples. Cores collected at different depths were crushed (when necessary) and placed in separate bags (paper and plastic bags were used). The samples were stored at room temperature after air-dried and taken to Dohne Agricultural Institute in the Eastern Cape for analysis. Precautionary measures observed included ensuring land-type similarity, avoiding cow dung, sampling close to stumps/trees (Figure 4.4) etc. The soil sample report describing sample names, sample sites, sampled points coordinates are detailed in Appendix A.

4.2 DESCRIPTIONS OF SAMPLED SITES

Three treatments, cleared, invaded and uninvaded patches were sampled on four sites in T35B and T12A. T35Brepresents the commercial farming area while T12A represents the communal. Samples were collected at three points, two consecutive depths (10 cm and 20 cm), at transect of 20 cm apart on each treatment in each of the four sites. Dominant grasses on sampled sites include *Sporobius africana*, *Eragiostus curvula*, *Themeda triandra* and *Heteropogon contortus*. Similar data were obtained for all the sampled sites including soil type, slope, climate, season of collection. Different *Acacia spp. (Acacia dealbata), rather* than *the Acacia mearnsii invaded treatments,* was sampled on a single treatment site in T35B. In T35B, two sites were sampled, WRC3 and WRC8, and these were labelled for patches cleared in 2005 and 2004 respectively. In T12A, two sites branded WRC9 and WRC10 were cleared in 2010, but the clearing date for WRC9 was not reported in the clearing data, therefore it was as '–'Salient characteristics of the sampled sites are listed in Table 4.2, but full details are discussed in the next section.

Table 4.2 Characteristics of sampled sites relative to the three treatments, cleared dates and density or age classes of IAPs

Site no	QC	Treatment			Clearing date	Density before clearing
		Cleared	**Invaded**	**Uninvaded**		
WRC3	T35B	Cleared of *A*, *Dealbata*; Grass Cover; Grazing	Infested by *A. Dealbata*, grass cover, no overgrazing	Natural grassland; Farming; no overgrazing	2005	High
WRC8	T35B	Cleared of *A. mearnsii;* Grass cover; Grazing	Invaded by *A. mearnsii;* Low grass cover	Natural grassland; Grazing	2004	High
WRC9	T12A	Cleared of *A. mearnsii*; Grazing	Invaded by *A. mearnsii;* No farming	Natural grassland; No farming	-	Low
WRC10	T12A	Cleared of *A. mearnsii;*	Invaded by *A. mearnsii*	Natural grassland; Old cultivated land	2005	High

Adapted from: Van der Waal (2009).

In WRC3, an expanse of cleared land (cleared in 2005) with sloping terrain was sampled at the catchment edge, in-between stumps, adjacent to burnt/invaded areas and covered with grasses (Figure 4.4b). The cleared patch was infested with *A. dealbata* and the cleared debris remained undisposed. An Exclosure (fence) was built around the cleared patch, but presence of cow dung indicated the likelihood of continued livestock grazing. The invaded patch had thick infestation of *A. dealbata*. Presence of grass cover, livestock grazing (but no overgrazing) were also observed.

Uninvaded was sampled close to the invaded patch. A small dam, horses, cows and a graveyard were identified at this patch but no overgrazing or cultivation was observed.

WRC8 was located on a flat plain with high grass cover and was cleared of *A. mearnsii* in 2004. It is littered with tree stumps, branches and cow dungs. A thick understorey of *A. mearnsii* was covered with sparse grass. This patch is fenced and no indication of grazing activities was observed. The uninvaded patch has a sloping landscape surrounded by burnt patches, presence of grazing but no cultivation. The location of T35B, the sampled points and the sampled locations are shown in Figure 4.5 and Figure 4.6.

WRC9 was cleared of *A. mearnsii,* and regrowth of removed invader as well as stumps and debris were visible (Figure 4.5a). The invaded patch had no understorey, little or no grass cover and no grazing as observed during the field study. The uninvaded patch that was situated alongside the invaded patch had no evidence of grazing or cultivation, probably as a result of the erected exclosure (Figure 4.4b).

(a) (b)

Figure 4.4 Cleared site showing (a) reinvasion and overgrazing and (b) old cultivated rangeland at T12A (WRC10**).**

WRC10 was cleared of *A. mearnsii* in 2005; natural regeneration and IAP reinvasion were noted with grazing activities and proximity to a school (). An *A. mearnsii* infested thick understorey with some cleared patches was observed close to the cleared patch. The uninvaded was an old cultivated land rejuvenated into grassland, surrounded by *A. mearnsii* with no grazing present. The map of T12A, the sampled points and the sampled locations are shown in Figure 4.5 and Figure 4.6.

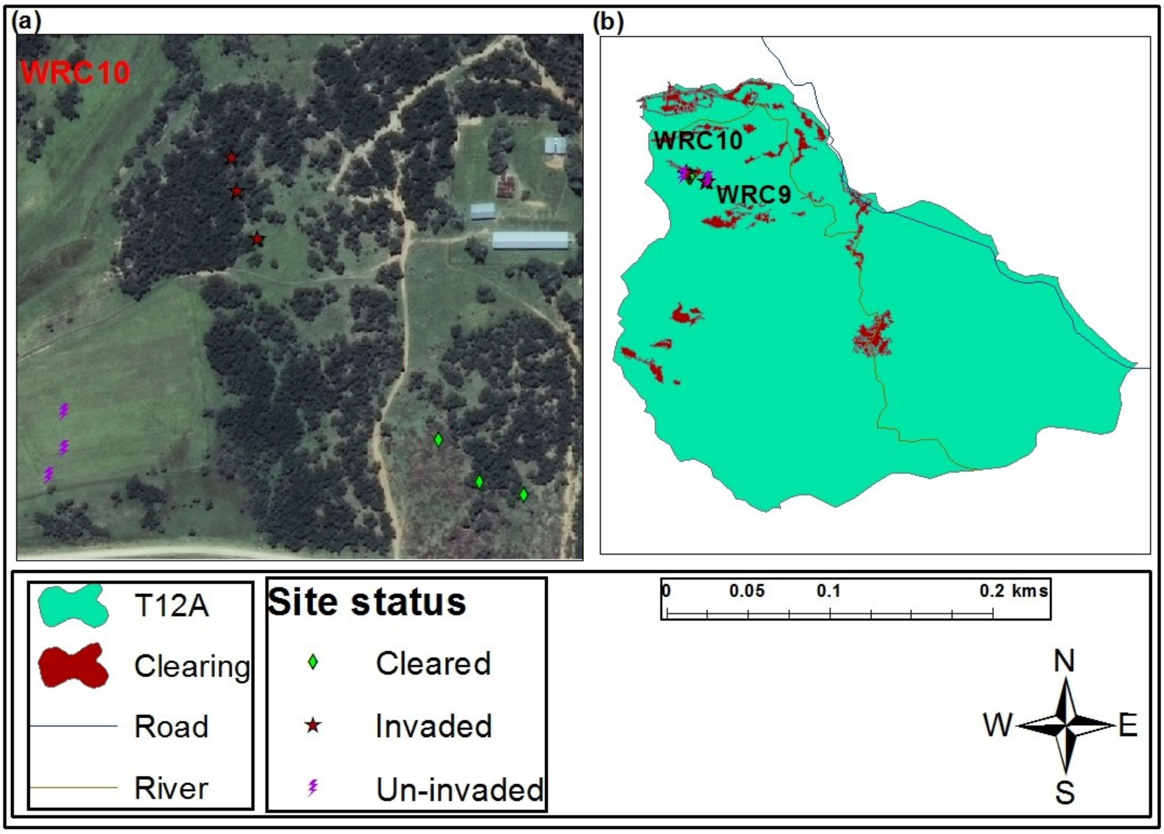


Figure 4.5 (a) WRC10 Aerial photographs and (b) map of QC T12A showing the WfW cleared patches, sampled sites and sampling points as well as road and river systems.

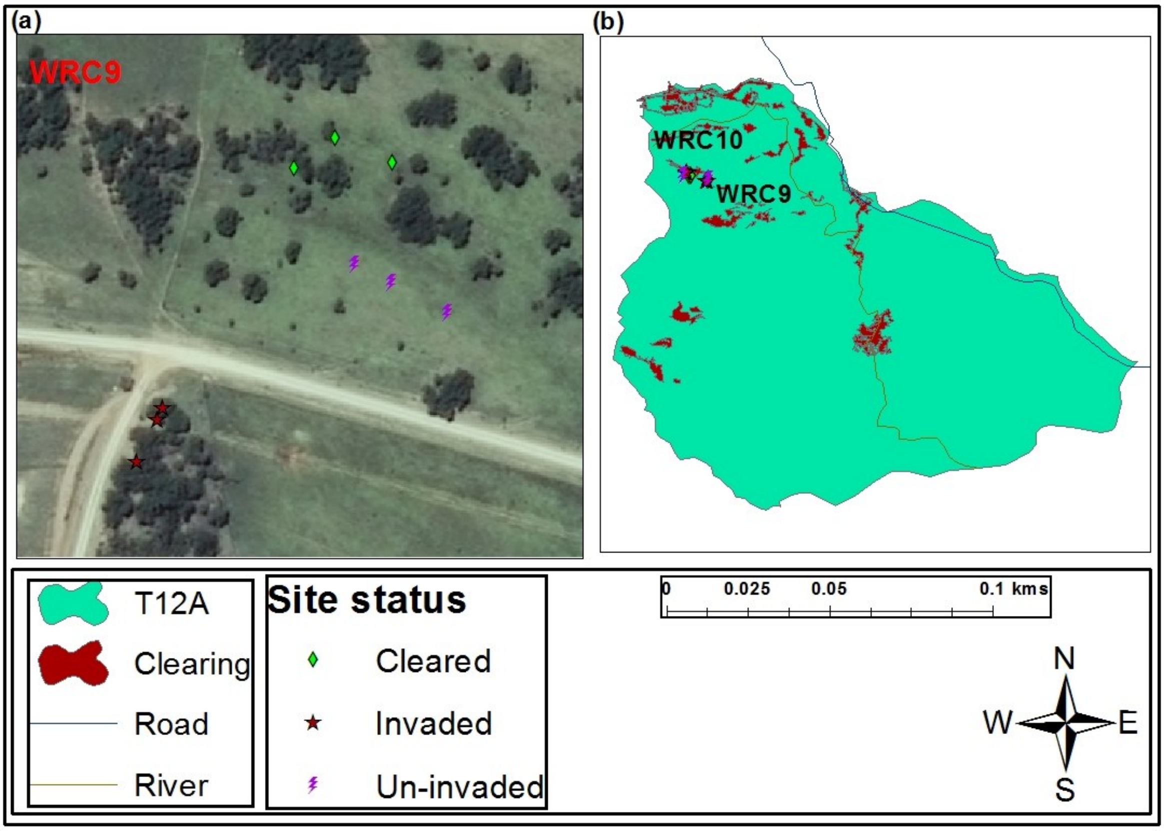


Figure 4.6 (a) WRC9 Aerial photographs and (b) map of QC T12A showing the WfW cleared patches, sampled sites and sampling points as well as road and river systems.

4.3 ANALYTICAL PROCEDURES

Laboratory testing and analytical statistics determine soil nutrient levels and carrying-capacities suitable for crop production. Soil testing and analytical statistics are two tools in agriculture that promote nutrient management and crop yield systems (Motsara & Roy 2008), and these are discussed in the following subsections.

There are six macro [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S)] and seven micro [boron (B), copper (Cu), iron (Fe), chloride (Cl), manganese (Mn), molybdenum (Mo) and zinc (Zn)] nutrient elements essential for plant yield. In this study, six nutrient elements (or variables) namely total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn) were analysed. In addition, five important variables that affect soil properties, namely pH, sample density, exchange acidity, total exchangeable cations and acid saturation were also tested.

Table 4.3 Tested soil nutrients and variables with different laboratory methods, extractants and procedures adopted for the assessment.

Soil nutrient elements and other variables		**Analytical methods and extractants**
Soil nutrients	Organic/Total Nitrogen	Kjeldahl method (Kjeldahl 1883)
	Nitrate (NO_3^--N)	Phenoldisulphonic acid method (Charles 1917)
	Exchangeable ammonia (NH_4^+-N)	Indophenol blue method (Tzollas et al. 2010)
	Phosphorus (P)	Bray's method No. 1 (Bray & Kurtz 1945)
	Potassium (K)	Flame photometer (Toth & Prince 1949)
	Total exchangeable cations	Extraction in ammonium acetate
	Calcium (Ca) and magnesium (Mg)	Ethylenediamine tetraacetic acid (EDTA) titration method (Cheng & Bray 1951)
	Zinc (Zn)	EDTA + ammonium acetate, EDTA + ammonium carbonate, DTPA + $CaCl_2$, HCl, HNO_3 and dithiozone + ammonium acetate (Lindsay & Norvell 1978)
Variables	pH	(see text for details)
	Exchange acidity and acid saturation	(similar to pH estimation; see text for details)
	Sample density	Drying and weighing

Adapted from: Motsara & Roy (2008).

Table 4.3 provides a summary of the variables tested and the analytical methods used. Total nitrogen (N) includes inorganic N (NH_4^+-N and NO_3^--N) and organic N compounds (amino acids, protein and other derivatives) and was analysed using the kjeldahl method. There are mainly two methods, namely the Bray's method No. 1 and Olsen method, for obtaining available phosphorus

(P) in soils, but the former method was chosen because of assumed acidity of the sampled soils (Miles & Farina 2013; Van der Waal 2009). Plant-available potassium (K) was extracted from soil samples with one-molarity of ammonium acetate using a flame photometer.

Calcium (Ca) and magnesium (Mg) are grouped as exchangeable cations among other positively charged nutrients such as potassium (K), sodium (Na), hydrogen (H) and aluminium (Al). Exchangeable cations were determined in neutral normal ammonium acetate extract of the soil samples, however Ca and Mg were measured using a titration method (Table 4.3) which was selected based on its exactness, speediness and simplicity. Zinc (Zn) was concurrently analysed using a combination of methods and series of extractants (Table 4.3).

Soil pH, the negative logarithm of hydrogen ion (H^+) measures the acidity, alkalinity and neutrality in soil solution. It affects nutrient transferability between plant-soil relationship (Miles & Farina 2013) but is the simplest method of estimation (Motsara & Roy 2008). The major apparatus, pH meter (with a pH range of 0 – 14) and basic reagents (water, buffer and calcium chloride solutions of pH 4, 7, 9 and 0.01M, respectively) were used to rate the soil reactions to pH scale as described in Table 4.4 (Yelenik, Stock & Richardson 2004).

Table 4.4 Range of pH values describing the soil reaction rating when measured.

pH colour	Purple	Yellow	Purple	Blue	Purple	Blue-green	Red-violet
pH range values	< 4.6	4.6 – 5.5	5.6 – 6.5	6.6 – 6.9	7.0	7.1 – 8.5	> 8.5
Soil rating	Extremely acidic	Strongly acidic	Moderatel y acidic	Slightly acidic	Neutral	Moderately alkaline	Strongly alkaline

Adapted from: Motsara & Roy (2008).

Exchange acidity in soils or cation exchange capacity (CEC) (containing hydrogen and aluminium cations, (often called titratable acidity) can be exchanged by a neutral salt in solution. This is an indicator used to measure lime requirement (quantity of alkali) for neutralising soil acidity. Exchange acidity is usually less than the lime requirement as some part of the acidity cannot be interchanged. The exchange acidity was measured using an indirect method similar to pH estimation, but at pH range of 6.6. Acid saturation, also an indicator of soil buffering capacity, determines liming potential suitable to alter the pH range and was estimated using the exchange acidity method described above. Measuring the dry weight of each sample volume determined soil compaction. Sample bulk density was measured by simply drying and weighing soil samples.

Due to their flexibility, software packages such as R (R Core Team 2013) and Microsoft Excel (Microsoft 2013) were used for the data analysis and computation. Sample mean values were used to extrapolate the population mean from which the sample sizes were obtained to enable empirical deductions of soil chemical compositions. Standard deviation estimated the population variability as well as normality or skewness of the sample distributions. Standard error of the mean determined the uncertainty surrounding mean dimensions and the confidence interval (conf. interval = 95%), i.e. the P-value.

The null hypotheses (no significance difference ($P>0.05$)) were tested for all variables. The significance level ($P<0.05$, $P>0.05$) was analysed using one-way analysis of variance (ANOVA). Post hoc multiple comparisons (pairwise t-test) such as Bonferroni method and Tukey Honest significance test (TukeyHSD) were used to filter differences between samples (Yelenik, Stock & Richardson 2004). The Bonferroni method of pairwise comparisons was specifically done for variables that were significantly different ($\sim P<0.05$) to validate TukeyHSD method of sample differencing.

4.4 SOIL ANALYSIS OUTPUT AND RESULT

A total of 72 soil samples were collected, three at each depth (10 cm and 20 cm) and six at each treatment (invaded, cleared and uninvaded). The sampling was done at two depths (or groups). The first depth contained soil cores collected at 10cm (hereafter top-soil or top-layer {Depth 1}) and the second depth was collected at 20cm (henceforth sub-soil or sub-layer {Depth 2}). Three core samples were taken from each treatment and analysed separately at two depths and labelled as: Depth 1 - ‘1.1 Cleared (A)’, ‘2.1 Invaded (B)’, ‘3.1 Uninvaded (C)’; Depth 2 - ‘1.2 Cleared (D)’, 2.2 Invaded (E)’, ‘3.2 Uninvaded (F)’.

In the next sections, the variations of sampled nutrients at each of the four sampled sites (hereafter WRC-site 3, WRC-site 8, WRC-site 9, and WRC-site 10) are reported. Since the number of samples tested per site was low (18 samples per treatment group, comprising invaded, cleared and uninvaded) as opposed to the standard sample size required for soil nutrients comparison and evaluation (Walworth 2006), no statistical inference was drawn from the analysis. Consequently, the soil sampling data were purely qualitative and exploratory in nature. However, the mean values for the three samples collected per site and depth for each variable were computed and used for evaluation of nutrient variability on the four sampled sites as will be discussed below.

The analytical results for the 72 samples from the four sampled sites (hereafter 'all sites') across treatments and depths were collated and compared. Statistical inferences were drawn to represent significance level coefficients ($P<0.05$) of variables across sites, treatments and depths.

For each site, the variables are discussed in the following groups according to their chemical properties in the subsequent subsections, as given below.

- Nitrogen, phosphorus and potassium;
- Calcium, magnesium and exchangeable cations;
- pH, exchange acidity and acid saturation; and
- Zinc and bulk density.

Representations of the variables values were omitted to reduce repetition and improve readability on the graphs (graphs mainly appended in the Appendices, Appendix C through G). Only the mean values were shown. Each boxplot contained three values (on the three treatments) at each depth and the mean values were given at the top-edge of the boxplots. Results from the top-soil (depth 1) are labelled 1.1, 2.1 and 3.1 for cleared, invaded and uninvaded samples, respectively. Similarly, results from the sub-soil (depth 2) are labelled 1.2, 2.2 and 3.2 in all graphs. Following the description of the soil analysis for each site, graphical analysis of the variations across patches at the four sites are described and presented in Appendix A. Additional information on the outcomes of the soil testing and the analysis performed on the soil samples will be presented in the following subsections.

Key characteristics of the three treatments that can affect soil chemical properties and quality in this site is highlighted in Table 4.2. The general descriptions of nutrient variations in this site using mean values are summarised in Table 4.5.

Table 4.5 Mean-value variations of variables on the three treatments measured at two depths in WRC-site 3.

Variable	**Depth 1**			**Depth 2**		
	Treatment			**Treatment**		
	1.1 Cleared A	**2.1 Invaded B**	**3.1 Uninvaded C**	**1.2 Cleared D**	**2.2 Invaded E**	**3.2 Uninvaded F**
Total N (%)	0.17	0.17	0.16	0.17	0.14	0.13
P (mg/L)	20	19.3	14.7	9	3.33	7.33
K (mg/L)	166.7	174.3	172	96.3	70.33	84.67
Ca (mg/L)	401.3	263.3	246.3	285	120.3	254.7
Mg (mg/L)	14.33	18	43	3.33	10.33	14.67
Zn (mg/L)	1.33	0.83	0.83	0.83	0.033	0.067
pH	3.65	3.59	4.077	3.54	3.75	4.02
Cations (cmol/L)	6.61	5.42	4.05	5.83	4.08	3.59
Exch. Acid. (cmol/L)	4.07	3.52	1.48	4.14	3.21	1.98
Acid sat. (%)	62.33	65.33	38.33	71.33	79.33	55
Density (g/ml)	1.097	1.21	1.17	1.13	1.22	1.17

The mean values of total nitrogen (N) on cleared (top and sub-layers) and invaded (top-layer) seem to be higher than invaded (sub-soil) and uninvaded (top and sub-layers). No clear difference in the mean values was observed between invaded and uninvaded (Table 4.5). The mean values of phosphorus (P) (20 mg/L, 19.33 mg/L and 14.67 mg/L) were higher on the three treatments of top-soil layers (depth 1) than sub-soil layers (depth 2) (9 mg/L, 3.33 mg/L and 7.33 mg/L). The maximum and minimum mean values of potassium (K) ranged from 174.3 mg/L {invaded top (2.1)} to 70.33 mg/L {invaded sub (2.2)}. The potassium mean values were observed to be higher at depth 1 than depth 2 on the three treatments (Table 4.5).

The highest mean values of calcium (Ca) were found on cleared patches (x= {1.1, 1.2} (Appendix C-Figure C. 4). Calcium (Ca) values on invaded and uninvaded top-soils (2.1 and 2.2) were relatively similar to the values on sub-soil layers (Appendix C-Figure C.4). The highest Magnesium (Mg) value was found on uninvaded top-soil (x=3.1) and the lowest value on sub-soil layer of the cleared patch (x=1.2 in Appendix C-figure C.5). There were differences in the mean values of total cations occurring between depths with the mean values highest in depth 1 (Table 4.5).

pH mean values were highest on uninvaded depth 1 and 2 showing less acidity when compared to pH mean values of cleared and uninvaded treatments (Table 4.5). Mean values of exchange acidity showed correlation with pH due largely to their chemical similarities. The highest mean was seen on cleared patches and lowest on uninvaded patches (Table 4.5). The mean acid saturation ranged from 79.3% to 38.3% and highest mean value was noted on 2.2 invaded E (Table 4.5).

Zinc was well distributed within the top-soil layers with the highest mean values on cleared patches of two depths (x= {1.1, 1.2} (Appendix C-Figure C.10). Bulk density mean values of the top-soil (1.1 g/mL, 1.21 g/mL and 1.19 g/mL) were similar with the sub-soil mean values of 1.13 g/mL, 1.22 g/mL and 1.17 g/mL on the three treatments.

Table 4.2 describes the site characteristics that might influence nutrient variation. The summarised mean values of nutrient variations are presented in Table 4.6.

Table 4.6 Mean-value variations of variables on the three treatments measured at two depths in WRC-site 8.

Variable	**Depth 1**			**Depth 2**		
	Treatment			**Treatment**		
	1.1 Cleared A	**2.1 Invaded B**	**3.1 Uninvaded C**	**1.2 Cleared D**	**2.2 Invaded E**	**3.2 Uninvaded F**
Total N (%)	0.12	0.25	0.25	0.13	0.20	0.21
P (mg/L)	55.67	26.33	7.67	2.67	6	5
K (mg/L)	55.67	124.3	193.7	56.67	60	130.3
Ca (mg/L)	176	197.7	608.3	311	77	398.3
Mg (mg/L)	0	0	81.33	0	0	38.67
Zn (mg/L)	0	0	0.8	0	0	2.8
pH	3.77	3.63	4.11	3.96	3.77	4.07
Cations (cmol/L)	4.8	6.85	6.45	3.79	5.48	5.47
Exch. Acid. (cmol/L)	3.78	5.55	2.25	3.38	4.94	2.97
Acid sat. (%)	78.67	81	36.67	89	90	53
Density (g/ml)	1.11	6.57	3.94	1.16	1.027	3.99

Dissimilar to the mean values of the total nitrogen (N) in WRC-site 3, variation of total nitrogen (N) in this site was sporadic with mean values higher on invaded and uninvaded top- and sub-soil layers (Table 4.6). The low mean values on cleared patches and the highest mean values on uninvaded might have been as a result of attenuation and N leaching properties, respectively. Compared to the WRC-site 3, high mean values of phosphorus (P) occurred only at the top soil layers of treatment, while the highest mean value appeared mostly in the cleared patch (top-soil) in WRC-site 8 (Table 4.6). There were high mean values (193.7 mg/L and 130.3 mg/L) of potassium (K) on uninvaded patches at both depths compared to cleared (55.67 mg/L and 56.67 mg/L) and invaded patches (124.3 mg/L and 60 mg/L).

Calcium (Ca) showed high mean values of 608.3 mg/L and 398.3 mg/L on uninvaded treatments that differed distinctly from cleared (176 mg/L {depth 1} and 69 mg/L {depth 2}) and invaded (197.7 mg/L {depth 1} and 77 mg/L {depth 2}). Such difference was not observed with calcium (Ca) mean values in WRC-site 3. Variation of magnesium (Mg) in WRC-site 8 showed a contradiction when compared with WRC-site 3. There were zero mean values recorded on two treatments at both depths except on uninvaded top and sub-soil layer. (Table 4.6). No distinct variations were observed in the mean values of the total cations in WRC-site 8 (Table 4.6).

The pH values in WRC-site 3 were similar to the pH values in WRC-site 8 ranging from extremely acidic (3.63 {Depth 1} and 3.77 {Depth 2}) on invaded to strongly acidic (3.77 {Depth 1} and 3.96 {depth 2}) on cleared and fairly acidic on uninvaded (4.11 (Depth 1) and 4.07 {Depth 2}). Observed likewise in WRC-site 8 was a similar relationship of pH and exchange acidity as seen in WRC-site 3. As the pH increased, the exchange acidity decreased and conversely. Acid saturation was higher in the mean values on invaded treatments at different top and sub-soil layers with the lowest values seen on uninvaded patches (Appendix D-Figure D.9).

Zinc (Zn) mean values were higher on uninvaded treatment at both depths with zero or no values recorded on cleared and invaded treatments Table 4.6 for bulk density variation in WRC–Site 8. Refer to Table 4.6 for bulk density variation in WRC–Site 8.

WRC-site 9 invaded by *A. mearnsii* did not have farming activities taking place on invaded and uninvaded treatments but grazing was occurring on cleared patch during field sampling (Table 4.2). The soil nutrients variability in this site is concisely represented in Table 4.7.

The mean value of 0.21% of total nitrogen (N) was observed on cleared patch (Depth 1) with 0.26% (Depth 1) and 0.2% (Depth 2) value on invaded patch differing with uninvaded treatment of 0.17% and 0.17% mean values (Depth 1 and 2 respectively) and cleared (0.18 % {Depth 2}). The mean phosphorus (P) varied from a minimum of 3.67 mg/L on invaded and uninvaded sub-soil to maximum of 10.33 mg/L on invaded top- soil layer. The mean values of potassium (K) ranged from 55.67 mg/L (invaded {Depth 1}) to 193.7 mg/L, with the highest on 3.1 uninvaded (Table 4.7).

Table 4.7 Mean-value variations of variables on the three treatments measured at two depths in WRC-site 9.

Variable	**Depth 1**			**Depth 2**		
	Treatment			**Treatment**		
	1.1 Cleared A	**2.1 Invaded B**	**3.1 Uninvaded C**	**1.2 Cleared D**	**2.2 Invaded E**	**3.2 Uninvaded F**
Total N (%)	0.21	0.26	0.17	0.18	0.20	0.17
P (mg/L)	4.33	10.33	5.33	4	3.67	3.67
K (mg/L)	55.67	124.3	193.7	56.67	60	130.3
Ca (mg/L)	521	573.7	333	286	370.7	346.7
Mg (mg/L)	76.67	83.67	50.33	22	95	58.67
Zn (mg/L)	2.4	2.1	1.4	2.27	1.27	1.3
pH	4	3.80	3.75	3.87	3.86	3.7
Cations (cmol/L)	4.10	6.68	5.48	4.43	5.98	5.71
Exch. Acid. (cmol/L)	1.57	2.57	3.22	2.67	2.41	3.32
Acid sat. (%)	32.33	39.67	58	60.33	41	56.67
Density (g/ml)	1.19	1.20	1.22	1.22	1.22	1.23

Calcium (Ca) mean values varied from 573.7 mg/L on invaded top-soil to 286 mg/L on cleared sub-soil. The variation was clearly defined with the highest mean values observed on invaded top- and sub-soil layers within groups (Table 4.7). The mean values of magnesium (Mg) on invaded patches were higher than other treatments at both depths with 22 mg/L lowest mean value on cleared sub-soil (Table 4.7). The mean values of total cations on invaded (depth 1 and 2) showed highest range than its counterpart (Table 4.7).

Soil pH was extremely acidic on the three treatments with uninvaded treatments having lowest pH mean values of 3.75 (Depth 1) and 3.7 (Depth 2) contrary to low pH recorded on invaded patches in WRC-site 3 and WRC-site 8. The highest pH was observed on cleared top-soil (Table 4.7). Exchange acidity mean values were low on the cleared patch (Depth I) (Table 4.7) but high with 3.22 cmol/L and 3.32 cmol/L mean values on uninvaded top- and sub-soil layers. High mean values of acid saturation were recorded on all three treatments (Table 4.7) with lowest mean value of 32.33% observed on cleared top-soil. All mean values appeared equal (Table 4.7).

The mean values of zinc (Zn) varied at the top-soils across treatments (Table 4.7). The highest mean value of 2.27 mg/L on cleared sub-soil was observed. There were no or less differences in bulk density mean values, thus equal values across patches (Table 4.7).

The uninvaded sampled patch was an old cultivated land that reverted into grassland and the cleared site was invaded by *A. mearnsii*. More information on the site-characteristics is detailed in Table 4.2. Different concentrations of soil chemical properties across treatments and depths observed in WRC–Site 10 are presented in Table 4.8.

The increasing mean values of total nitrogen (N) from uninvaded to cleared treatments at the top-soil layers varied similarly with the sub-soil layers (Table 4.8). Similar to WRC-site 3, total nitrogen (N) on the cleared treatment (sub-soil) was observed to be higher than invaded and uninvaded sub-soils, which was contrary to WRC-site 8 and WRC-site 9, where the total nitrogen (N) mean values reduced significantly from 0.25% on invaded to 0.12% on cleared (WRC-site 8), and 0.26% on invaded to 0.21 on cleared (WRC-site 9).

Table 4.8 Mean-value variations of variables on the three treatments measured at two depths in WRC-site 10.

Variable	**Depth 1**			**Depth 2**		
	Treatment			**Treatment**		
	1.1 Cleared A	**2.1 Invaded B**	**3.1 Uninvaded C**	**1.2 Cleared D**	**2.2 Invaded E**	**3.2 Uninvaded F**
Total N (%)	0.26	0.22	0.16	0.18	0.17	0.14
P (mg/L)	25	20.33	10.33	12.67	10.67	3
K (mg/L)	138.3	140.67	157.33	146.3	125.7	112.7
Ca (mg/L)	279	284	342.7	541.7	346.3	371.7
Mg (mg/L)	33	71	64.67	84.67	51.33	62.33
Zn (mg/L)	2.53	7.10	13.67	3.2	8.57	4.53
pH	3.34	3.67	3.61	3.49	3.60	3.67
Cations (cmol/L)	7.22	7.32	5.17	7.34	5.9	4.84
Exch. Acid. (cmol/L)	4.87	3.57	2.52	3.56	3.43	2.19
Acid sat. (%)	67.67	52.33	47	49.67	57.33	46.33
Density (g/ml)	1.18	1.33	1.33	1.24	1.35	1.28

Phosphorus (P) highest mean values were obtained from 1.1 (cleared top-soil) followed by 3.1 (uninvaded top-soil), 1.2 (cleared sub-soil), 2.2 (invaded sub-soil). The lowest mean value was observed on 3.2 (uninvaded sub-soil) (Table 4.8). Potassium (K) was seen to be present in equivalent values across treatments and depths (Table 4.8).

Calcium (Ca) concentration was higher on cleared sub-layer with mean values of 541.7 mg/L and the lowest mean value was seen on cleared top-layer (Table 4.8). Magnesium (Mg) mean value was observed to be higher on invaded top-layer and cleared sub-layer with low concentration on cleared top-layer (Table 4.8). Total cations was found to be higher on cleared and invaded top- and sub-layers with minimum mean values occurring on uninvaded groups (Table 4.8).

Having shown ‘extreme to strong pH range’ (Table 4.4) at the three sites already discussed, the pH at both depths and treatments in WRC-site 10 was observed to be equal in low values (Table 4.8) for extreme acidity. The exchange acidity mean value was highest on cleared top-soil but lowest on uninvaded sub-soil (Table 4.8). Acid saturation mean values seemed to be equally distributed across treatments and groups (Table 4.8).

High mean value of zinc (Zn) was observed on uninvaded top-layer (Table 4.8) with lowest mean value of 2.53 mg/L on cleared sub-layer. Similar mean values of bulk density were observed across patches and depths (Table 4.8).

This subsection analyses the combined multivariate comparisons between sites by determining nutrient variability within the four sites. For this analysis, each variable was compared within and across sites, depths and treatments using the mean, standard error and significance level coefficients (ANOVA paired t-test) (Table 4.9). The mean values for 'all sites' were calculated from the 'mean of the mean' (which equals the mean of values of variables per site at different treatments and depths).

Total nitrogen (N) mean value was highest on invaded top-soil and lowest on uninvaded sub-soil. No significant difference (P>0.05) was observed (Table 4.9). *Phosphorus (P)* was the only variable that was significantly different on 'all sites' (Table 3.1Table 4.9). There were generally low phosphorus concentrations, however, high phosphorus (P) mean value was observed on cleared top-soil with the lowest values occurring on uninvaded groups (Table 4.9). Higher potassium (K) mean values were observed on invaded and uninvaded top-soil layers and lowest on cleared sub-soil layer (Table 4.9). Nevertheless, there was no significant difference (P>0.05).

The mean values of calcium (Ca) and magnesium (Mg) were observed to be higher on cleared and uninvaded depths although the null hypothesis (P>0.05) was accepted on 'all sites' (Table 4.9). Total cations mean values seemed to be relatively similar, but higher values were observed on invaded and cleared groups having the mean values of 6.57 cmol/L and 5.68 cmol/L respectively. Thus no significance value was observed between treatments (Table 4.9).

The lowest pH mean values were recorded on cleared and invaded treatments and corresponded with high mean values of exchange acidity observed on cleared and invaded treatments across 'all sites' (Table 4.9). There were no significant differences (P>0.05) observed for both variables (Table 4.9). Acid saturation mean value was lowest on cleared sub-soil with similar mean values observed on other treatments and groups (Table 4.9), but there was no significant difference (P>0.05).

Table 4.9 Summary of the soil nutrients variation across treatments and depths showing the mean, standard error, significance value, maximum and minimum values on all the sites (WRC-site 3, WRC-site 8, WRC-site 9 and WRC-site 10).

Note: Treatment = 1-3; Depth = 1(A-C), 2 (D-F);

Variable	**1.1 Cleared A**			**2.1 Invaded B**			**3.1 Uninvaded C**			**1.2 Cleared D**			**2.2 Invaded E**			**3.2 Uninvaded F**			**P-value**
	Mean ±S.E	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	
Total N (%)	0.195±0.029	0.26	0.12	0.22±0.019	0.25	0.17	0.185±0.022	0.25		0.165±0.012	0.18	0.13	0.18±0.014	0.2	0.14	0.16±0.018	0.21	0.13	P>0.05
P (mg/L)	**26.25±10.75[ab]**	**55.7**	**4.33**	**15.33±4.67**	**26.33**	**5.33**	**9.5±2.003**	**14.67**	**5.33**	**7.085±2.31**	**12.67**	**2.67**	**6.78±1.78[b]**	**10.67**	**3.67**	**4.75±.096[a]**	**7.33**	**3**	**P<0.05**
K (mg/L)	109.5±25.87	167	55.67	151±11.36	174.3	124.3	148.8±26.65	193.6	72	97.83±18.45	146.3	56.67	100.5±20.92	146	60	99.59±13.46	130.3	70.67	P>0.05
Ca (mg/L)	344.3±74.76	521	176	329.7±83.35	573.7	197.97	382.6±78.31	608.3	246.33	294.7±97.24	541.7	66	228.6±75.69	370.6	77	342.8±31.22	398.3	254.67	P>0.05
Mg (mg/L)	31±16.65	76.7	0	43.17±20.24	83.67	0	59.83±8.46	81.33	43	27.5±19.66	84.67	0	39.17±21.66	95	0	43.59±10.95	62.33	14.67	P>0.05
Zn (mg/L)	1.57±0.59	2.53	0	2.68±1.76	7.8	0	4.18±3.17	13.67	0.8	3.2±0.72	3.2	0	8.57±2.01	8.57	0	2.18±0.96	4.53	0.07	P>0.05
pH	3.69±0.14	4	3.34	3.67±0.046	3.8	3.59	3.89±0.12	4.11	3.61	3.72±0.12	3.96	3.49	3.75±0.054	3.86	3.6	3.87±0.21	4.07	3.67	P>0.05
Cations (cmol/L)	5.68±0.74	7.22	4.1	6.57±0.41	7.32	5.42	5.29±0.49	6.45	4.05	5.345±0.79	7.34	3.79	5.36±0.44	5.98	4.08	4.90±0.47	5.71	3.59	P>0.05
Exch. Acid. (cmol/L)	3.57±0.71	4.87	1.57	3.80±0.62	5.55	2.57	2.37±0.36	3.22	1.48	3.44±0.30	4.14	2.67	3.50±0.53	4.94	2.41	2.62±0.32	3.32	1.98	P>0.05
Acid sat. (%)	60.25±9.91	78.7	32.33	59.58±8.85	81	39.67	45±4.89	58	36.67	67.58±8.40	89	49.67	66.92±10.10	90	41	52.75±2.27	56.67	46.33	P>0.05
Density (g/ml)	1.15±0.023	1.19	1.1	2.58±1.33	6.57	1.2	1.92±0.67	3.94	1.19	1.19±0.028	1.24	1.12	1.21±0.066	1.35	1.03	1.92±0.69	3.99	1.17	P>0.05

Similar letters indicate means that are significantly different (P<0, 0.001, 0.01, 0.05)

P<0, P<0.001, P<0.01 = highly significant difference

P<0.05 =significance difference

P>0.05 = no significance difference

High mean value of zinc (Zn) on ‘all sites’ was observed on uninvaded (top-soil layers) and lowest mean values were recorded on cleared (top- and sub-soil layers) (Table 4.9). The bulk density provided support for the null hypothesis across sites (Table 4.9).

4.5 EFFECTS ON SOIL CHEMICAL PROPERTIES

Analytical statistics were carried on two factors that were expected to influence the soil system. Effects of these two factors, *Acacia spp* (and farming) and time (time of clearing) was evaluated by analysing hypothetical assumptions and testing to understand their impact. The null hypotheses were postulated and tested for variables across different sampled categories (sites, treatments and depths) according to the inducing factors.

The null hypothesis indicating that *Acacia* species had no impact on the soil chemical compositions was tested. The tested null hypothesis was that the difference in nutrient concentration between invaded, cleared and uninvaded remained the same over time since invasion and clearing following natural gradients. This was hypothetically tested for these variables on ’all sites’ for top and sub-soil layers: N, P, K, Ca, Mg, Zn, pH, total cations, exchange acidity (CEC), acid saturation and bulk density. For all the variables, the null hypothesis was accepted with the exception of *phosphorus* (P) (Table 4.9).

In order to measure the degree of invasion impact, another null hypothesis was tested – the difference between invaded and uninvaded treatments on ‘all sites’ at both depths remained the same regardless of invasion rate and degree (Musil & Midgley 1990). The null hypothesis was accepted for N, P, K, Ca, Mg, Zn, pH, total cations and acid saturation, but was rejected for *exchange acidity* (CEC) with a percentage change of 32% decrease over time (Table 4.10).

Table 4.10 Paired t-test for chemical soil properties on invaded and uninvaded patches on 'all sites'.

Variable	2.1 Invaded	2.2 Invaded	3.1 Uninvaded	3.2 Uninvaded	P-value	% change
Total N (%)	0.22	0.18	0.185	0.16	P>0.05	-14
P (mg/L)	15.33	6.78	9.5	4.75	P>0.05	-36
K (mg/L)	151	100.5	148.8	99.59	P>0.05	-1
Ca (mg/L)	329.7	228.58	382.58	342.8	P>0.05	30
Mg (mg/L)	43.17	39.17	59.83	43.59	P>0.05	26
Zn (mg/L)	2.68	8.57	4.18	2.18	P>0.05	-43
pH	3.67	3.75	3.89	3.87	P>0.05	5
Cations (cmol/L)	6.57	5.36	5.29	4.9	P>0.05	-15
Exch. Acid. (cmol/L)	3.8	3.5	2.37	2.62	**P<0.05**	**-32**
Acid sat. (%)	59.58	66.92	45	52.75	P>0.05	-23

Note: Significant change (P<0.05) highlighted.

Effect of time was used as a substitute for rejuvenation of soil chemical compositions (Van der Waal 2009). Another null hypothesis was tested – the difference in soil chemical properties between cleared and invaded treatments remained the same since the time of clearing (Van der Waal 2009). The null hypothesis was rejected for *Mg* and accepted for N, P, K, Ca, Zn, pH, total cations, exchange acidity and acid saturation between cleared and invaded treatments when observed on 'all sites' at both depths (Table 4.11).

Table 4.11 Paired t-test for chemical soil properties on cleared and invaded patches for all sites

Variable	1.1 Cleared	1.2 Cleared	2.1 Invaded	2.2 Invaded	P-value	% change
Total N (%)	0.195	0.165	0.22	0.18	P>0.05	11
P (mg/L)	26.25	7.085	15.33	6.78	P>0.05	-34
K (mg/L)	109.5	97.83	151	100.5	P>0.05	21
Ca (mg/L)	344.3	294.7	329.7	228.58	P>0.05	-13
Mg (mg/L)	31	27.5	43.17	39.17	**P<0.05**	**41**
Zn (mg/L)	1.57	3.2	2.68	8.57	P>0.05	136
pH	3.69	3.72	3.67	3.75	P>0.05	0
Cations (cmol/L)	5.68	5.345	6.57	5.36	P>0.05	8
Exch. Acid. (cmol/L)	3.57	3.44	3.8	3.5	P>0.05	4
Acid sat. (%)	60.25	67.58	59.58	66.92	P>0.05	-1

Note: Significant change (P<0.05) highlighted

There was an increase in Mg after nine years of clearing but 0 % and 81 % increase after 8 years of removing high and low density of *A. mearnsii* invasion (Table 4.12). However, N, P, K, Ca, total cations, exchange acidity fairly decreased after nine years of clearing, while significant increases occurred after eight years of clearing in N, K, total cations and exchange acidity (see Table 4.12).

Table 4.12 Soil variables analysed between cleared and invaded patches on 'all sites' showing degree of invasion and percentage change with time.

Variable	WRC-site 3 High density Cleared for 9 years	WRC-site 10 High density Cleared for 9 years	WRC-site 8 High density Cleared for 8 years	WRC-site 9 Low density Cleared for '-'
	% change	% change	% change	% change
Total N (%)	-13	-12	82	18
P (mg/L)	-22	-18	-96	68
K (mg/L)	-7	-6	64	83
Ca (mg/L)	-44	-23	12	17
Mg (mg/L)	60	4	0	81
Zn (mg/L)	-60	188	0	-28
pH	2	6	-4	-3
Cations (cmol/L)	-24	-9	44	34
Exch. Acid. (cmol/L)	-18	-17	46	17
Acid saturation	8	-7	2	-13

Note: + value indicate increase, - value indicate decrease.

4.6 SOIL ANALYSIS TOWARDS REHABILITATION

This section will provide a preliminary discussion of the soil sample results given above, with the aim of addressing objective 1 of this thesis and the research questions asked at the beginning of this chapter. Nutrient status prior and after clearing as well as the required nutrient pools toward effective rehabilitation and land use options will be discussed. Also, the proposed rehabilitation program that will be suitable for rangeland-soil amendments and productivity (objective 5) at the QCs will be addressed.

Limited significant implications were inferred from the soil analysis evaluated per site largely due to the low numbers of samples (18 samples per site). Mean values of the variables were used to explore nutrient variability on each site, which showed high irregularities across different sampled treatments, above and below-ground pools and IAPs types. This could be due to different seasonality and environmental conditions at each QC or perhaps discrepancies surrounding the soil samples and analysis (details will be provided later). These per site analyses, which are self-explanatory analyses, were done to supplement the knowledge of nutrient variations for each site and also as a pre-requisite for subsequent nutrient analysis.

Unlike other sampled sites, WRC-site 3 was invaded by *Acacia dealbata*. Studies on this species have identified its impacts on soil *nitrogen (N)* and inorganic components (Lazzaro et al. 2014;

González-Muñoz, Costa-Tenorio & Espigares 2012). Contrary to previous research (González-Muñoz, Costa-Tenorio & Espigares 2012), *Acacia dealbata* invasion on *total N* in WRC-site 3 showed little or no difference along cleared, invaded and natural soils. This finding has been supported by May & Attiwill (2003) who noted the presence of *N* inputs influenced by the abundance of *A. dealbata* stands in both soil and plants in a mountain ash forest. Since the impacts of IAPs are context-dependent and often volatile, more sampling is required to ascertain the state of soil impact by *A. dealbata* at the QCs. This was not achieved by a single-sample protocol.

Due to the observation of *Acacia* measuring impacts from the research results, in relation to cleared and natural systems, the statistical significance for the three treatments were analysed for 'all sites' by collating the top and sub-soil samples (72 samples). The statistical inferences drawn showed no significant differences ($P>0.05$) in the soil chemical compositions tested except for *phosphorus (P)*. Contrary to Musil & Midgley (1990), the post-clearing effect on soil *P* was significant as there was an elevated *P* on cleared soils for aboveground and belowground layers at the QCs (Figure 4.7). It was established from the literature that removing *Acacia* stands increases nutrient pools (or lowers nutrient availability to native species) by restoring soil functional community and microclimate, and then stimulating soil microbial community for N mineralisation (Yelenik, Stock & Richardson 2004). This was seen when reduced soil *P* was elevated in cleared *Acacia* soils after eight to nine years of clearing. This might also predict the probable effects of *Acacia* invasion on *P* since low *P* was recorded on uninvaded soils (Figure 4.7). Other studies contradicted the findings from soil *P* across *Acacia* infested, cleared and uninvaded soils (Yelenik, Stock & Richardson [1]2004; Musil & Midgley 1990). More research should be directed at further validation of the soil *P* levels across treatments at the QCs in Eastern Cape.

[1] Italicised keywords represent the point-emphases in the sections (or subsections) and provide better dimensions of the discussions.

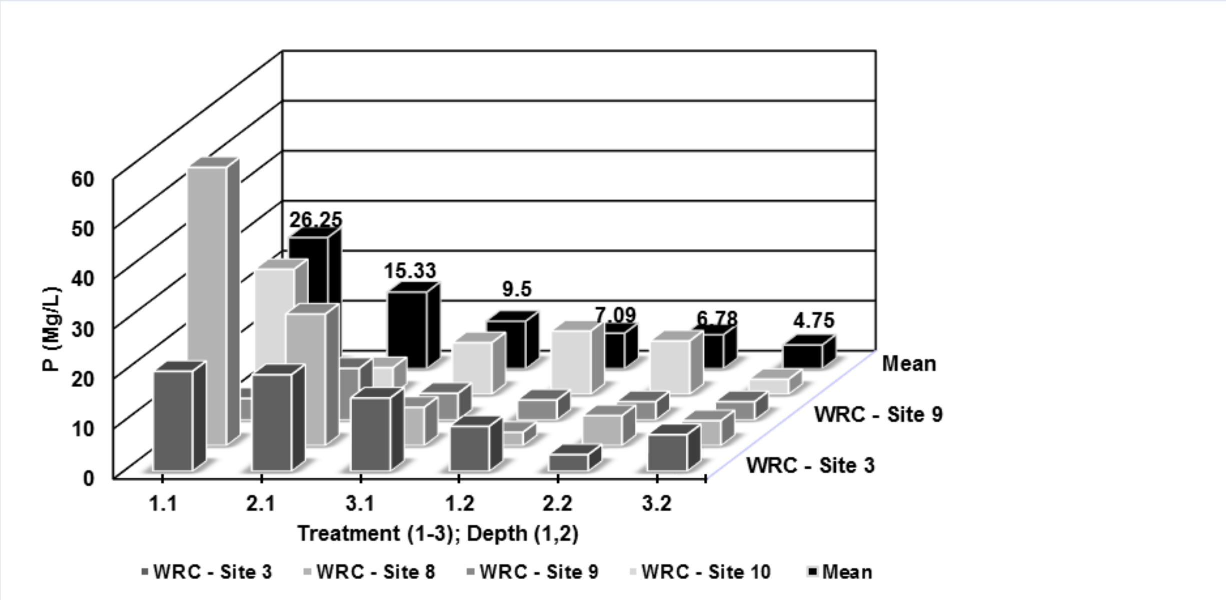


Figure 4.7 Phosphorus variability on cleared (1.1 and 2.1), invaded (2.1 and 2.2) and uninvaded (3.1 and 3.2) treatments at 10 cm and 20 cm depths on 'all sites'.

Like soil P, N and N cycling rates was confirmed to be altered by *Acacia spp* (Pysek et al. 2012; Vila et al. 2011). Invaded and cleared patches were significantly higher than uninvaded soils in *total N* (Figure 4.8). This concurred with literature espousing that *Acacia spp* are nitrogen-fixing plants that alter N-cycling processes optimal for rangeland productivity (Van der Waal 2009; Yelenik, Stock & Richardson 2004; Musil & Midgley 1990). However, in line with the literature, *Acacia* invaded soils had higher concentrations of N, P, K (Van der Waal 2009; Yelenik, Stock & Richardson 2004; Musil & Midgley 1990). This could be as a result of fast decomposition of nutrient-rich litter fall of *Acacia spp.* (Musil & Midgley 1990). Yelenik, Stock & Richardson (2004) confirmed high *total N* in fynbos soils invaded by another *Acacia spp* on Riverlands Nature Reserve that altered the N-cycling regime after clearing. The reduction of *total N* on invaded soils from 0.22% to 0.2% above-ground and 0.18% to 0.17% below-ground, after eight to nine years of clearing clearly indicates that the process of natural attenuation might not be feasibly attained. Again, between invaded and cleared soils, tested variables tend to remain the same (P>0.05) over the years, except Mg. This salient finding has provided further proof of the unreliability of natural remediation. However, the optimum concentration of *total N* for rangeland productivity on uninvaded soils is equivalently similar to the *N* content on invaded soils (Figure 4.8). As a result, the *Acacia* impact on soil *N* status is probably not profound for *N* remediation of the tested soils.

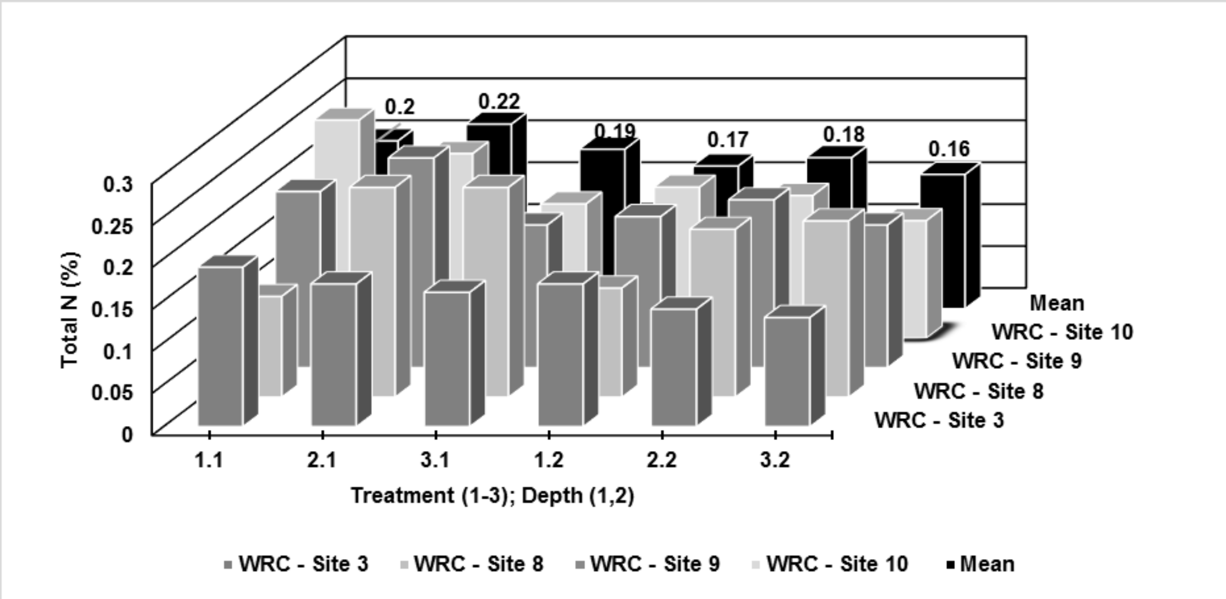


Figure 4.8 Total nitrogen variability on cleared (1.1 and 2.1), invaded (2.1 and 2.2) and uninvaded (3.1 and 3.2) treatments at 10 cm and 20 cm depths on 'all sites'.

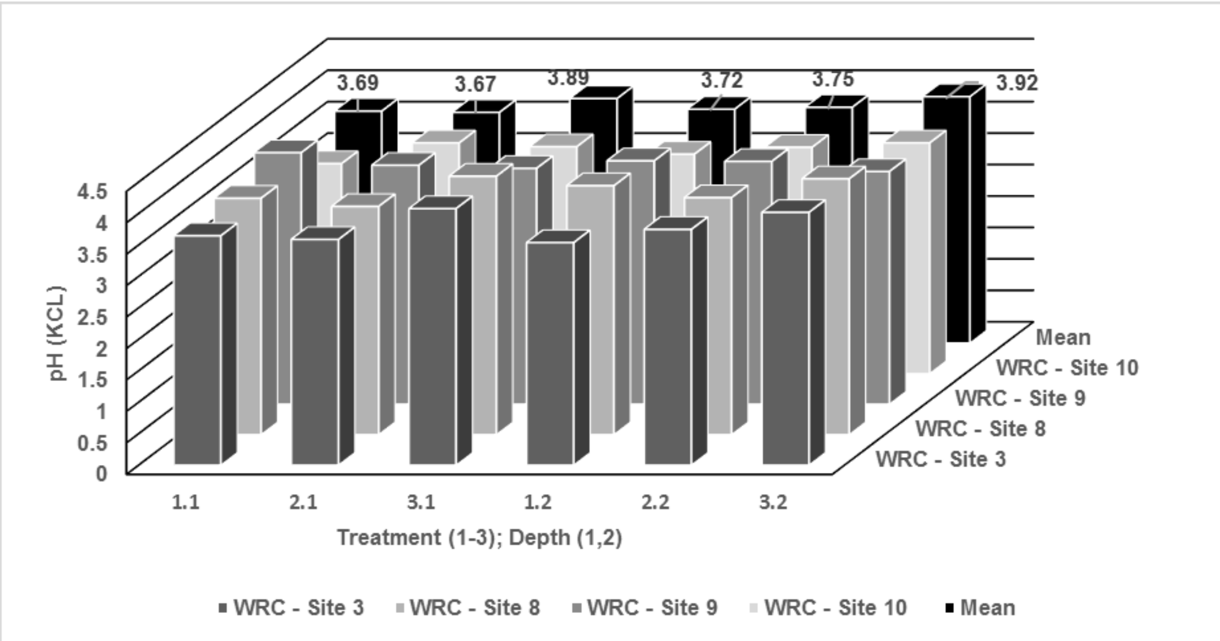


Figure 4.9 pH variability on cleared (1.1 and 2.1), invaded (2.1 and 2.2) and uninvaded (3.1 and 3.2) treatments at 10 cm and 20 cm depths on 'all sites'

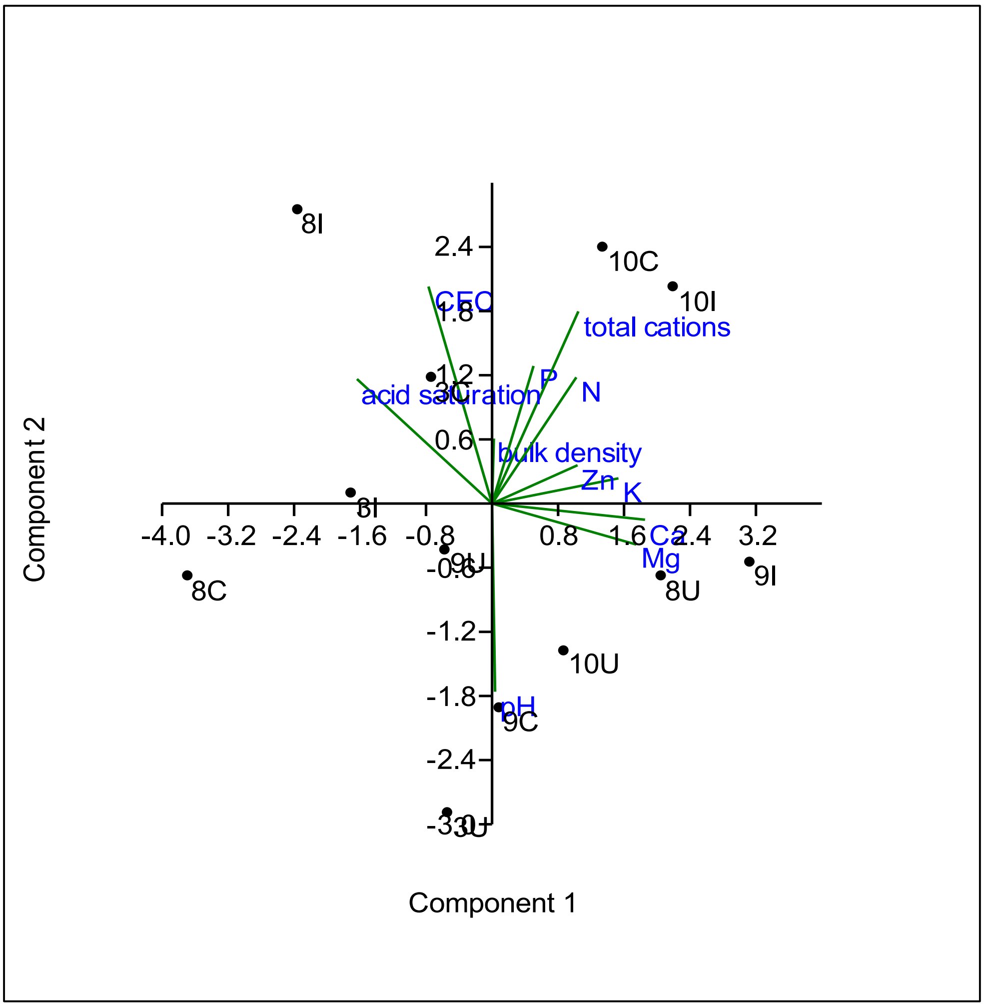
No significant differences were seen in the *pH* value but the *pH* status for the four sampled sites (Figure 4.9) and treatments were constantly lower than the soil standard pH needed for plant productivity (Table 4.4). This is in agreement with the findings by Yelenik, Stock & Richardson (2004) where no statistical difference was seen in the soil pH between acid sandplain of low fynbos and *Acacia* infested soils. Acidic soil plain was reported for one-third of the Eastern Cape (Miles

& Farina 2013). Van der Waal (2009) confirmed pH variability between *A. mearnsii* invaded soil and fynbos slopes in the Kouga Mountains of the Eastern Cape.

The formulated null hypothesis was purely exploratory and valuable to the understanding of the impact-focus of *Acacia* spp (and farming) in determining nutrient depletion (or upsurge) between treatments, with expected effect of time. Comparatively, the hypotheses that the differences in soil chemical properties remained the same between 'invaded and uninvaded treatments' and 'cleared and invaded treatments' showed invasion impact, with positive effect of time, since clearing. Significant difference in *exchange acidity* between invaded and uninvaded soils showed 32 % decrease from 3.8 cmol/L of invaded soils to 2.37 cmol/L uninvaded soils after many years since clearing (Table 4.10). The 41% *Mg* increase on invaded soils clearly identified the novelty of *Acacia spp.* in nutrient upsurge, when compared with cleared soils of eight to nine years (Table 4.11). Low *Mg* concentrations on cleared soils agreed with the findings of Van der Waal (2009) on low *Mg* on cleared slopes of *A. mearnsii* but contradicted the findings of Musil & Midgley (1990). These inconsistent results on the nutrient variables could be ascribed to many factors such as localised effects, wide-variability and irregularities of natural systems (Musil & Midgley 1990).

To confirm the validity of the soil sampled results, the soil samples collected from the study sites were also analyzed by Gwate et al. (2015). The soil results were established by upon examination of the nutrient variables using principal component analysis (PCA) on the correlation matrix of the raw data (Gwate et al. 2015). The null hypotheses stating that the variables were uncorrelated were rejected. The first three axes of PCA explained approximately 82 % of the total variation.

The scree-plot technique in Figure 4.10 shows that the first rotated component has high loadings for K, Ca, Mg, CEC and acid saturation. However, K, Ca, Mg negatively correlated with exchange acidity (or CEC) and acid saturation. Therefore, increases in K, Ca and Mg are associated with decreases in CEC and acid saturation. The second component was positively correlated with P, total cations, CEC and Zn and negatively correlated with pH. The third component was strongly positively correlated with bulk density, total cations and N.



Source: Gwate et al. (2015)

Figure 4.10 The first two principal components (scree-plot technique) of the variables and sampled sites.
Note: Numbers 3, 8, 9, 10 = WRC3, WRC8, WRC9 and WRC10; Letters = I-invaded, U-uninvaded and C-cleared).

There were 21 (38%) non redundant residuals with absolute values greater than 0.05. This means that the three factor solution can explain about 62% of the observed correlations between the variables providing an accurate summary of the relationships in the data. The scree-plot showed that sites 10C and 10I were similar and had the highest concentration of total cations, *P*, *N*, *bulk density*, *Zn* and *K*, while sites 8C, 3U and 9U are projected on the opposite side of the vector and lower than average concentration or values for sites 8C, 3U, and 9U are expected (Figure 4.10). At the same time, site 8U, 9I and 10U had above average *Ca* and Mg while sites 8I, 3C are had below average values of these variables. It was also expected that sites 8I and 3C would have above average *CEC* and *acid saturation* and the opposite was true for sites on the opposite side of the vector. The graph also shows that *acid saturation* is strongly positively correlated with *CEC* while *P*, *total cations*, *N, bulk density Zn* and *K* were also positively correlated. The *pH* was negatively correlated with the rest of the variables, while *Mg, Ca* were not correlated with *acid saturation* and *CEC*. Based on principal components, *A. mearnsii* altered the soil by impacting on *macronutrients*, *bulk density* and *micronutrients* due to *P* absorption dynamics (Gwate et al. 2015).

Change in land cover between invaded and cleared soils of nine years showed irregularities in variables over time (Table 4.12). Cleared sites of eight years showed similar nutrient fluxes (Table 4.12). Nutrient pools (N, P, K, Ca, Mg, Zn, pH, acid saturation) before (invaded) and after clearing (cleared) over many years practically remained constant except exchange acidity (Table 4.10). Many of these nutrients such as P, K, Ca, Mg and Zn, are assumed to be available in required limits suitable for plant growth and may be acceptable for soil productivity when compared to uninvaded sampled soils (assumed as the control sites). Nitrogen and pH were not significant on 'all sites' but varied across sites in accordance with soil acidity and increase in N, which is generally associated with *Acacia* (Pysek et al. 2012; Vila et al. 2011). High N content on invaded soils decreased on cleared soils. This equalled the N concentrations on uninvaded soils (control sites) (Table 4.12). This showed that although natural N remediation is taking place on cleared soils, the rate of attenuation is quite slow. The pH also shows level-increase from higher acidity on invaded sites to lower acidity on cleared sites similar to the trend in uninvaded soils (Table 4.12). However, all sampled soils and treatments that were recorded were extremely acidic (Table 4.9) against pH soil reaction ratings (Table 4.4) for crop production.

The nutrient pool to be remediated for soil fertility among tested variables basically includes the enhancement of soil pH. The soil pH showed negative correlative behaviour with all the variables in a general linear modelling (PCA) (Figure 4.10), where the *pH* elevation in the soil lowers the availability of other soil nutrients, and contrariwise (Gwate et al. 2015). Soil acidity limits nutrient-exchange between plant-soil interaction that affects plant fecundity as well as soil community (Miles & Farina 2013). Most nutrient elements become available in the pH range of 5.5 – 6.5 (Motsara & Roy 2008). pH values recorded in this study ranged from 3.59 to 3.89 (Table 4.9). As a result, neutralising soil acidity is important for any selected land use options and this can be achieved through lime addition.

High yield of crop production are often achieved at the pH range of 6.0 – 7.5. Lime addition reduces the acidity of soils by increasing the pH of acid soils. The quantity of lime needed to increase pH to optimum level can be termed lime requirement. This could be measured using various methods such as the woodruff method. The amount of different limes (such as $CaCO_3$, Ca (OH), marl, limestone, dolomite) required to raise acid soils to pH ranges optimal for high crop yields are detailed in Motsara & Roy (2008).

For land use options, soils with pH of 6.6 – 7.2 required no lime or gypsum application because it is assumed to be neutral. Soils with pH below (acidic) or above (alkaline) these limits require growing of acid- and salt-tolerant crops, respectively. Due to economic challenges associated with lime addition, only very high acidic and alkaline soils require amendments through chemical remediation (Motsara & Roy 2008). The study sites have generically acidic soils that require chemical amendments after other factors must have been considered. It is also noteworthy that growing of acid-tolerant crops will maximise soil potentiality for productivity.

Moreover, clearing in itself is not a rehabilitation protocol as adopted by WfW programs and other bodies (Reid et al. 2009). Invasion impact has proven not to be curbed simply by mere removal of plant stands without post-remediation as deduced from the soil analysis (Cairns 2002; Hobbs & Harris 2001). Aside from the proposed rehabilitation programs suggested above (lime addition), many other protocols can be adopted. Exclosures were already erected on some of the sampled sites to wade off livestock grazing and enabling natural soil remediation. Exclosures could also be used in further rehabilitation procedures. As observed from the analysis, natural attenuation has shown to be unreliable, and as a result, there is a need for chemical remediation of soil acidity neutralisation or growing acid-tolerant plants if cultivation was selected as a land use option. Some nutrients (such as N, P, Mg, CEC), upsurge by IAPs, can also be lowered by growing plants that have affinity for such nutrients.

4.7 CONCLUSION AND RECOMMENDATIONS

Several findings were deduced from the various analyses targeted at addressing the objectives and the 'hypothetical questions' posited at the beginning of this chapter. These are briefly highlighted as:

- There were irregularities in variables per site analysis that seemed out of sync when compared within and across categories.

- P significantly varied across all categories while exchange acidity (CEC) varied significantly between invaded and uninvaded soils, whereas Mg was significant between invaded and cleared soils.
- While no significant difference was seen in pH, linear modelling of component analysis identified pH to be negatively correlated with other variables, implying that an increase in pH resulted in a decrease in soil nutrients and vice versa.
- N was not significant, but exploratory analysis showed *Acacia* novelty in N upsurge as well as elevated soil acidity of QCs, which cannot be overlooked but require chemical remediation for future land use option(s).
- Uninvaded soils may have showed many irregularities for variables but offered adequate soil nutrients standard for land productivity, only for some variables.
- Effect of time is an unreliable surrogate for natural rehabilitation.

Some discrepancies surrounding the soil sampling and analysis may have altered validation of the soil results. Few recommendations are therefore given to further validate these results as well as to assist future research in this field. They are:

- Higher number of sample sizes per site must be collected for nutrients validation at each study site.
- It was previously mentioned that this analysis was dependent on the treatment gradients rather than the QC, however it is still important to analyse soil compositions pertinent to each QC for effective rehabilitation programmes to be adopted.
- As a result of the distance travelled from the study sites to the laboratory, the length of time taken to deliver the samples may have influenced the soil results. The soil analysis was, however, not carried out soon enough. This also may have affected the soil results and findings. (Ras 2014 Pers com).
- Two *Acacia spp.* were studied; this gives non-specific impacts of the species. In order to identify each specie-impact, sampling of soils solely invaded by a particular species (either *A. mearnsii* or *A. dealbata*) must be carried out.

Lastly, reviewed literature for this research showed that little research has been carried out on rangelands, soil chemical and physical properties, *Acacia spp* in Eastern Cape or any other regions.

Therefore, future research must be directed towards rangeland-soil degradation induced by various factors, including alien invasion, farming, clearing, fire regimes and outbreaks in the Eastern Cape or any other rangeland biomes in South Africa to address the discrepancies encountered in this study as discussed above.

CHAPTER 5: **EVALUATING RANGELAND CLASSIFICATION AND CHANGE**

This chapter addresses objectives 2, 3 and 4 of this study, which centred predominantly on land cover mapping and change analysis. These objectives are:

- To determine the extent of degradation through land cover classification and change analysis.
- To develop a novel framework for land cover change that will measure the rehabilitation progresses in the study sites.
- To quantify the trends in NPP and ET prior and after eradication of alien plants.

An object-orientated approach, known as GEOBIA was selected for supervised classification of the satellite imagery as adapted from literature (Steele et al. 2013; Blaschke 2010; Lang 2008). Change analysis techniques were developed and applied based on a framework adapted from Benini et al. (2010), Mas (1999) and Vos (2014). Monitoring the ET/NPP rates to demonstrate reclamation trends were evaluated using MODIS products (Mu, Zhao & Running 2011; Mu et al. 2007; Zhao et al. 2005; Hunt et al. 2003). The sequential procedures for achieving these steps are represented in Figure 5.1. This section comprises a description of the methodology used for land cover classification, change analysis and detection, the ET/NPP estimation followed by results and discussion. This section will begin with an explanation of how the data was sourced, the pre-processing of datasets and modifications of legends for the study sites from the land cover classification system (LCCS).

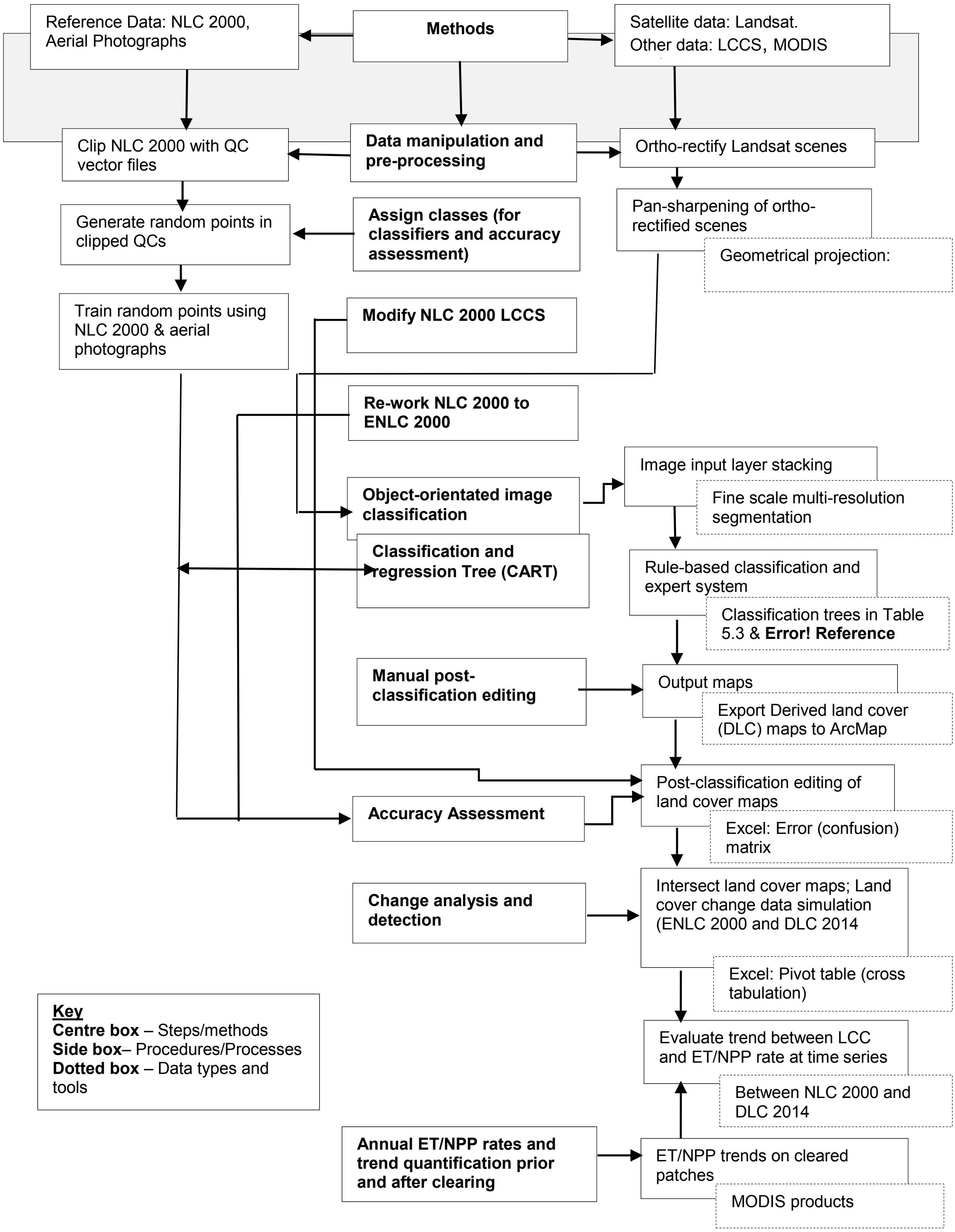


Figure 5.1 Flow chart for the methodology on data training collection, land cover classification, accuracy assessment, and land cover change analysis as well as ET/NPP quantifications
Note: key procedures are presented in the centre column in bold text.

5.1 DATA ASSEMBLAGE AND PRE-PROCESSING

Single-date Landsat imagery was selected to derive new land cover mapping. As a result of the supervised classification method chosen, aerial photographs and NLC 2000 (Van den Berg et al. 2008) were used as reference sets. Other products and ancillary data were also used. The spatial data used with their relevant information are shown in Table 5.1 and these will be discussed in detail in this section.

Table 5.1 Informational details of the datasets used.

Data theme	**ID**	**Cloud cover (%)**	**Colour bands**	**Resolution**	**Dates**	**Source**
Aerial photographs			Multispectral	0.5 m	2000-07	Chief Directorate: National Geo-spatial Information (CD: NGI)
					2013-05	
Landsat scenes (used for classification)	LC81690812014121LGN00	0.03	Multispectral (M) Panchromatic (P)	M = 30 m P = 15 m	2014-05-01	USGS
	LC81700822014160LGN00	0.02			2014-6-09	
Landsat scenes (for IAPs delineation)	LC81700822014016LGN00	0.19			2014-01-16	
	LC81700822014080LGN00	0			2014-03-21	
	LC81700822014256LGN00	0.51			2014-09-13	
	LC81700822014352LGN00	2.1			2014-12-18	
1:50K Topographic data	3028 (CC, CD) 3127 (BC, BD, CB, CD, DA, DB, DC, DD), 3128 (AA, AB)					CD: NGI via CGA
NLC 2000				30 m		Council for Scientific and Industrial Research and Agricultural Research Council (CSIR/ARC) via CGA
SUDEM				5 m		Van Niekerk (2013)
SPOT Building Count (SBC)						Eskom, CSIR: SAC
Vegetation type						Mucina & Rutherford (2006)
LCCS				30 m		CD: NGI
NIAPS						Kotze et al. (2010)
Other vector (rivers, roads, sea etc.)						CD: NGI via CGA
MODIS products	MODIS 16A3 ET			1 km	2001-2014	Mu et al. (2007)
	MODIS 17A3 NPP				2000-2014	Zhao et al. (2005)
Tropical Rainfall Measuring Mission (TRMM)					2000-2014	NASA (2011b)
Clearing data and vector files						WfW (East London office)

Due to its spatio-temporal coverage and no acquisition cost, high-resolution Landsat 8 OLI and TIRS imagery of winter seasonality (May/June 2014) (Table 5.1) was acquired for land cover classification. Two scenes, one covering QCs T12A and S50E, the other over QC T35B, were downloaded using the USGS Glovis Visualisation viewer. Additional Landsat imagery for January, March, September and December were also downloaded for trend analysis purposes.

The Landsat scenes were atmospherically corrected by normalising the solar radiance through conversion of spectral radiance to atmospheric reflectance. This was done in ATCOR (Richter & Schlapfer 2013) using radiance-conversion-to-top of atmosphere (ToA) reflectance model by converting digital numbers (DN) to radiance using the gain and bias values found in the metadata of each image file (Vos 2014). The Landsat scenes had little or no cloud cover. Haze removal was done using ToA reflectance correction method to eliminate atmospheric effect that can cause image contamination and obscure ground features (Richter & Schlapfer 2013). This was followed by scene sharpening to improve spatial resolution of the multi-bands in order to separate interspersed land cover classes by extracting small feature objects (Laliberte, Fredrickson & Rango 2007).

NLC 2000 (CGA, originally from CSIR) was used as a base dataset to compare class-classification and change over time. The low overall accuracy of 65.8% (Van den Berg et al. 2008) of the NLC 2000 prompted the need to edit the dataset in order to generate reliable results. The NLC 2000 was edited using aerial photographs of July 2000 (CD: NGI). The core reasons for the revision of NLC 2000 and the comparison with the edited NLC 2000 (henceforth ENLC 2000) were to:

- Provide valid results for the overarching project, as pre-requisite for carrying out other functional aspects of the research.
- Ascertain the level of uncertainty of NLC 2000 in comparison with the edited version.
- Serve as a guide and information base for future researchers and scientists that will undertake similar research(es).

Since few ground control points (GCPs) were collected in the field, random sample points were generated and classes assigned from NLC 2000 and aerial photographs for training data. A portion of the training data produced was used for classification and the remaining part for the accuracy assessment of the derived maps and ENLC 2000 maps. Boundaries of some land cover classes –

cultivated fields, plantation clear-felled, young pines and forest plantations –were digitised using aerial photographs.

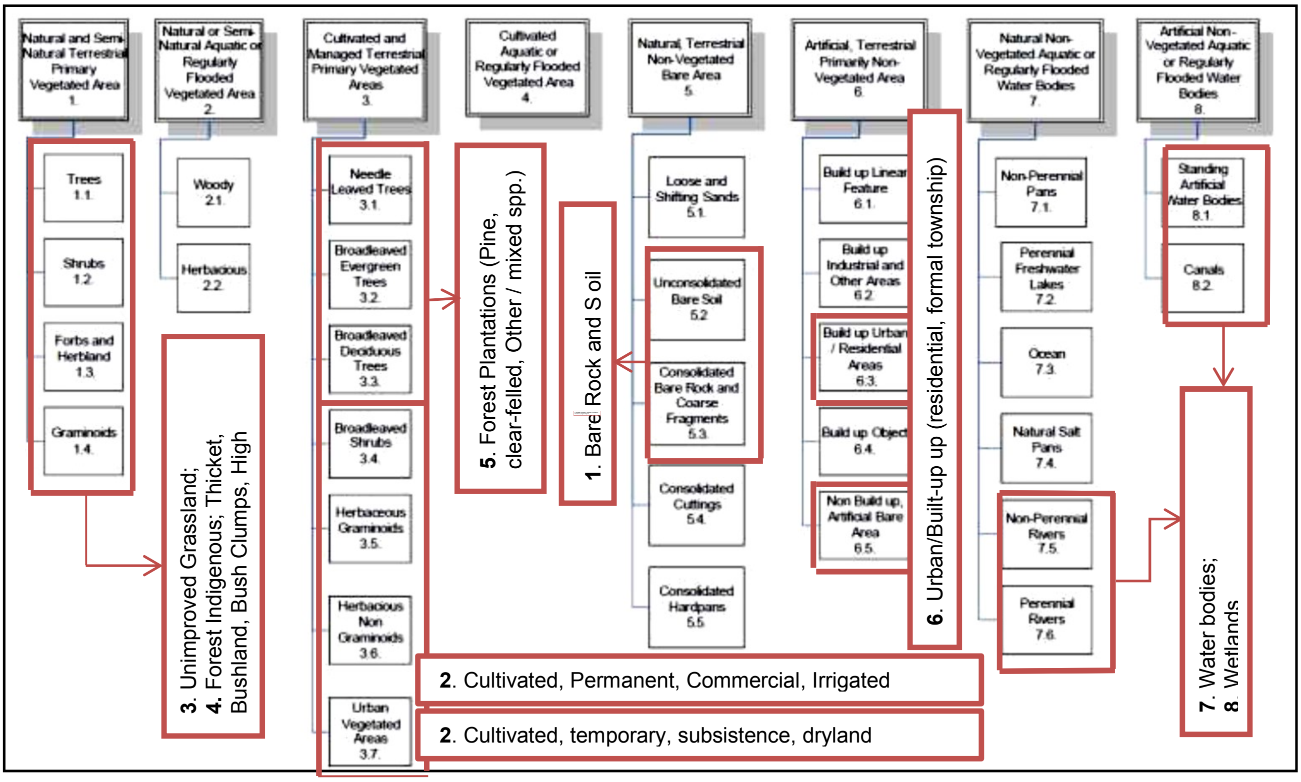
The SPOT building count (SBC) (CSIR: SAC) and a DEM (Van Niekerk 2013)-derived slope dataset were used to reduce overlapping of similar spectral classes. Vegetation indices such as NDVI, normalised difference water index (NDWI), SAVI and EVI were computed from the corrected satellite imagery in order to train the classifier to enhance separability between overlapping features. Other vegetation indices used include wide dynamic range vegetation index (WDRVI) for trend analysis.

MODIS products were used to provide continuous estimates of ET/NPP trends over cleared patches. MODIS annual ET and NPP obtained from the numerical terradynamics simulation group (NTSG 2015) with 1km spatial resolution was used. MOD17A3 NPP data (Zhao et al. 2005) used for NPP modelling is based on the light use efficiency (LUE) logic (Monteith 1972) which assumes that ecosystem productivity is a function of solar radiation, maximum efficiency of photosynthesis, and environmental constraints (Tan et al. 2011). For ET estimation, MOD16A3 ET (Mu, Zhao & Running 2011) uses a Penman-Monteith approach (Monteith 1965).

MODIS data from 2000 to 2014 were downloaded. MODIS tile H20V12 covered all the study sites. Precipitation (rainfall) data was generated using the tropical rainfall measuring mission (TRMM) dataset, downloaded from NASA Echo/Reverb. All MODIS datasets were processed using MODIS reprojection tool (MRT) for resampling and re-projection (UTM 35S) (Indiarto & Sulistyawati 2014). Spatial analysis was done in ArcMap (ESRI 2009) and the statistical analysis was performed using Excel (Microsoft 2013).

5.2 LAND COVER CLASSIFICATION SYSTEM

In order to standardise land cover legends throughout Africa, land cover classification system (LCCS) was developed using dichotomous and hierarchical classification trees. Developed by the Food and Agriculture Organisation (FAO), LCCS provides inherent flexibility and applicability to land cover mapping for various climatic and environmental ranges. The main reason for generating land cover maps is the creation or modification of a legend that is compatible with the area of study. The land cover legend (modified version) of the CD: NGI was reviewed to establish compatibility with the legend for the final land cover maps. Based on NLC 2000 classes, this LCCS was modified to contain eight super classes (numbered 1-8 in Figure 5.2), while giving full consideration to the FAO's LCCS (Lück & Diemer 2008) as shown in Figure 5.2.



Source: Lück & Diemer (2008: 13).

Figure 5.2 CD: NGI LCCS representing merged and eight final land cover classes encapsulated in red-rectangular outlines.

The LCCS was further modified to create a legend suitable for the study sites. The NLC 2000 classes for the study areas are comparatively similar in terms of phenology, spectral and textural properties and relatively difficult to classify as separate entities using coarse Landsat imagery. Therefore, similar classes are merged into group(s) integrating details of each class. As diverse land tenure systems are practised in T35B and T12A/S50E, two separate classes showing the two kinds of agricultural activities were created for the QCs (see Figure 5.2, Class 2). The final legend (eight classes) for the study sites and the descriptions of each class as they pertain to the LCCS and NLC 2000 legend are presented in Table 5.2.

Table 5.2 Modified QCs LCC from CD: NGI LCCS into eight final legends (merged classes) used for classification and their definitions.

CD:NGI Land cover class	DEFINITION	NLC 2000 class	Merged class - Final legend	Abbreviation
Natural, terrestrial non-vegetated bare areas	Mainly bare areas including unconsolidated bare soils, loose and shifting sand (coastal dunes and beaches), landslides, steep riverbed embankments, cuttings (roads) and consolidated hard pans that have less than four per cent vegetation coverage of the total area and lack non-natural surfaces (Lück 2006).	Bare Rock and Soil (natural)	Bare Rock and Soil (natural)	BRS
Cultivated and managed terrestrial primarily vegetated areas	Naturally vegetated areas radically altered to artificially vegetated areas by anthropogenic means such as planted, harvested, managed, tilled and bare surfaces prior to crop cultivation (Lück 2006). They are comprised in the subtypes of broadleaved shrubs, herbaceous graminoids, herbaceous non-graminoids and urban vegetated areas (Figure 5.2).	Cultivated, permanent, commercial, irrigated Cultivated, temporary, commercial, dryland	Cultivated, Permanent, Commercial, Irrigated	CLs
		Cultivated, temporary, subsistence, dryland	Cultivated, temporary, subsistence, dryland	
		Forest Plantations (Pine spp) Forest Plantations (clear-felled) Forest Plantations (Other / mixed spp)	Forest Plantations (clear-felled, Pine spp, Other / mixed spp)	FPs
Natural and semi-natural terrestrial primary vegetated areas	Naturally and semi-naturally vegetated areas without human intervention for its proliferation (Lück 2006). One subtype include primarily indigenous trees, shrubs, forbs, herb land and graminoids while the other subtype, primarily degraded or alien trees, shrubs, forbs, her bland and graminoids include naturally degraded areas that are influenced by human activities.	Degraded Unimproved (natural) Grassland Unimproved (natural) Grassland Shrubland and Low Fynbos	Unimproved (Degraded / Natural) Grassland	UGd/n
		Forest (indigenous) Thicket, Bushland, Bush Clumps, High Fynbos	Forest Indigenous, Thicket Bushlands, Bush Clumps, High Fynbos	FITBs
Artificial, terrestrial primarily non-vegetated areas	Include urban and built-up areas ranging from commercial, residential, low density rural settlements. These areas comprise of less than four per cent vegetation cover with an artificial cover resulting from human impacts (Lück 2006).	Mines & Quarries (surface-based mining) Urban/Built-up (residential, formal township)	Urban/Built-up (residential, formal township)	UrBu
Natural or artificial primarily non-vegetated aquatic or regularly flooded water bodies	Areas covered with perennial or non-perennial water originated either by anthropogenic or natural impacts with no vegetation cover or tendencies (Lück 2006). Examples included rivers, lakes, dams, reservoirs, canals, artificial lakes.	Water bodies	Water bodies	Wb
Natural and semi-natural aquatic or regularly flooded vegetated areas	A transitional stage between terrestrial and aquatic areas with a near-surface water table and significant vegetation covers (constituting mostly of hydrophytes) are termed natural and semi-natural aquatic or regularly flooded vegetated areas. Common examples include riparian zones, mangrove, marshes and wetlands.	Wetlands	Wetlands	Wl

5.3 IMAGE PROCESSING AND LAND COVER MAPPING

An object-orientated approach using GEOBIA in eCognition Developer (Definiens 2003) was selected for classification of the satellite imagery. A rule-based decision tree classification with defining threshold conditions was implemented to categorise related object-features into respective classes. For this approach, various ancillary datasets were used in addition to the Landsat 8 satellite imagery to inform the classification. These ancillary datasets included the SBC (CSIR: SAC, Eskom), slope derived from a digital elevation model (DEM) (Van Niekerk 2013) and digitised boundaries of cultivated lands and forest plantations.

Georectified, pan-sharpened Landsat 8 scenes captured in May/June 2014 (Table 5.1) (LC81690812014121LGN00 and LC81700822014160LGN00) were clipped to the extent of the aerial photographs sourced over the study sites. The supplementary datasets were rasterised using the Euclidean distance tool in ArcMap (ESRI 2009). An output cell size of 2.5 m was used to capture relatively small polygons from the input features. All datasets were re-projected to transverse Mercator (WGS_1984_UTM_35S). For each Landsat 8 scene, the first eight OLI bands were stacked together with the rasterised supplementary datasets as the input layers for the classification. In order to construct the decision tree, additional spectral and vegetation indices were prepared from the stacked Landsat dataset in eCognition (Definiens 2003). These included the NDVI, EVI, NDWI, SAVI and Brightness as described in the next paragraph.

NDVI was calculated to reflect strongly on vegetation cover and was used to separate indigenous forest from grasslands.

$$NDVI = (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red}) \quad \text{Equation 1}$$

To address the limitations of NDVI (Wang et al. 2002), EVI was calculated because it shows greater sensitivity to vegetation change and reduces atmospheric effects on vegetation index values using NIR, red and blue bands with the addition of a gain factor (G), aerosol resistance coefficients (C1 and C2) and soil-adjustment factor (L) (Jiang et al. 2008).

$$EVI = G * (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + C_1 * \rho_{Red} - C_2 * \rho_{Blue} + L) \quad \text{Equation 2}$$

Where: $G = 2.5$,
$C_1 = 6$,
$C_2 = 7.5$,
$L = 1$

NDWI was used to improve delineation of wetlands as a result of its sensitivity to changes in liquid water content of vegetation canopies.

$$NDWI = (\rho_{Green} - \rho_{NIR})/(\rho_{Green} + \rho_{NIR}) \qquad \text{Equation 3}$$

Since NDVI and NDWI do not completely remove the background soil reflectance effects, SAVI was computed. For areas with low vegetation cover (<40%) and exposed soil surface where the light reflectance of red and NIR spectra influences vegetation index values, SAVI was used as a corrective index on soil brightness. Similar to NDVI, SAVI was structured with the addition of a 'soil brightness correction factor' (Haboudane et al. 2004). The soil brightness correction factor L of 0.5 was used.

$$SAVI = (\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + \rho_{Red} + L) * (1 + L) \qquad \text{Equation 4}$$

The brightness algorithm was calculated to represent the reflectance intensity of bare rocks and soils among other features sharing similar spectral radiance.

$$Brightness = (\rho_{Blue} + \rho_{Green})/2 \qquad \text{Equation 5}$$

Image pixels with relative homogeneity were clustered using multi-resolution segmentation (MRS) algorithm in eCognition (Xiaoxiao et al. 2014; Definiens 2003). MRS is an ascending area-merging technique where smaller objects are progressively merged into larger objects controlling the advancement in heterogeneity with three input parameters – scale, shape and compactness (Laliberte, Fredrickson & Rango 2007). Shape and compactness were weighted at 0.1 and 0.5, respectively. Scale, a unit-less parameter that regulates the size and homogeneity of image objects, referred to as a 'window of perception' by Marceau (1999), was weighted at two due to land cover heterogeneity in the QCs (Muller 2015 Pers com). Image layer weights in the segmentation settings were weighted at one except NIR and red band layers that were weighted at two to increase their response signal to vegetation greenness. After segmentation, image classification was done using rule-based expert system.

Using training data derived from aerial photographs based on the eight class land cover classification system (LCCS) described in Table 5.2 (Palmer et al. 2015a; Lück & Diemer 2008), (using classification and regression trees (CART) software (Salford System 2014)), a preliminary DT (or classification tree (CT)) was generated. Refer to the literature on DT and expert systems in subsection 3.2.1 for more details. This data mining tool was used on multiple explanatory variables (such as the spectral band, vegetation indices, DEM derived data and rasterised vector data) to predict a single response variable. The multiple variables determine the appropriate characteristics for a cover-class by recursively splitting the predictor data into increasingly more homogenous groups with the result of producing a hierarchical tree composed of rules. The rules developed by CART were used to inform the final set of rules for the actual land cover mapping (Laliberte, Fredrickson & Rango 2007; Yu et al. 2006).

A unique rule-set CT was developed for each of the two Landsat scenes. The algorithms and threshold conditions used for each classification are shown in Figure 5.3 and Figure 5.4, which were used for QCs S50E, T12A and QC T35B, respectively. At each node, in Figure 5.3 and Figure 5.4, variables and their threshold values and conditions are represented in a hexagonal box. Terminal nodes representing the classified classes are highlighted in bold. The CT developed for each of the two Landsat scenes showed slight variations in algorithms and threshold conditions, which could be attributed to the different land tenure systems recognised in the three study sites as well as the general climatic conditions.

Since no clear definition exists of what exactly defines a wetland (Ollis et al. 2013; SANBI 2009), classification of wetlands based on spectral characteristics only can be problematic. The definition for wetland adopted in the current study was "limited to natural or artificial areas in terrestrial and aquatic systems where the water level is permanently or temporary at (or very near) the land surface" (Van den Berg et al. 2008).

Shadows were initially classified using the rasterised DEM-derived slope. These shadows were then reclassified using the 'relative border' algorithm in eCognition to assign the representative classes of the surrounding vegetative cover e.g. for *grassland* and *forest indigenous*[1]. This approach was supported by visual assessment of aerial photographs. Shadows bordering other land cover classes such as *forest plantation*, *plantation clear-felled* and *young pines* were also re-classified to their neighbouring classes, while small areas within class *bare rock and soil* as well as *waterbodies* and *forest indigenous* were reclassified to the class that they were completely surrounded them. Even though *plantation clear-felled* and *young pines* were classified as separate

[1] Italicised keywords represent the point-emphases in the sections (or subsections) and provide better dimensions of the discussions.

classes on the Landsat scene for T35B, these were merged into the class *forest plantation* to control the uniformity of the output datasets.

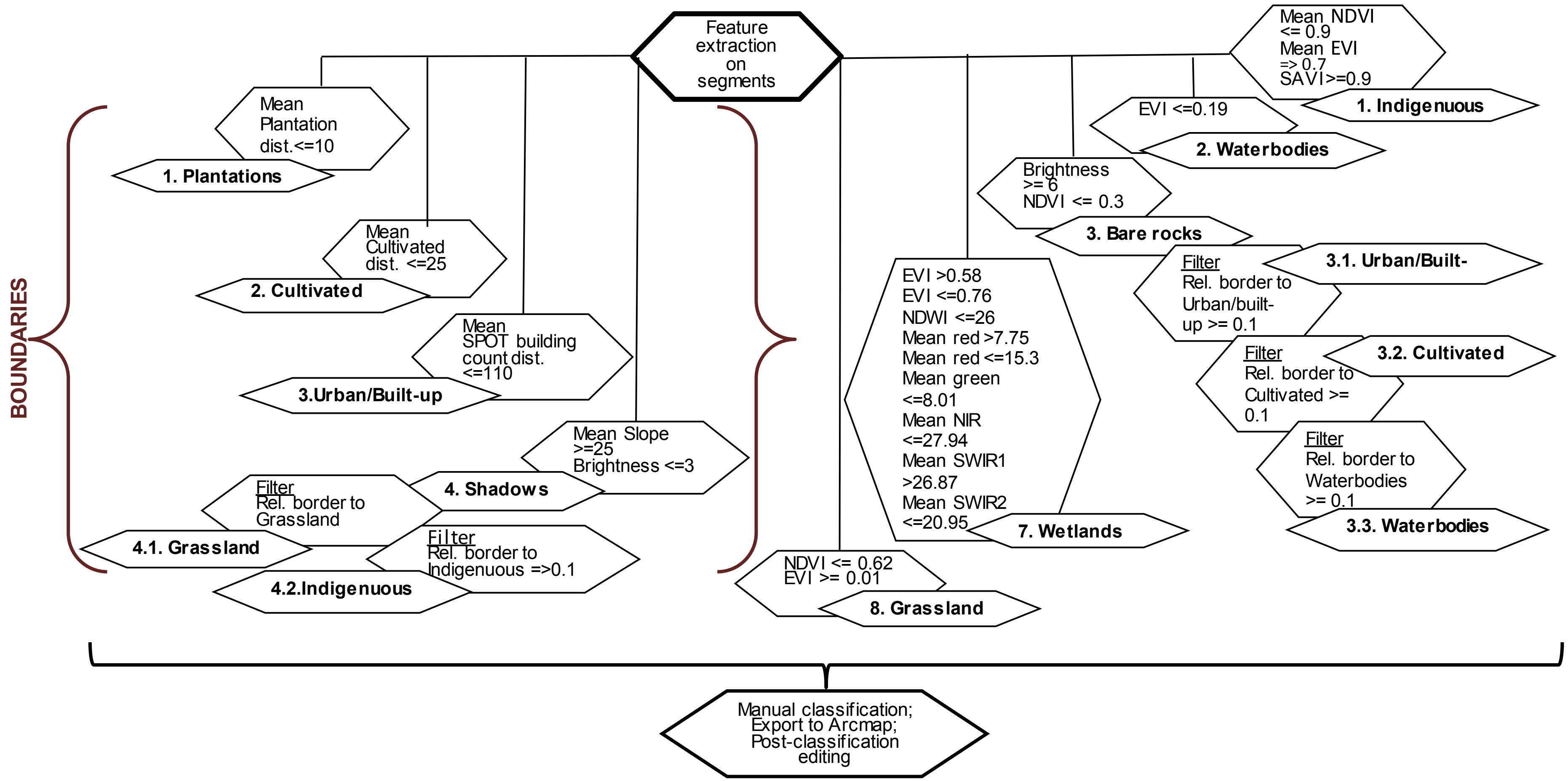


Figure 5.3 Rule-based classification tree for segmentation level of the Landsat scene covering S50E and T12A.
Note: At each node, variables and their threshold values and conditions are represented in a hexagonal box. Merge in this context means 'merge region'. Terminal nodes representing the classified classes are highlighted in bold. Post-classification using manual classification tool for editing and refining of the classes. The figure or number attached to each class represents the sequential steps followed during the land cover classification.

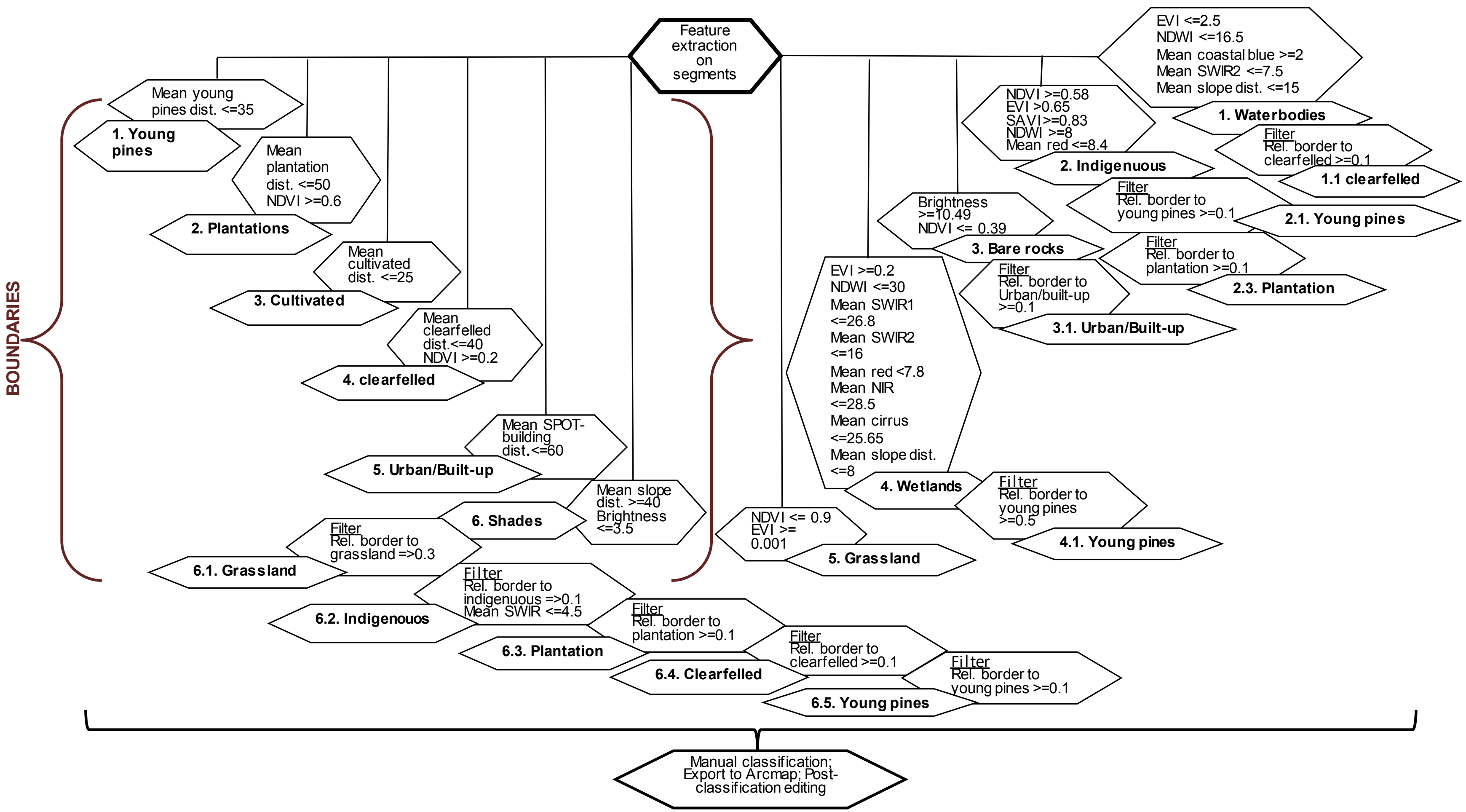


Figure 5.4 Rule-based classification tree for segmentation level of the Landsat scene covering T35B.
Note: At each node, variables and their threshold values and conditions are represented in a hexagonal box. Merge in this context means 'merge region'. Terminal nodes representing the classified classes are highlighted in bold. Post-classification used manual classification tool for editing and refining of the classes. The figure or number attached to each class represents the sequential steps followed during the land cover classification.

A number of discrepancies consistently occurred during the classification. Roads were classified but constituted no particular land cover. Some *shadows* were not identified by the rasterised slope parameters and were incorrectly classified as *vegetation*. *Urban* areas were confused with *bare rock and soil,* including those that were identified by the SBC boundaries, owing to the spectral similarity of these classes. Therefore, the derived land cover maps were manually edited to minimise discrepancies and classification errors. Roads and rivers were fused into the adjoining land cover class as they were unable to be delineated homogeneously.

These changes were methodically applied to all the generated land cover maps and further compared with one another to affirm uniformity in classification. Following manual classification, derived land cover (DLC) maps were created and exported to ArcMap (ESRI 2009) for further post-classification editing, accuracy assessment and change detection analysis.

Other post-classification editing performed included the conversion of raster DLC maps to vector shape files, merging and correlating legend between the reference state (NLC/ENLC 2000 maps) and DLC 2014 maps.

An attempt was made to delineate the extent of IAPs and model alien impact in order to measure rehabilitation progress. No class was specifically assigned to alien plants in NLC 2000. From visual inspection during data processing, the IAPs were found to share physiological and phenological properties with *forest indigenous* and *thicket* that were all classified together. Classifying IAPs using coarse pixel-size Landsat 8 was impossible due to similar spectral characteristics with other vegetation types. As a result, other methods were investigated to delineate IAPs after classification.

Ortho-rectified 2014 Landsat scenes obtained for four months (January, March, September and December) in addition to the June scene that was used for the land cover classification, were used for NDVI and WDRVI calculation in ArcMap (ESRI 2009). The *FITBs* class from DLC land cover classification was used as base dataset. Vegetation type data from Mucina & Rutherford (2006) were used to extract class *forest*. This represents the theoretical extent of indigenous forests. Clearing data obtained from WfW in East London were used to mask out regions in T12A and T35B. *Thicket* was identified as the residual after *IAPs* and *forest* had been extracted.

While NDVI is known to respond to the biophysical characteristics of vegetation, WDRVI enables a more robust characterisation of vegetation phenology and physiology (Gitelson 2004). These two indices were calculated for the Landsat scenes and the values were extrapolated on the *forest indigenous, alien plants* and *thicket* using zonal statistics in ArcMap (ESRI 2009). Different response signals were produced for the three categories as shown Figure 5.5.

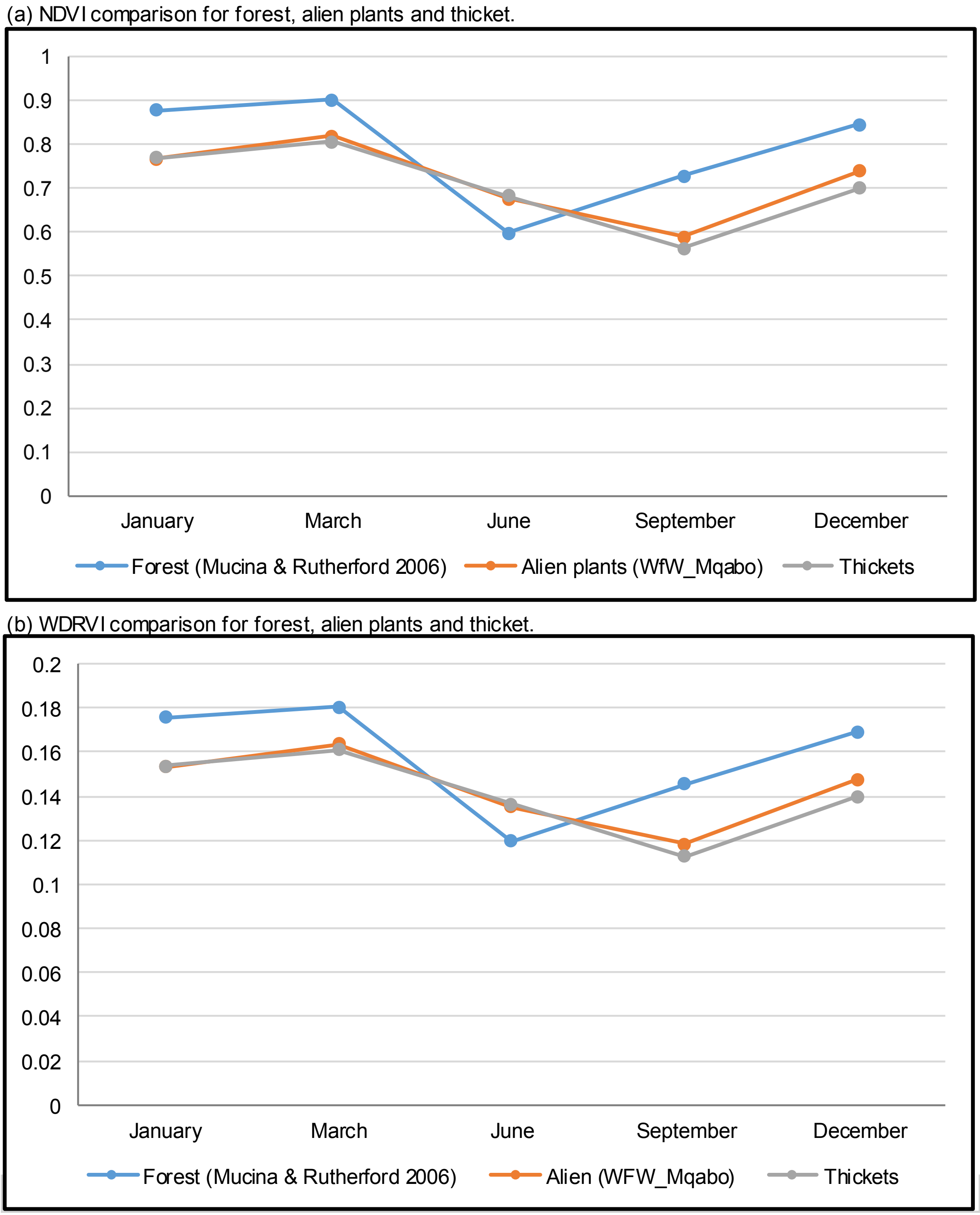


Figure 5.5 (a) NDVI and (b) WDRVI variability of alien plants, forest and thickets for evaluating their separability.

Both indices seem to share similar response in modelling the three specified categories. There were generally high NDVI and WDVRI variations for *forest* (Mucina & Rurherford 2006) in all the months except June (Figure 5.5). Uneven variations in all the months among *Alien plants* and *thicket* could be attributed to seasonal fluctuations in the QCs. No distinct trend was seen for each of the categories. This might be as a result of their similarities in spectral and textural properties that translated into the NDVI/WDRVI quantification. However, delineating these categories was impossible since no separability was established between the NDVI/WDRVI trends across the five sampled months. Therefore, delineating *alien plants* using Landsat satellite imagery might be impractical but could be achieved using hyperspectral imagery. *Alien plants*, *thicket* and *forest indigenous* are still grouped and maintained as one class termed *FITBs*.

A minimum number of 100 reference samples per class are recommended for mapped areas of about 4000 km^2 (Stuckenberg 2012). Training and accuracy sample points for classes were developed using aerial photographs. Random points were selected per land cover class using ArcMap (ESRI 2009) and through visual inspection of aerial photographs, and then a class was assigned to each point. Additional points were generated for land cover classes such as *grassland* that covered larger areas. Field data (in-situ) collected during field visits were also included in the training data.

Some points (40% of the collected samples) were used to build the decision tree for use during classification, while the rest were used for the accuracy evaluation. The ENLC 2000 class values were assigned using a spatial join, while the DLC class values were extracted from the classified raster in ArcMap by using ‘extract values to point’ tool. The attribute tables were exported to Excel (Microsoft 2013), followed by an analysis of the accuracy assessment (error or confusion matrix) using a pivot table (cross tabulation). Other measured parameters for different degrees of accuracy estimations included error of omission, error of commission, producer’s accuracy, consumer’s or user’s accuracy and Kappa coefficient.

The DLC 2014 image was thematically compared to the new national land cover dataset (Geoterraimage 2014) obtained from Department of Environmental Affairs (DEA)[1], using overlay analysis (Okoye & Münch 2015). The reported overall map accuracy for the 2013-14 South African National Land cover dataset (referred to as 2013-14 SANLC further in text), which was

[1] This report was developed using Department of Environmental Affairs Geographic Information System digital data, but this secondary product has not been verified by DEA.

modelled from multi-seasonal Landsat 8 imagery, was 81.73%, with a Kappa value of 0.8 (Geoterraimage 2014). In order to compare the new dataset with a LCCS of 72 classes (of which 33 land cover/-use classes were verified) with the eight class system used for DLC 2014, classes were standardized to comparable classes (Schoeman et al. 2013). Table 5.3 describes the assignment of DLC 2014 classes for the selection of 2013-14 SANLC land cover classes that appear in the study area.

Table 5.3 Comparative land cover classification systems (LCCS).

DLC 2014 class	**NLC 2000 class**	**DEA SA Lcov 2013-2014 GTI classes**
Grassland (UG)	Degraded Unimproved (natural) Grassland Unimproved (natural) Grassland Shrubland and Low Fynbos	Grassland Low shrubland
Forest indigenous (FITBs)	Forest (indigenous) Thicket, Bushland, Bush Clumps, High Fynbos	Indigenous Forest Thicket /Dense bush Woodland/Open bush
Bare Rock and Soil (BRS)	Bare Rock and Soil (natural) Mines and Quarries (surface-based mining)	Erosion (donga) Mines 1 bare / 2 semi-bare Bare none vegetated
Cultivated (CLs)	Cultivated, permanent, commercial, irrigated Cultivated, temporary, commercial, dryland Cultivated, temporary, subsistence, dryland	Cultivated comm fields (high)/(med)/(low) Cultivated comm pivots (high)/(med) Cultivated subsistence (high)/(med)/(low)
Forest Plantations (FPs)	Forest Plantations (clearfelled) Forest Plantations (Other / mixed spp) Forest Plantations (Pine spp)	Plantation / Woodlots clearfelled Plantation / Woodlots young Plantations / Woodlots mature
Urban/Built-up (UrBu)	Urban/Built-up (residential, formal township)	Urban village (bare)/(dense trees / bush)/ (low veg / grass)/(open trees / bush)
Waterbodies (Wb)	Waterbodies	Water permanent / seasonal
Wetlands (Wl)	Wetlands	Wetlands

The 'Intersect' tool in ArcMap (ESRI 2009) was used to combine the two pairs of land cover datasets based on geometry. The new dataset now features polygons with a land cover class for both time periods. After calculating the areas of each of the cover class, the attribute table was exported to Excel (Microsoft 2013). The calculated areas were used to determine change using pivot tables for cross-tabulation analysis. The statistics on gains and losses of the land cover and percentage area-change were computed.

According to Benini et al. (2010), an indicator-based approach to land cover change, can simplify the evaluation of land use change and related environmental impacts. Land cover/use conversions, defined and classified by the changes in land use class that have occurred in a given area, can be used to identify trends. Adapted from Benini et al. (2010) and Vos (2014), a conceptual schema of using such land cover/-use conversion labels in analysing change was developed to describe patterns and trajectories both qualitatively and quantitatively. The land use conversion label was assigned to each intersection created by the overlay of the successive land use maps (NLC/ENLC 2000 and DLC 2014), allowing a thematic representation of the spatial distribution of changes (Benini et al. 2010) which can be represented on a map. These labels are presented in Table 5.4 and they symbolise the intensification, sustainability and productivity dynamics of a class. When no land cover change has occurred, it is labelled as *Persistence*. Of particular importance in the study areas, are areas where forests (indigenous or alien) have persisted (*FITBs persistence*), disappeared or been removed (*Reclamation*) or another land cover has been replaced by IAPs (*FITBs Intensification*). Due to the resolution of the satellite imagery, it is not possible to determine change in the intensity of agricultural activities, but conversion to agricultural practices can be identified (*Agrarian intensification* and *Afforestation*).

For each NLC/ENLC 2000 - DLC 2014 land cover combination, a land use conversion label was assigned using a model for land cover change adapted from Benini et al. (2010) and Vos (2014). The model, illustrated in Figure 5.6, depicts the change trajectories between the classified classes in the study area. The diagonal cells represent *persistence* (no change in LULC) of a cover class or land use. Conversion of a class such as *Urban/Built-up* could be labelled *Abandonment* when urban areas are converted to *grassland*, *shrubland* or *bare* soil but as *Exceptionality* when an improbable conversion occurs such as to *wetlands*. The simplified change matrix provides a less complex interpretation of the land cover dynamics in the study area between 2000 and 2014. The area for each land use conversion label was calculated and expressed as a percentage of the total area for each of the QCs.

<table>
<tr><th colspan="3"></th><th colspan="8">2014</th></tr>
<tr><th></th><th colspan="2">LULC class</th><th>UG</th><th>FITs</th><th>BRS</th><th>Wb</th><th>Wl</th><th>CLs</th><th>FPs</th><th>UrBu</th></tr>
<tr><th></th><th colspan="10">Natural (vegetation) cover</th></tr>
<tr><th rowspan="10">2000</th><td>Unimproved (Degraded / Natural) Grassland</td><td>UG</td><td>P</td><td>I</td><td>De</td><td></td><td rowspan="4">Dn</td><td rowspan="5">Ia</td><td rowspan="5">R</td><td rowspan="3">Iu</td></tr>
<tr><td>Forest Indigenous, Thicket Bushlands, Bush Clumps, High Fynbos</td><td>FITs</td><td>Re</td><td>PI</td><td>Re</td><td rowspan="2">E</td></tr>
<tr><td>Bare Rock and Soil (natural)</td><td>BRS</td><td rowspan="3">Dn</td><td rowspan="3">I</td><td>P</td></tr>
<tr><td>Waterbodies</td><td>Wb</td><td rowspan="2">Dn</td><td>P</td><td>E</td></tr>
<tr><td>Wetlands</td><td>Wl</td><td></td><td>P</td><td>Iu</td></tr>
<tr><th colspan="10">Land use</th></tr>
<tr><td>Cultivated, Permanent / Temporary, Commercial / Subsistence, Irrigated / Dryland</td><td>CLs</td><td>A</td><td rowspan="3">I</td><td>A</td><td colspan="2" rowspan="3">E</td><td>P</td><td>R</td><td rowspan="2">Iu</td></tr>
<tr><td>Forest Plantations (clear-felled, Pine spp, Other / mixed spp)</td><td>FPs</td><td>D</td><td>D</td><td rowspan="2">Ia</td><td>P</td></tr>
<tr><td>Urban / Built-up (residential, formal township)</td><td>UrBu</td><td>A</td><td>A</td><td>R</td><td>Pu</td></tr>
</table>

Adapted from: Benini et al. (2010) and Vos (2014).

Figure 5.6 LULC classes in the study area with land use conversion labels representing conversion trajectory from 2000 to 2014.

Table 5.4 Labels and descriptions for conversion patterns and trajectories.

Conversion class	**Description**
PF – FITBs persistence	Areas where infestations persist
IF – FITBs intensification	Areas where infestations substitute previous land use
Re - Reclamation	Infested areas converted to grassland and bare area
Pu – Urban persistence	Areas where settlements persist over time
Iu – Urban intensification	Areas converted to urban
P – Persistence	Areas with no change in land use
Ia – Agrarian intensification	Areas where agricultural activities substitute previous land use
R – Afforestation	Areas where other land uses are converted into plantation
D – Deforestation	Plantation converted to other land uses
De – Degradation	Shrub areas converted to grassland or bare areas
Dn – Natural dynamic	Areas where natural changes occurred
A – Abandonment	Urban and agricultural areas converted to grassland and bare areas
E – Exceptionality	Unusual conversion - Not expected / possible misclassification / active intervention

Adapted from: Benini et al. (2010).

5.4 LAND COVER CLASSIFICATION AND CHANGE DETECTION RESULTS

The accuracy assessment based on the confusion matrix for each QC is presented in Table 5.5 for S50E, T12A and T35B. The number of reference points used for the assessment is given in column *Count*. The abbreviations and the descriptions used for the classes can be found in Figure 5.6.

Table 5.5 Summarized accuracy assessment for QCs T35B, T12A and S50E.

T35B DLC (2014)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	5.9	51.0	31.6	33.9	65.4	3.8	7.0	33.3	
	% Error of Commission	18.7	14.8	18.8	17.0	38.8	10.1	7.0	25.0	
	Producer Accuracy	94.1	49.0	68.4	66.1	34.6	96.2	93.0	66.7	
	User Accuracy	81.3	85.2	81.3	83.0	61.2	89.9	93.0	75.0	
	Overall Accuracy	83.2			Kappa		0.822			2129
T12A DLC (2014)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	13.0	21.2	0.0	18.2	3.6	7.7	0.0	18.0	
	% Error of Commission	12.1	6.8	20.0	30.8	13.1	30.7	0.0	16.4	
	Producer Accuracy	87.1	78.8	33.3	81.8	96.4	92.3	100.0	82.0	
	User Accuracy	87.9	93.3	80.0	69.2	86.9	69.3	100.0	83.6	
	Overall Accuracy	85.3			Kappa		0.784			1503
S50E DLC (2014)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	4.8	13.6	0.00	11.4	94.9	4.6	9.7	12.2	
	% Error of Commission	18.2	6.7	36.4	0.0	37.5	6.0	1.7	6.7	
	Producer Accuracy	95.2	86.4	100.0	88.7	5.1	95.5	90.3	87.8	
	User Accuracy	81.8	93.3	63.6	100.0	62.5	94.0	98.3	93.3	
	Overall Accuracy	89.88			Kappa		0.867			4399

The overall accuracy for the three QCs based on reference point data ranged between 83% (T35B) and 89% (S50E). Based on the user's accuracy, *wetland* in S50E (62.5%) and T35B (61.2%) were poorly predicted, while *cultivated land* was underestimated in QC T12A with a user's accuracy of 69.3%. In all three QCs, the Kappa is greater than 0.7 (0.867, 0.784 and 0.822 for S50E, T12A and T35B, respectively) which shows a strong agreement between the classified image and the reference data (Montserud & Leamans 1992).

In comparison to the 2013-14 South African National Land-cover (SANLC) dataset, a commercial product produced by GEOTERRAIMAGE, the overall thematic agreement with DLC 2014 was 81.5% with a Kappa value of 0.62. T35B compared best with an agreement of 85.8% (Kappa 0.58), while both T12A and S50E presented with an agreement of 79% and Kappa of 0.55 and 0.65, respectively. Greatest confusion could be attributed to the "tree" classes of *forest indigenous* and *forest plantation* as is suggested by the low producer's accuracy of only 60% and 57%. *Wetlands* and *bare soil and rock* were also poorly predicted by comparison. The combined confusion matrix for all three catchments is shown in Table 5.6.

Table 5.6 Confusion matrix for thematic accuracy between DLC 2014 and 2013-14 SANLC.

		DLC (2014)								
Land cover labels		**UG**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Area(ha)**
2013-14 SANLC	UG	70025	3419	201	57	350	3776	718	3026	81573
	FITBs	2585	4584	5	29	10	62	283	90	7649
	BRS	168	38	3	14	0	5	6	2	236
	Wb	35	2		1187	5	19	2	0	1251
	Wl	1162	108	3	31	143	206	16	27	1696
	CLs	1306	75	6	1	16	8806	1	318	10529
	FPs	597	1655	0	1	25	21	3141	30	5470
	UrBu	32	17	1		0	182	3	3533	3768
	Area (ha)	75910	9899	221	1319	550	13077	4171	7026	112172
Accuracy	% Error of Omission	14	40	99	5	92	16	43	6	
	% Error of Commission	8	54	98	10	74	33	25	50	
	Producer Accuracy	86	60	1	95	8	84	57	94	
	User Accuracy	92	46	2	90	26	67	75	50	
	Overall Accuracy	81.5			Kappa		0.62			

The overall accuracy for the DLC 2014 land cover dataset was deemed acceptable based on the emerging value of greater than 80% as compared to reference points (Table 5.5) as well as to other existing data (Table 5.6). In order to provide a better distinction between different wooded classes, higher spatial resolution data needs to be investigated.

The overall accuracy of the NLC 2000 was only 65.8% with a Kappa index of 0.57 (Van den Berg et al. 2008). As a result, NLC 2000 was edited by visual inspection using 2000 aerial photographs, and editing of misclassified polygons to increase the accuracy ratio of land transformations. The overall accuracy based on reference point data extracted from 2000 aerial photographs for the three QCs are greater than 80%, with the Kappa index agreement at the range of 0.75 to 0.80 (Table 5.7).

Table 5.7 Summarized accuracy assessment of the ENLC 2000 for QCs T35B, T12A and S50E.

T35B ENLC (2000)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	7.7	39.3	0.0	11.8	26.0	19.7	17.6	0.0	
	% Error of Commission	19.7	21.8	0.0	6.3	42.1	14.1	3.3	5.6	
	Producer Accuracy	92.3	60.7	0.0	88.2	74.0	80.3	82.4	100.0	
	User Accuracy	80.3	78.2	0.0	93.8	57.9	85.9	96.7	94.4	
	Overall Accuracy			82.4	Kappa				0.753	2975
T12A ENLC (2000)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	6.5	20.7	0.0	40.0	66.7	16.5	3.4	17.3	
	% Error of Commission	13.2	3.4	0.0	25.0	87.5	12.3	24.3	21.2	
	Producer Accuracy	93.5	79.3	100.0	60.0	33.3	83.5	96.6	82.7	
	User Accuracy	86.8	96.6	0.0	75.0	12.5	87.7	75.7	78.8	
	Overall Accuracy			87.14	Kappa				0.807	2450
S50E ENLC (2000)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	8.4	31.3	0.0	3.8	55.4	14.2	4.4	9.8	
	% Error of Commission	18.2	10.5	100.0	1.4	28.3	6.8	17.1	22.7	
	Producer Accuracy	91.6	68.7	0.0	96.2	44.6	85.8	95.6	90.2	
	User Accuracy	81.8	89.5	0.0	44.6	71.7	93.2	82.9	77.3	
	Overall Accuracy			86.38	Kappa				0.830	4723
ALL-QCs ENLC (2000)										
Land cover labels		UG	FITBs	BRS	Wb	Wl	CLs	FPs	UrBu	Count
Accuracy	% Error of Omission	7.6	28.8	0.0	4.5	35.6	16.1	10.1	12.8	
	% Error of Commission	17.2	9.8	0.0	1.8	42.4	9.8	12.6	21.6	
	Producer Accuracy	92.4	71.2	100.0	95.5	64.4	83.9	89.9	87.2	
	User Accuracy	82.8	90.2	0.0	98.2	57.6	90.2	87.4	78.4	
	Overall Accuracy			85.39	Kappa				0.808	10148

Bare rock and soil (natural) were poorly classified at the three QCs as shown by the user's accuracy prediction, with *wetlands* in T35B (57.9%) and T12A (12.5%) also being poorly mapped. Based on the user's accuracy, *Waterbodies* were not correctly mapped in S50E. The overall accuracy of ENLC 2000 (All-QCs) with increasing data reliability is greater than 85% (Table 5.7) when compared to NLC 2000 with overall accuracy of 65.8% (Van den Berg et al. 2008).

To assess the land cover change dynamics in the study area, a comparison is made between the derived dataset (DLC 2014) and the reference, NLC/ENLC 2000. The land cover maps at the two time steps are shown in Figure 5.7 to Figure 5.9. (Note that full page maps are presented in Appendices). While a comparison is made between the two time steps, it must be recognised that the final map accuracy for the base dataset NLC 2000 was only 65.8% with a Kappa index of 0.57 (Van den Berg et al. 2008) and the edited version was at 85.39% with a Kappa index of 0.80. The two data scopes were adopted to investigate two-dimensional change concept, with the intent of assessing the integrity and uncertainty of the two datasets. Many of the observed changes may in actual fact be uncharacteristic of actual land cover dynamics, especially the NLC 2000.

Slightly different datasets were used for editing of ENLC 2000 and this resulted in having some negligible variances in area-sizes for each QC between NLC and ENLC 2000. The area and class-cover percentage at the two-time periods 2000 and 2014 for NLC and ENLC 2000 is presented in Figure 5.8.

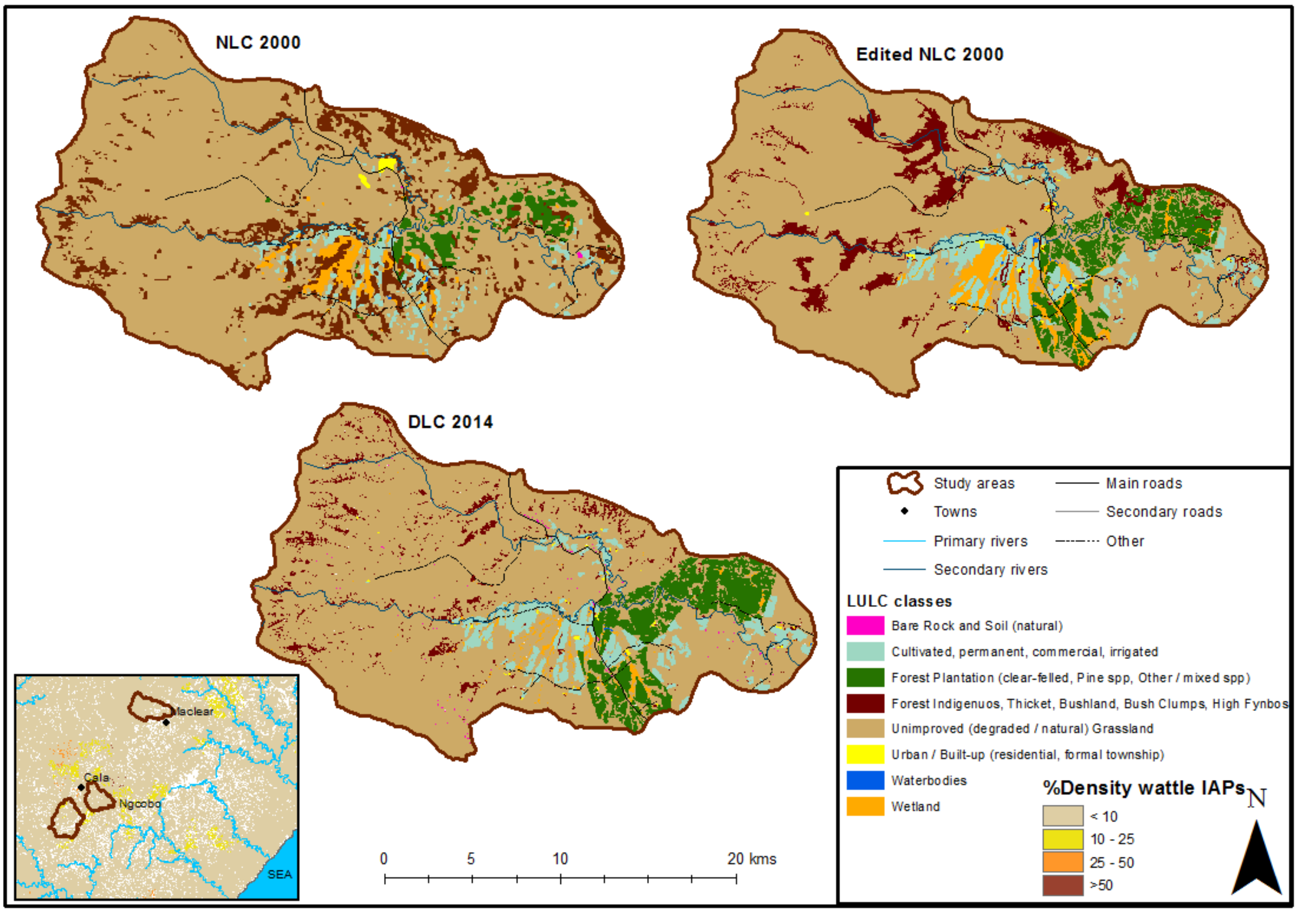


Figure 5.7 Land cover maps of the reference state (NLC/ENLC 2000) and derived land cover maps (DLC 2014) for T35B.

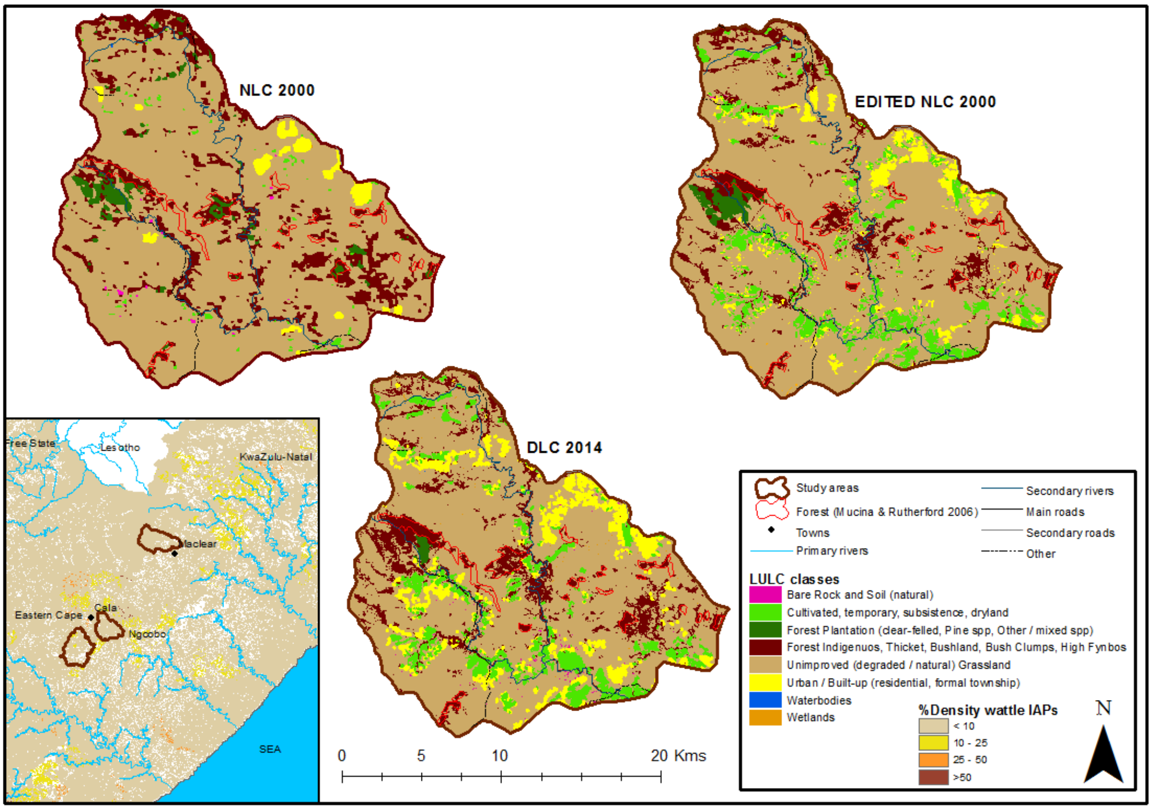


Figure 5.8 Land cover maps of the reference state (NLC/ENLC 2000) and derived land cover maps (DLC 2014) for T12A.

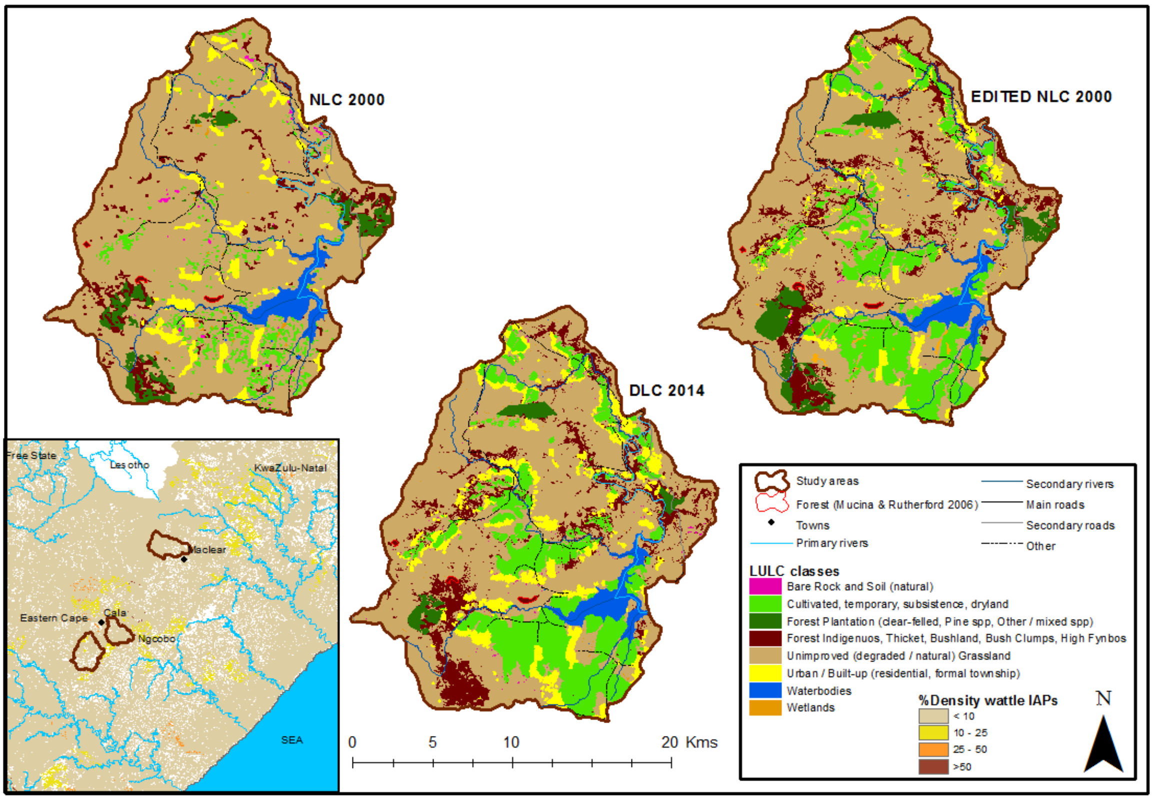


Figure 5.9 Land cover maps of the reference state (NLC/ENLC 2000) and derived land cover maps (DLC 2014) for S50E.

Table 5.8 Comparison of land cover class areas for 2000 and 2014.

NLC 2000												
	QC T35B				**QC T12A**				**QC S50E**			
	2000		**2014**		**2000**		**2014**		**2000**		**2014**	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Natural / Semi-natural (Vegetation) Cover												
UG	31491.7	79.6	31564.3	79.8	**22484.5**	80.7	**18997.5**	68.2	**34360.7**	76.8	**25346**	56.6
FITBs	**4874**	12.3	**1628.1**	4.1	3712.2	13.3	3455.2	12.4	**2390.3**	5.3	**4813.8**	10.8
BRS	**8.6**	0	**76.3**	0.2	37.3	0.1	47.7	0.2	141.7	0.3	95.6	0.2
Wb	13.8	0	17.1	0	1.7	0	0.7	0	1566.8	3.5	1300.8	2.9
Wl	**772.9**	2	**470.4**	1.2	**3.8**	0	**19.2**	0.1	**111.5**	0.2	**59.2**	0.1
Land use												
CLs	**1159**	2.9	**2441.8**	6.2	**226.8**	0.8	**2533.1**	9.1	**2089.5**	4.7	**8101**	18.1
FPs	**1145**	2.9	**3272.1**	8.3	**741.8**	2.7	**94.6**	0.3	**1721.8**	3.8	**804.5**	1.8
UrBu	82.1	0.2	77.3	0.2	**653.9**	2.3	**2714**	9.7	**2373.9**	5.3	**4234.3**	9.5
TOTAL	39547.2	100	39547.2	100	27862.4	100	27862.4	100	44756.2	100	44756.2	100
ENLC 2000												
	QC T35B				**QC T12A**				**QC S50E**			
	2000		**2014**		**2000**		**2014**		**2000**		**2014**	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Natural / Semi-natural (Vegetation) Cover												
UGd/n	**29910.3**	75.6	**31564.3**	79.8	**20947.4**	75.2	**18998.8**	68.2	**27509.6**	61.5	**25347.0**	56.6
FITBs	**3307.6**	8.4	**1628.3**	4.1	2734.2	9.8	3456.1	12.4	4329.7	9.7	4814.9	10.8
BRS	2.5	0.0	76.3	0.2	3.5	0.0	48.1	0.2	13.2	0.0	96.6	0.2
Wb	**33.9**	0.1	**17.1**	0.0	1.4	0.0	0.7	0.0	1368.6	3.1	1300.8	2.9
Wl	**1219.9**	3.1	**470.4**	1.2	14.0	0.1	19.4	0.1	**193.1**	0.4	**59.9**	0.1
Land use												
CLs	2416.6	6.1	2441.8	6.2	2402.3	8.6	2534.0	9.1	7267.8	16.2	8101.0	18.1
FPs	**2565.5**	6.5	**3272.1**	8.3	**397.2**	1.4	**94.6**	0.3	**2027.5**	4.5	**804.5**	1.8
UrBu	91.1	0.2	77.3	0.2	**1365.6**	4.9	**2714.0**	9.7	**2049.7**	4.6	**4234.3**	9.5
TOTAL	39547.5	100.0	39547.5	100.0	27865.7	100.0	27865.7	100.0	44759.0	100.0	44759.0	100.0

Note: Significant change in values (either decrease or increase) is indicated in bold. Refer to Figure 5.6 for the legend to LULC category codes.

In 2000, the dominant land cover was natural grasslands stretching from the mountainous highlands of T35B to the low-lying flat plains of Tsomo in T12A and S50E and has remained so until 2014. In NLC 2000, the 2014 trend in all three catchments was an intensification in agrarian activities, both in *permanent, commercial cultivation* (T35B) as well as *subsistence and dryland farming* (T12A and S50E). This may be an artefact of the low accuracy of NLC 2000 where large expanses of subsistence agriculture were classified as grassland. A significant increase in cultivated land was noted in S50E in NLC 2000. This is predominantly due to land used for subsistence farming not being classified as such in NLC 2000. As evidenced by inspection of aerial photographs, these were allocated to the class *Degraded (unimproved) grassland*. The reverse scenarios were seen in ENLC 2000 where the agrarian activities appeared to remain same over time for the three QCs. An increase in *forest plantations* was observed in T35B with a reduction in *indigenous or alien forests* in both NLC and ENLC 2000. This reduction of eight per cent may be attributed to the work done by WfW in the catchments or maybe as a classification error.

The class *forest indigenous* contains IAPs since it is almost impossible to discriminate indigenous from IAPs at Landsat spatial resolution used for both NLC/ENLC 2000 and DLC 2014. In SA_lcov_2013-14_GTI, there is also no distinction between indigenous and alien trees and bushes (Geoterraimage 2014). The land cover class *FITBs*, which include forest indigenous, alien plants and thickets, have increased on low-lying, rolling flatlands and agrarian regions. Such increase was not found except the decrease of *FITBs* observed in T35B in ENLC 2000.

Urban intensification is mostly visible in T12A where the nature of the land tenure was not identified as such in NLC 2000 but merely manifested as *Degraded (unimproved) grassland*. On the contrary, the intensification rate of *Urban and townships* in T12A in ENLC 2000 was small when compared to the original size. *Wetlands* have been converted into *cultivated lands*, *commercial afforestation* and *grasslands* which and this could have been as a result of agricultural intensification. Moreover, the conversion of *Wetlands* does reflect different frameworks adopted for wetland identification and classification as well as demonstrating a natural dynamic that is dependent on precipitation. However, such conversion was not overly significant in T12A in ENLC 2000.

The NLC 2000 conversion matrix (Table 5.9) indicates the transformation of cover classes, highlighting some of the changes between the periods in the QCs. Some of the changes noted are quite large, where almost an entire class has been replaced by a new class, e.g. *urban/built-up* by *grassland* in T35B. This may be due to the lower accuracy of the reference data set (NLC 2000), differences in classification schemes, classification errors or natural dynamics. The conversion matrix for ENLC 2000 presented in Table 5.10 shows land cover transformation with minimum conversion rate to other land use. Unlike in NLC 2000, the nearly total conversion (98.3% change) of *urban/built-up* to *grassland* in T35B was not seen in ENLC 2000, but only at 69.4% change.

In NLC 2000, T35B *grassland* and *forest plantations* remained constant accounting for less than 10% change, while *forest indigenous, urban/built-up* and *bare rock and soil* were transformed, mostly to *grassland*. In ENLC 2000, T35B *grassland*, *forest plantations* and *cultivated lands* persisted with less than 30% change, while *forest indigenous,* and *bare rock and soil* have been largely transformed, mostly to *grassland* and *forest plantation,* respectively. In T12A and S50E, *wetlands* were either transformed or had previously been misclassified (NLC 2000 - 100% and 96.5%; ENLC 2000 - 90.8% and 97.5% correspondingly) in both base datasets. Natural dynamics may explain this loss. During wet years, wetlands would be more prominent than in drier periods, where agriculture is likely to be practiced in the surroundings of the wetlands. *Forest plantations* lost ground to *forest indigenous* with 74.3% of data classified as such in T12A and only 42.2% in S50E in NLC 2000, but increased with 89.6% classified pixels in T12A and 64.8% in S50E in ENLC 2000. *Forest indigenous* and *forest plantations* were difficult to differentiate from each other and could have been confused in the classification. In all three QCs, *bare rock and soil* presented as either *cultivated land* or *grassland* in 2014 for both base datasets. *Grassland* remained the dominant land cover in all three QCs over the entire study period and still covers approximately 70% of the total area in NLC 2000 but above 80% in ENLC 2000.

Table 5.9 Historical land cover change from 2000 (NLC) to 2014 at the three QCs.

REFERENCE DATA (2000)

DERIVED DATA (2014)										
QC T35B										
Row (%)	**UG**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Area(ha) 2000**	**Total % change**
Natural / Semi-natural (Vegetation) Cover										
UG	87.4	3.0	0.2	0.0	0.3	3.5	5.4	0.1	31491.7	12.6
FITBs	66.7	13.8	0.0	0.0	3.4	9.3	6.3	0.4	4874.0	86.2
BRS	22.7	0.0*	0.3	0.0*	0.0*	76.9	0.0*	0.0*	8.6	99.7
Wb	14.6	0.0*	0.0*	47.1	31.3	3.4	3.6	0.0	13.8	52.9
Wl	57.7	0.1	0.0*	0.7	22.0	15.7	3.7	0.0	772.9	78.0
Land use										
CLs	18.5	0.4	0.1	0.1	1.6	62.0	15.1	2.2	1159.0	38.1
FPs	4.7	1.1	0.2	0.0	0.5	2.2	91.2	0.2	1145.0	8.8
UrBu	89.2	0.6	1.6	0.0*	0.0*	7.0	0.0*	1.7	82.1	98.3
Area(ha) 2014	31564.3	1628.1	76.3	17.1	470.4	2441.8	3272.1	77.3	39547.2	
QC T12A										
Row (%)	**UG**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Area(ha) 2000**	**Total % change**
Natural / Semi-natural (Vegetation) Cover										
UG	75.0	6.4	0.2	0.0	0.1	8.9	0.2	9.2	22484.5	25.0
FITBs	48.5	39.0	0.0*	0.0*	0.0	10.3	0.0	2.1	3712.2	61.0
BRS	19.1	1.7	1.2	0.0*	0.0*	74.3	0.0*	3.7	37.3	98.8
Wb	14.1	0.0*	0.0*	29.4	56.6	0.0*	0.0*	0.0*	1.7	70.6
Wl	53.2	7.6	0.0*	0.0*	0.0	39.2	0.0*	0.0*	3.8	100.0
Land use										
CLs	38.3	4.9	0.5	0.0*	0.0	45.9		10.5	226.8	54.1
FPs	19.1	74.3	0.0*	0.0	0.0	0.2	6.0	0.3	741.8	94.0
UrBu	13.4	0.6	0.5	0.0	0.0	2.8		82.6	653.9	17.4
Area(ha) 2014	18997.5	3455.2	47.7	0.7	19.2	2533.1	94.6	2714.0	27862.4	
QC S50E										
Row (%)	**UG**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Area(ha) 2000**	**Total % change**
Natural / Semi-natural (Vegetation) Cover										
UG	67.2	7.5	0.2	0.0	0.1	16.9	0.5	7.5	34360.7	32.8
FITBs	28.2	57.5	0.1	0.0*	0.1	6.3	6.7	1.2	2390.3	42.5
BRS	25.1	3.9	0.0	0.0*	0.0*	69.7	0.0*	1.3	141.7	100.0
Wb	7.4	1.3	0.0	82.4	0.0*	8.5	0.0*	0.4	1566.8	17.6
Wl	54.2	2.3	0.4	0.0	3.5	36.1	2.5	1.1	111.5	96.5
Land use										
CLs	20.7	2.0	0.1	0.0	0.6	72.8	0.0	3.8	2089.5	27.2
FPs	29.4	42.2	0.7	0.0	0.1	0.1	27.1	0.4	1721.8	72.9
UrBu	17.6	2.3	0.4	0.0	0.0	14.8	0.0	64.9	2373.9	35.1
Area(ha) 2014	25346.8	4813.8	95.6	1300.8	59.2	8101.0	804.5	4234.3	44756.2	

Table 5.10 Historical land cover change from 2000 (ENLC) to 2014 at the three QCs.

REFERENCE DATA (EDITED 2000)

DERIVED DATA 2014											
QC T35B											
Row (%)	**UGd/n**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Total %**	**Total: 2000 (ha)**	**Total % change**
Natural (Vegetation) Cover											
UGd/n	92.0	3.0	0.2	0.0*	0.5	1.4	2.8	0.1	100.0	29910.3	8.0
FITBs	72.3	20.8	0.1	0.0*	0.6	2.9	2.8	0.5	100.0	3307.6	79.2
BRS	22.8	0.0	0.0*	0.0	0.0	8.8	65.5	2.9	100.0	2.5	100.0
Wb	44.5	0.4	0.3	18.3	21.8	9.3	5.2	0.1	100.0	33.9	81.7
Wl	61.8	0.5	0.3	0.5	14.9	10.6	11.3	0.1	100.0	1219.9	85.1
Land use											
CLs	20.6	0.9	0.1	0.1	2.6	73.3	2.2	0.2	100.0	2416.6	26.7
FPs	13.9	0.1	0.2	0.0	1.5	0.4	83.9	0.0*	100.0	2565.5	16.1
UrBu	38.7	4.7	0.0*	0.2	1.5	22.2	2.0	30.6	100.0	91.1	69.4
Total: 2014 (ha)	31564.3	1628.3	76.3	17.1	470.4	2441.8	3272.1	77.3		39547.5	
QC T12A											
Row (%)	**UGd/n**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Total %**	**Total: 2000 (ha)**	**Total % change**
Natural (Vegetation) Cover											
UGd/n	84.2	5.6	0.2	0.0	0.1	3.4	0.2	6.3	100.0	20947.4	15.8
FITBs	23.9	72.6	0.0	0.0	0.1	1.7	0.4	1.4	100.0	2734.2	27.4
BRS	38.3	10.1	6.3	0.0	0.0	0.3	0.0	45.1	100.0	3.5	93.7
Wb	77.3	7.3	0.0	12.2	2.7	0.0	0.0	0.4	100.0	1.4	87.8
Wl	86.5	2.4	0.0	0.2	9.2	1.7	0.0	0.0	100.0	14.0	90.8
Land use											
CLs	18.2	3.1	0.1	0.0	0.0	69.6	0.0	9.0	100.0	2402.3	30.4
FPs	34.2	55.1	0.0	0.0	0.1	0.0	10.4	0.3	100.1	397.2	89.6
UrBu	8.7	0.8	0.1	0.0	0.0	7.4	0.0	83.0	100.0	1365.6	17.0
Total: 2014 (ha)	18998.8	3456.1	48.1	0.7	19.4	2534.0	94.6	2714.0		27865.7	
QC S50E											
Row (%)	**UGd/n**	**FITBs**	**BRS**	**Wb**	**Wl**	**CLs**	**FPs**	**UrBu**	**Total %**	**Total:2000 (ha)**	**Total % change**
Natural (Vegetation) Cover											
UGd/n	82.2	4.2	0.3	0.1	0.2	5.7	0.1	7.3	100.0	27509.6	17.8
FITBs	29.6	63.3	0.1	0.1	0.0*	1.5	1.5	3.9	100.0	4329.7	36.7
BRS	39.0	4.3	4.8	0.0	0.0	0.8	2.6	48.4	100.0	13.2	95.2
Wb	4.1	0.5	0.0	92.4	0.0*	2.9	0.0	0.1	100.0	1368.6	7.6
Wl	52.6	0.8	0.0	0.0	2.5	42.4	0.0	1.7	100.0	193.1	97.5
Land use											
CLs	9.3	2.6	0.1	0.1	0.0*	85.8	0.0*	2.1	100.0	7267.8	14.2
FPs	28.2	35.5	0.7	0.0*	0.1	0.1	35.2	0.3	100.0	2027.5	64.8
UrBu	2.1	0.3	0.1	0.0	0.0	5.2	0.1	92.3	100.0	2049.7	7.7
Total: 2014 (ha)	25347.0	4814.9	96.6	1300.8	59.9	8101.0	804.5	4234.3		44759.0	

Using the conceptual schema of land cover conversion labels (Figure 5.6) in analysing the change matrix statistics (Benini et al. 2010), quantitative analysis was performed on the empirical data of land change between the two-time periods. This provided a suitable framework to evaluate land use dynamics in the QCs (Vos 2014). Land use conversion that occurred in the three QCs from 2000 to 2014 is defined by the class changes described in Table 5.4 and shown in Figure 5.6. The spatial distribution of the land cover/-use conversion using this indicator based approach is mapped for NLC and ENLC 2000 in Figure 5.10 and Figure 5.11, correspondingly. The overview map also indicates the density of the Wattle species of invasive alien plants as mapped by Kotze et al. (2010) as part of the National Invasive Alien Plant Survey (NIAPS).

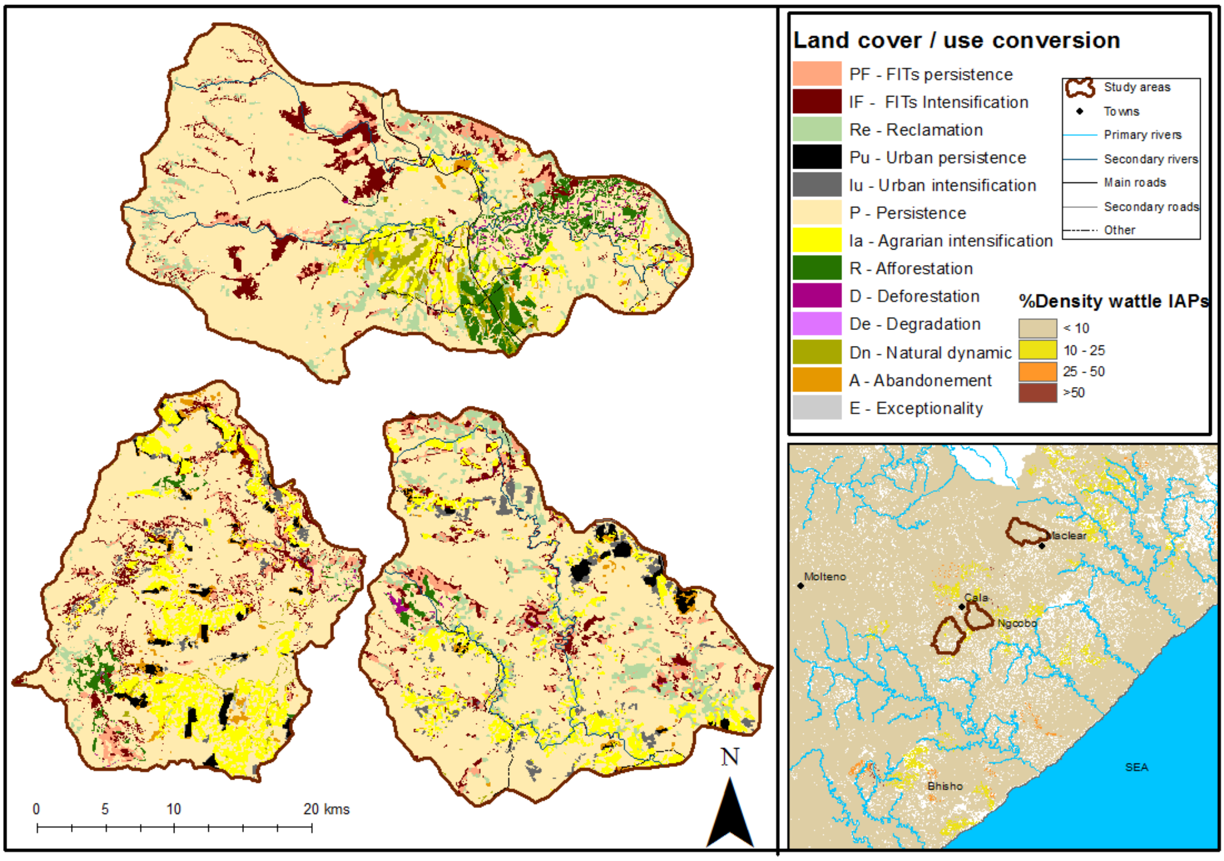


Figure 5.10 Indicator based approach for land cover conversion using NLC 2000.
Note: Full maps presented in the Appendices.

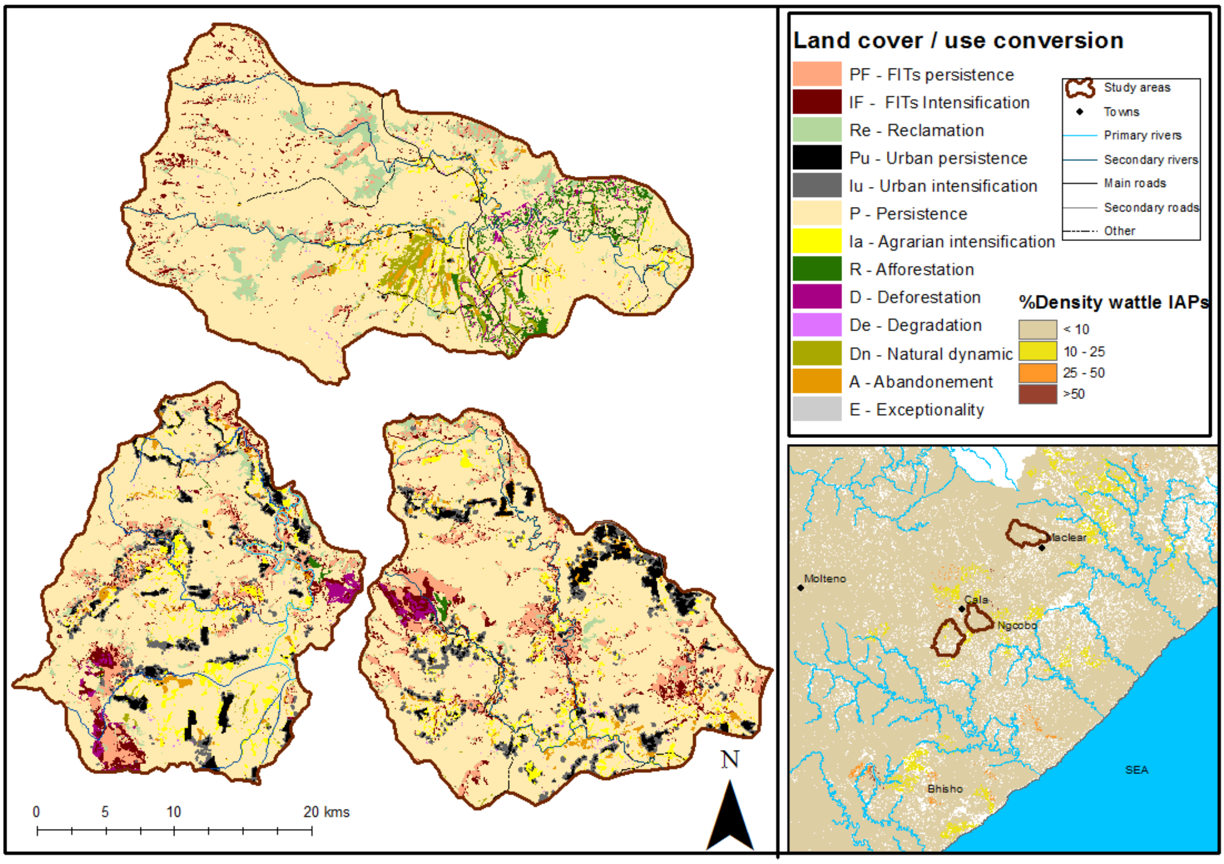


Figure 5.11 Indicator based approach for land cover conversion using ENLC 2000.
Note:Full maps presented in the Appendices.

Land use patterns in all three QCs are characterized by high persistence with more than 60% of the total area indicating no change in land use, with 71.8%, 68.5% and 66.9.0% *Persistence* in NLC 2000 as well as 80%, 69.5% and 68.9% in ENLC 2000 in T35B, T12A and S50E, respectively(Table 5.11). Agricultural activities increased in each QC with S50E showing the highest intensification (13.0%), attributed to conversion from grassland, bare rock and soil and wetlands in NLC 2000 (Table 5.11). A small conversion from urban/built-up was also noted, which could be attributed to incorrect classification of the urban villages with subsistence farming that characterize the land tenure type existing in the catchment. Such conversion into agricultural use with a higher intensity (4.2%) in S50E was however transformed mainly from grassland, wetlands and urban/built-up in ENLC 2000 (Table 5.11). *Abandonment* is defined as alterations from urban and agricultural areas to grassland or bare areas. T12A (NLC 2000) and S50E (ENLC 2000) demonstrated higher percentages (2.4% and 2.0%) in *abandonment,* which might be as a result of the nomadic type of farming practised at the catchments where farmers abandon their dwellings and move on to new locations.

Table 5.11 Land cover/use conversion per QC.

Conversion class	Description	Conversion (2000-2014)			Conversion [(Edited) 2000-2014]		
		% of QC			% of QC		
		T35B	T12A	S50E	T35B	T12A	S50E
PF – FITBs persistence	Areas where infestations persist	2.7	4.5	3.1	1.7	7.1	6.1
IF – FITBs intensification	Areas where infestations substitute previous land use	6.2	4.8	6.1	2.4	5.3	4.6
Re - Reclamation	Infested areas converted to grassland and bare area	6.7	7.3	1.2	6.0	2.3	2.9
Pu – Urban persistence	Areas where settlements persist over time	0.0	1.6	2.7	0.1	4.1	4.2
Iu – Urban intensification	Areas converted to urban	0.2	3.3	2.0	0.1	5.7	5.2
P – Persistence	Areas with no change in land use	71.8	68.5	66.9	80.0	69.5	68.9
Ia – Agrarian intensification	Areas where agricultural activities substitute previous land use	4.4	8.2	13.0	1.7	3.1	4.2
R – Afforestation	Areas where other land uses are converted into plantation	4.2	0.6	1.6	2.8	0.2	0.2
D – Deforestation	Plantation converted to other land uses	0.5	0.3	0.1	0.9	0.5	1.3
De – Degradation	Grassland converted to bare areas	0.0	0.0	0.0	0.2	0.2	0.2
Dn – Natural dynamic	Areas where natural changes occurred	2.3	0.1	0.7	2.4	0.1	0.5
A – Abandonment	Urban and agricultural areas converted to grassland and bare areas	0.6	0.9	2.4	1.4	2.0	1.6
E – Exceptionality	Unusual conversion - Not expected / possible misclassification / active intervention	0.2	0.0	0.1	0.3	0.0	0.0

Forest indigenous, thicket, bushland, bush clumps, high fynbos and alien plants were grouped together into a class, FITBs, as they were unable to be delineated using coarse-pixel imagery. *FITBs persistence* (2.7%) in NLC 2000 is higher than 1.7% persistence rate in T35B in ENLC 2000. This low rate of *FITBs persistence* in T35B (Freehold system) when compared to T12A and S50E (NLC 2000 - 4.5% & 3.1%; ENLC 2000 – 7.1% and 6.1%) (Communal system) could be associated with the type of land tenure system practised in these QCs. Other land use converted to FITBs ranged from 4.8% to 6.2% at the three QCs in NLC but the *FITBs intensifications* were minimal in ENLC 2000 for T35B (2.4%), T12A (5.3%) and S50E (4.6%). Natural reclamation after clearing of infestation were generally less than 10% in NLC/ENLC 2000. Regarding conversion of forest indigenous to grassland, *Reclamation* were higher in T35B than in T12A and S50E in NLC and ENLC 2000. Unfortunately, the classification was unable to distinguish between indigenous and alien trees. Similarly, *Degradation* linked to conversion from grassland to bare soil characterised less than one per cent transformation. Interestingly, T12A and S50E have been the focus targets for Working for Water (WfW) with the aim of eradicating alien trees in these catchments.

The dynamics of land cover conversion classes, *Agrarian intensification* and *Afforestation* can be regarded as an *increase in the productivity* of the landscape which accounts for 11.09% of the QCs in NLC 2000 and 4.15% in ENLC 2000. Land use intensification is therefore associated with a productivity-driven landscape. In contrast, a *decrease in productivity* is signified by classes –

Abandonment, *Deforestation* and *Degradation* which marks 1.74% in NLC 2000 and 2.75% in ENLC 2000. S50E shows the highest increase (14.7%) and decrease (2.6%) in productivity in NLC 2000 as well as highest 4.3% increase and 3.1% decrease in ENLC 2000. Productivity increase of 8.7% in T35B is offset by high decrease of 1.2%, while in T12A the gain is 8.8% and the loss 1.2% in NLC 2000. In ENLC 2000, productivity increase and decrease of 4.2% and 2.4% in T35B is greater than 3.3% increase and less than zero per cent decrease in T12A. *Urban intensification* is highest in S50E and T12A where subsistence farming is practiced at even larger scales.

Other land cover conversion classes, *FITBs persistence* and *intensification,* can be referred to as one degradation gradient existing in the landscape. T50E and T35B showed highest infestation of 9.1% and 9.3% against T12A (8.8%) in NLC 2000. The highest degradation in S50E and T12A (10.7% and 12.4%) compared to T35B (4.11%) in ENLC provides further proof of the different land tenure systems practised at both landscapes. The land tenure system of communal ownership practised in T12A and S50E where livestock owners may exploit rangelands (grassland) could lead to degradation or even aggravated infestation intensity. The context of *reclamation* in this study indicates the extent of anthropogenic rehabilitation, where areas infested with FITBs are replaced with grassland and bare rocks. The highest recovered landscape is found in T35B where six per cent FITBs infested areas are returned to grassland in ENLC 2000. Minimum *reclamation* of less than three per cent was seen in T12A and S50E and these are areas where clearings have been done extensively by WfW.

The question therefore arises on whether these land use conversions could have a detrimental influence on the natural systems of the QCs. This would be addressed using the Driver-Pressure-State-Impact-Response (DPSIR) framework (Alfieri, Hassan & Lange 2004) to contextualize problems and identify connections between parameters that may affect conversion, rehabilitation and sustainability and will be addressed in the final chapter of this thesis. Indicator-based methodologies are but one of the approaches that can be used to evaluate land cover/use changes and related environmental impacts (Petrosillo et al. 2012) since they effectively reduce the volume and complexity of information (Benini et al. 2010) that is required by stakeholders and decision makers (Donnelly et al. 2007).

5.5 EVAPOTRANSPIRATION/NET PRIMARY PRODUCTIVITY RELATIONSHIP WITH CLEARING

The WfW clearing data were used to evaluate rehabilitation progress of the catchments in terms of invaded and cleared areas as well as reclamation strength. The clearing data (EC Engcobo WfW_QC T12A and EC Pott River WfW_QC T35B) acquired from WfW East London office were only available for the two QCs (T35B, T12A). The cleared patches overlaying the land cover/use conversion for T12A are shown in Figure 5.12 (NLC 2000) and Figure 5.13 (ENLC 2000) in sync with the details of clearing history and costs tabulated in Table 5.12.

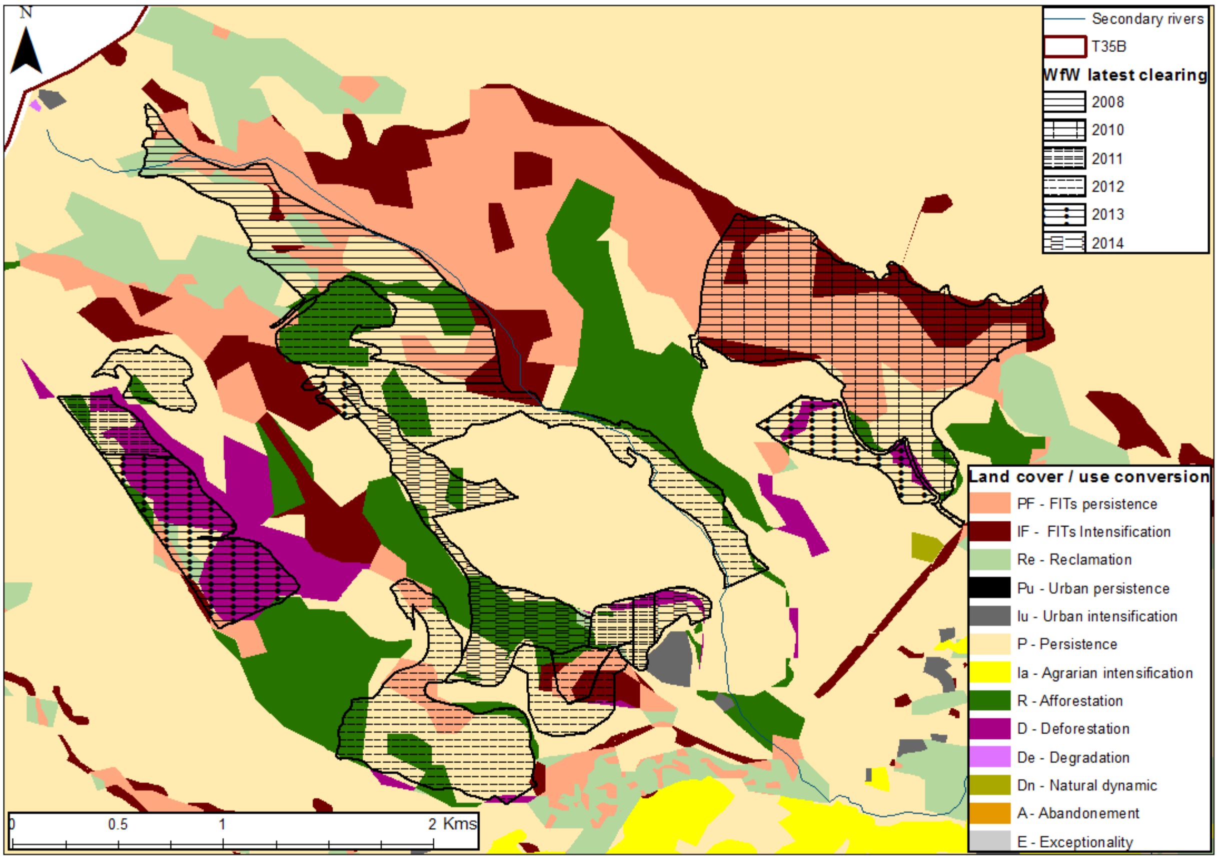


Figure 5.12 WfW clearing in T12A compared to land cover/use conversion (NLC 2000).

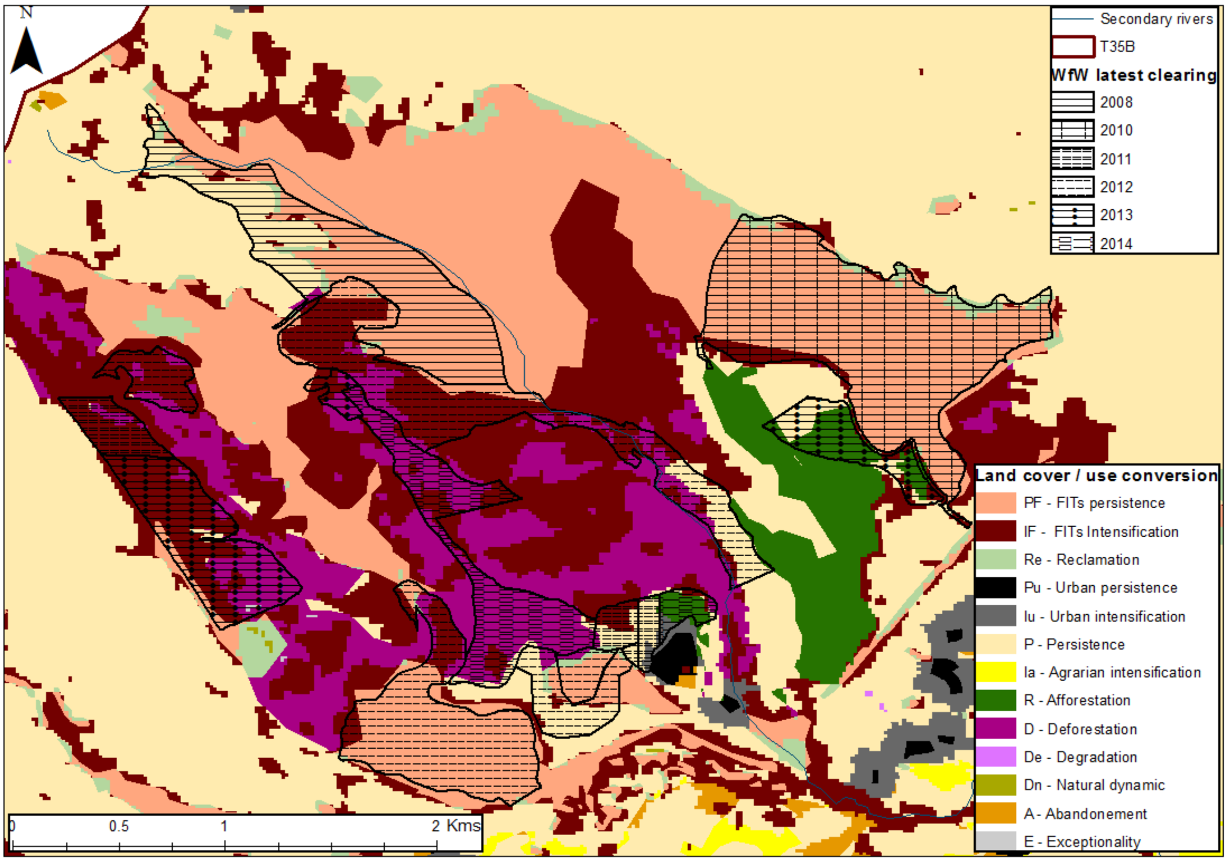


Figure 5.13 WfW clearing in T12A compared to land cover/use conversion (ENLC 2000).

Clearings with the latest clearing dates beyond 2007 are shown in Figure 5.12 and Figure 5.13. *Agrarian* and *Urban intensification* can be noted in the south east corner in NLC 2000. Areas of *Deforestation* (magenta) and *Degradation* (purple), which signify a decrease in trees and woody vegetation, are interspersed with *Afforestation* and *FITBs persistence*, which could signify regrowth of IAPs or replanting of new plantations in ENLC 2000.

As seen in WfW clearing data in Table 5.12, the cleared polygons were predominantly *Acacia* invaded. FITBs infested areas in T12A accounts for 3456 ha (ENLC 2000) but only 365.3 ha has been cleared by WfW. More than R3 000 000 has so far been spent in clearing a minimum of 531 ha of *Acacia* invaded from a maximum of 5084 ha FITBs infested sites in T35B and T12A. According to the same WfW data, the total *Acacia* (including other IAPs) invaded regions of more than 1721 ha has been cleared with the large sum of R5 885 540 over the past 12 years (2002 – 2014) in both QCs.

Table 5.12 Summary of the clearing history and costs done by WfW at the T35B and T12A.

Dominant IAPs	**Area (ha)**	**Earliest clearing date**	**Latest clearing date**	**No of follow-ups**	**Total cost of clearing (rand)**
EC Pott river WfW_T35B					
Acacia dealbata	35.3	2002	2013	59	119 037
	37.5	2002	2013	169	309 029
	2.2	2003	2004	17	4 579
Acacia mearnsii	7.7	2004	2012	26	28 534
	60.9	2005	2013	80	378 703
Acacia dealbata	21.9	2012	2012	16	6 826
EC Engcobo WfW_ T12A					
	83.8	**2002**	**2010**	**4**	**91 593**
	6.7	**2002**	**2011**	**25**	**50 244**
Acacia mearnsii	24.8	2002	2012	19	289 927
Acacia dealbata	7.5	2002	2012	8	37 854
	26.8	**2002**	**2013**	**27**	**231 481**
	22.2	2002	2014	24	291 050
	51.9	**2003**	**2008**	**4**	**79 646**
	7.0	2003	2011	5	34 407
	43.9	2003	2012	41	354 921
	13.1	2003	2013	6	78 138
Acacia mearnsii	**10.8**	**2003**	**2014**	**13**	**169 163**
Acacia decurrens	19.0	2003	2014	13	169 540
	14.0	2007	2013	7	97 823
Acacia mearnsii	**33.8**	**2008**	**2012**	**4**	**182 402**
Total	**531**			**567**	**3 004 898**

Note: Data only available for the two QCs.

Similar to areas cleared in 2010 and 2012 (Figure 5.13), areas cleared in 2008 showed relative degrees of *FITBs persistence.* It could be a classification error, WfW data validity or as a result of the number of follow-ups done on each cleared patch as shown in Figure 5.13 and as defined in Table 5.12. No *reclamation* was visible in the cleared patches, but this was rather observed at the peripheral of the interspersed vegetation in ENLC 2000 and north-west/south-east regions in NLC 2000. *Deforestation* was seen around the cleared regions, which could be presumed to be the areas cleared by WfW in ENLC 2000, since FITBs and forest plantations were difficult to delineate. However, the highest degree of *reclamation* (areas where FITBs are cleared) was mostly seen in T35B as shown in Figure 5.14.

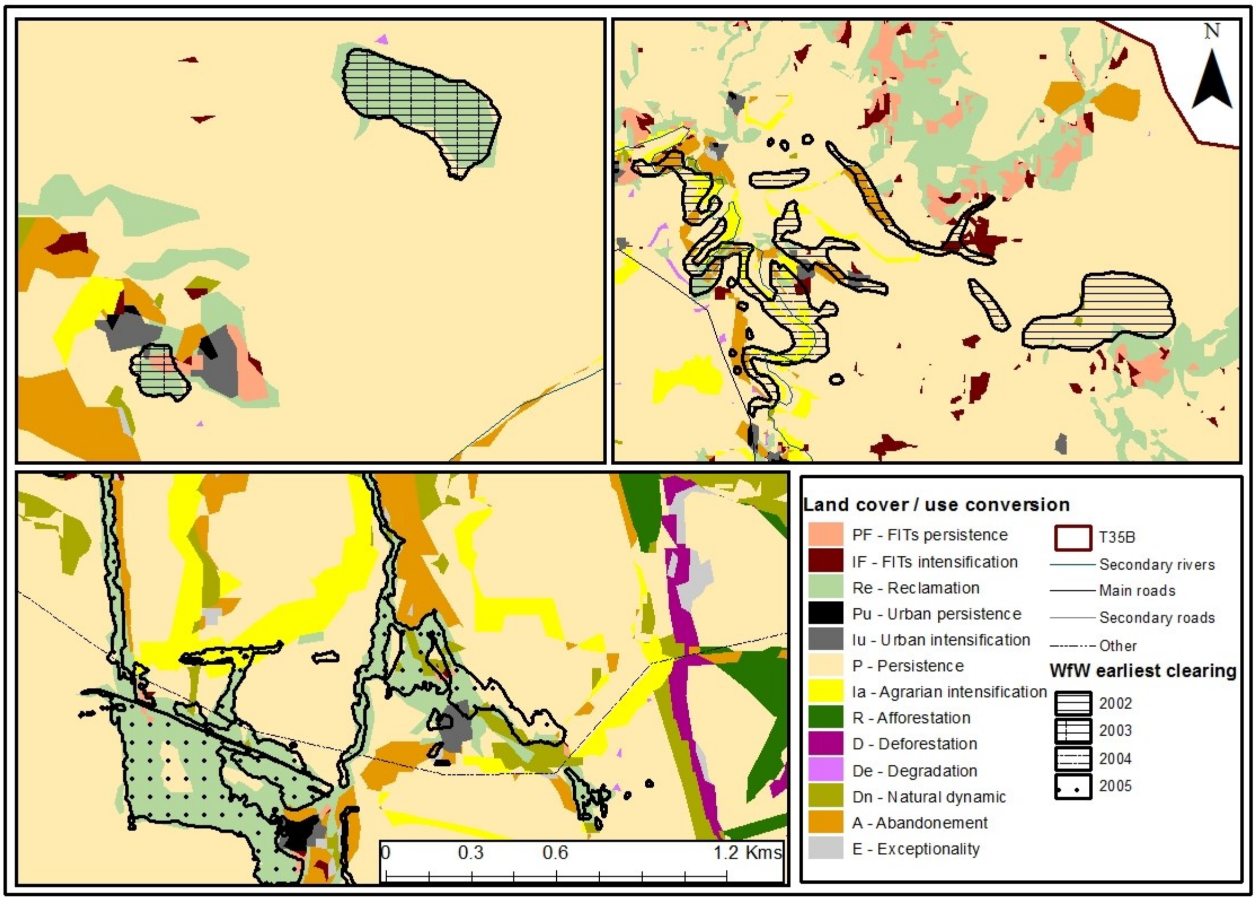


Figure 5.14 WfW clearing in T35B compared to land cover/use conversion (ENLC 2000).

Patches of agricultural activities visible in and around cleared patches signify agrarian intensification while abandoned areas (orange) of cultivated lands and urban/built-up indicate the nomadic type of farming practised in these catchments (see Figure 5.14). Long strip area observed at the south east in T35B representing *Exceptionality* (light grey), shows areas where *waterbodies* and *wetlands* are converted to other land use (cultivated lands, forest plantations and urban/built-up) (Figure 5.14). These land use alterations require active intervention followed by immediate remediation as such conversion is not expected (or could be as a result of misclassifications). Commonly sprawled throughout the catchments are urban/built-up (black and grey) interspersed with FITBs infestations (peach) as exemplified at the north-west in T35B (Figure 5.14).

The NPP is the total net carbon amassed in plant biomass per unit space and time. Spatial and temporal dynamics of NPP describe the ecosystem state and predict response of changes or disturbances (Indiarto & Sulistyawati 2014). The water loss during photosynthesis coupled with evaporation from soil and plant is termed evapotranspiration (ET). Dynamics of ET/NPP trends modelled for the T12A clearing data presented in Figure 5.13 and Table 5.12 are shown in Figure 5.15 and Figure 5.16. The rainfall variable was investigated to scale the role of climate in affecting the ET/NPP trends. Analysis of variance (ANOVA) within parameters (ET, NPP and rainfall) seemed significantly different (P < 0.05) with F-critical values shown in Table 5.13, as well as correlation coefficient analysis.

Table 5.13Analysis of variance and correlation coefficient analysis (showing degree of linearity) between NPP, ET and rainfall.

			ET	**NPP**					**NPP & ET**
		[Earliest: Latest]	All groups	All groups	[2003: 2014]	[2008: 2012]	[2002: 2010]	Other groups	All groups
ANOVA (single factor)	**Rainfall**	All groups	P < 0.05	P < 0.05					
F-Critical value			4.225	4.196					
Correlation Coefficient (Cc)	**ET**	[2003:2014]			**0.795**				
		[2008:2012]				**0.783**			
		[2002:2010]					**0.629**		
		Other groups						< 0.41	
	Rainfall	All groups							< 0.44

Note: Clearing date – [Earliest:Latest] = [2003:2014], [2008:2012], [2002:2011], [2003:2008], [2002:2013], [2002:2010] is referred to as 'Group'. 'All groups' refer to all the categories of clearing groups having same values between variables (NPP, ET and rainfall). 'Other groups' {[2002:2011], [2003:2008], [2002:2013]} represent groups that are not found significant between variables. (Highlighted in bold shows strong positive linear relationship between analogous variables; P < 0.05 = high significance difference).

Looking at the clearing done in [2003:2014] with latest clearing in 2014 and earliest clearing in 2003, it demonstrated a drop in NPP from 1.4 Kg C m^{-2} yr^{-1} in 2000 to ~1.01 Kg C m^{-2} yr^{-1} in 2003, showing increasing trends prior and after the clearing dates (Figure 5.15). Such decline in NPP for this group [2003:2014] can be seen in 2007, 2010 and 2014 that might replicate the years of follow-up by WfW (Figure 5.15) but contrasted with the number of follow-ups reported in Table 5.12. 'Other groups' followed similar inclination showing irregularities in the year of earliest/latest clearing but corresponded to the number of follow-up provided by WfW clearing data, except patches cleared latest in 2011 and 2013 (compare Figure 5.15 and Table 5.12).

The NPP of [2003:2014], [2003:2008], [2008:2012] and [2002:2013] appear to be independent on rainfall because where the NPP of cleared areas was low, the rainfall was lower. High precipitation was seen on clearing date [2002:2011] and [2002:2010]. However, the NPP barely reduced from 1.1 Kg C m^{-2} yr^{-1} of the previous year to 1.0 Kg C m^{-2} yr^{-1} on the earliest clearing and increased from ~0.87 Kg C m^{-2} yr^{-1} to 1.1 Kg C m^{-2} yr^{-1} on the latest clearing. The statistical difference (P < 0.05) between NPP and rainfall indicate that the biomass gains on cleared patches might be reliant on rainfall, but appeared more dependent on clearing activities as deduced from the NPP assessment.

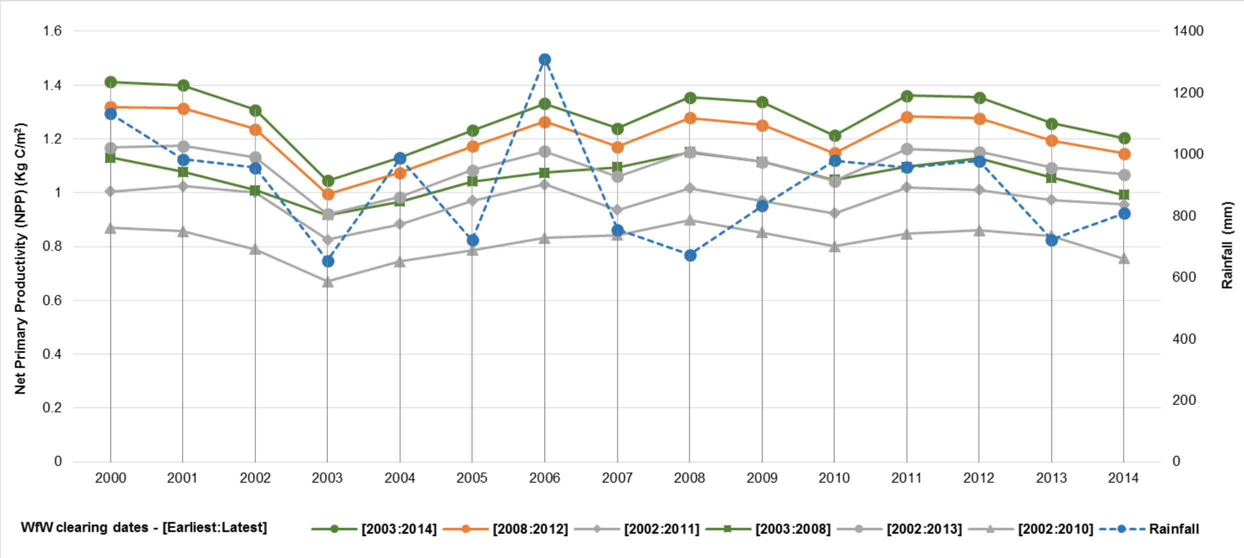


Figure 5.15 Net primary productivity of the cleared patches (with dates of clearing) carried out by WfW in T12A (as represented in Figure 5.13) with the rainfall pattern spanning across a 15-year period.

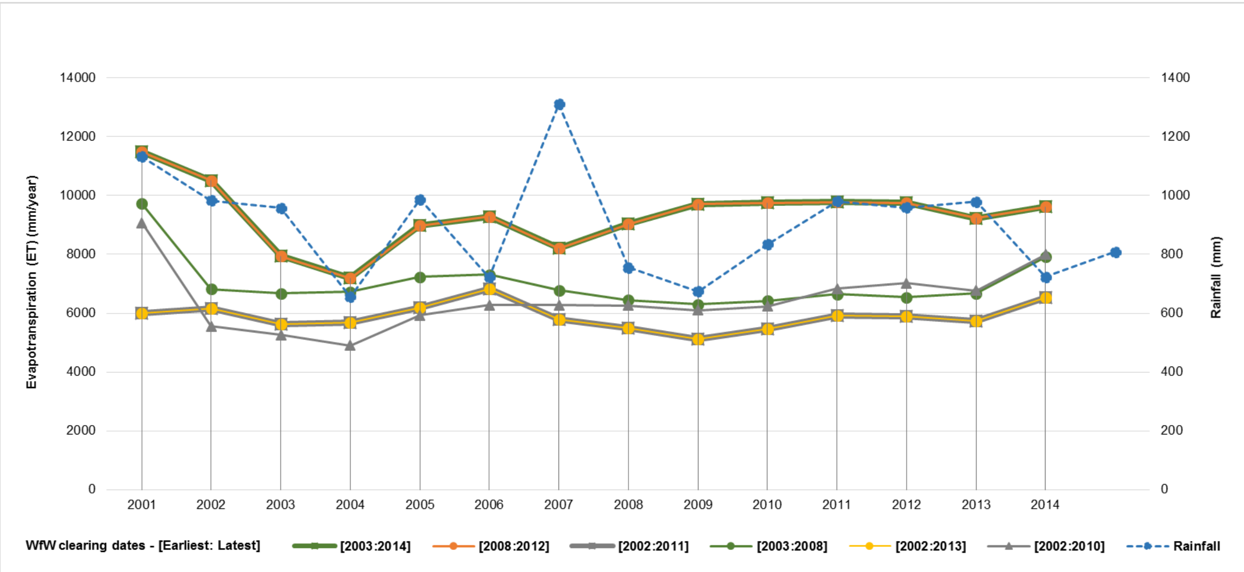


Figure 5.16 Evapotranspiration of the cleared patches (with dates of clearing) carried out by WfW in T12A (as represented in Figure 5.13) with the rainfall pattern spanning across a 14-year period.

Correlation analysis presented in Table 5.13 showed stronger relationships between ET and NPP for these clearing dates – [2003:2014], [2008:2012] and [2002:2010]. Less than 0.41 correlation coefficients were observed for ‘Other groups’ ([2002:2011], [2003:2008], [2002:2013]) implying a non-correlation between NPP and ET on clearing dates (Table 5.13). This describes the high rainfall pattern equalling high ET trends witnessed for the ‘Other groups’ in Figure 5.16. The high ET rates may be estimated more from adsorbed soil moisture other than the trees, since clearing often exposes soil surface to rapid evapotranspiration. On the other hand, NPP and ET for ‘all groups’ seem not to strongly correlate with rainfall (Cc <0.44). This further affirms that NPP (biomass gain) and ET (water loss) might be unpredictably reliable on rainfall, but particularly dependent on clearing activities. It further reveals that the WfW clearing activities are not sustainable. After year(s) of clearings, there were regrowth of IAPs almost instantaneously that completely could not be attributed to the climatic conditions prevailing at the QCs. Other factors that might cause such rapid regrowth must be assessed and managed. Such factors include fluxes in soil chemical properties (see details in Chapter 4).

5.6 LAND COVER OF THE QUATERNARY CATCHMENTS

As previously stated in Chapter 1, the SES existing in the rural landscapes practices two different types of land tenure systems namely freehold farms and communal/leasehold areas. The landscapes comprise diverse land cover types inter alia areas of irrigation agriculture, dryland cultivation, residential, extensive rangeland and forest. T35B includes examples of recent commercial afforestation, commercial rangelands and the socio-ecological system associated with communal tenure (Palmer 2014). QC S50E and T12A are exclusively under communal tenure with extensive agricultural practices. No river systems aside small dams and reservoirs are seen in QC T35B and QC T12A, unlike the large Ncora dam with its tributaries quite visible in QC S50E. Grasslands predominated as the natural habitats of the catchments and their replacement or removal ought to augment the cost of event and thus require strong consideration (Vos 2014).

Until the early nineteenth century, rural dwellers extensively grazed livestock on the communal rangelands (traditional homelands) of the Eastern Cape as a livelihood strategy (Bennett & Barrett 2007). Since the nineteenth century, livestock farmers have practised seasonal herding where livestock are herded to more productive valleys during dry seasons and open plains in spring. However, such movement is no longer practical within the confines of modern regulatory frameworks (De Wet 1987; Peires 1982). By 1930s, human impacts infringing on the natural resources were more evident and commercialisation defined a new landscape-land use system. During the study period, it has become evident that human development has had increasing impacts on the size of the rangelands and productivity.

In NLC 2000, having a low accuracy, natural grasslands indicate large areas of persistence from the mountainous highlands of Southern Drakensberg Highland and East Griqualand grasslands of T35B to the low-lying flat plains of Tsomo and Drakensberg grasslands of T12A and S50E (DWAF 2004). Significant man-made impacts are not profound at the three QCs. However, *commercial afforestation* started at a slower rate with higher *agricultural cultivation* in S50E (Figure 5.9). Alien plants subsumed under *FITBs* appear to be heavily infested in T35B and T12A but scantily distributed in S50E, mostly at the low-lying, hilly, slightly inclined flatlands and agrarian regions. Few areas of *urban/built-up* are distinct in T35B when compared to urban intensity that are visible in T12A and S50E. Mainstream river system (Tsomo River) are seen in S50E, which supplies the Ncora dam by gravitational flow via irrigation vents to designated agricultural lands.

When compared to NLC 2000, by 2014, high *FITBs* infestation concealed greater fragments of grasslands in T12A and S50E with reverse scenarios occurring in T35B where the infested areas were replaced by *commercial afforestation* and *cultivation*. The infestations were seen along the peripheral mountainous escarpment to the central gentle declining flatlands. Extensive *commercial afforestation* is prominent at the eastern-lowland region and the agrarian activities are maximised at the central-low lying valley bottoms of the QCs. *Agricultural cultivation* had consolidated its tractions along these sections where it signified a fairly unremitting extensive development incline. The land use pattern under freehold landowners of the T35B seems to be a recent development on land use tenure as unequal afforestation and infestation were clearly distinguished between the two time analyses. Small patches of urban density observable in 2000 appear to be replaced by agrarian activities and grassland in 2014. This activity could be attributed to small landholdings by farmers who might have built shacks or cottages on the farms for shelter but were abandoned or demolished in time. These observations were made during data processing and manipulation. Small irrigation dams and reservoirs were located amidst arable lands and wetlands to obstruct upstream flowing stream and direct water supply to the agricultural stands. *Wetlands* were however observed to be converted into cultivated lands, commercial afforestation and grasslands. This conversion might have resulted from technological advancement in agricultural mechanisation, which was used to construct ditches and level the land for extensive crop cultivation. Additionally, the conversion of *Wetlands* could have been as a result of the different frameworks adopted for wetland identification and classification at both time-periods.

Agricultural practises intensified along the landscapes in T12A and S50E with the cultivated areas showing dominance at the foothills of Tsomo river in S50E (Figure 5.8). *Grasslands* and *commercial afforestation* were replaced by *FITBs* in both QCs, where the land tenure systems were of communal ownership and the livestock owners exercised over-exploitation of the rangeland because it was free (Palmer 2014) and this might have aggravated infestation intensity. Development as a product of civilisation was hugely exploited as the rate of urbanisation skyrocketed largely in T12A but fairly intensified in S50E. Built-up regions were interspersed with

FITBs infestation in these catchments. Such symbiotic co-existence may have been as a result of human activities that have placed man as a promotor of such infestation since agrarian practices are also prevalent around the urban zones. Given that wetlands are minuscule in these catchments, their conversion cannot be evidently established.

In ENLC 2000, with an accuracy higher than NLC 2000, grassland distributions similar to NLC 2000 were observed. Unlike the NLC 2000, man-made activities appeared to be apparent at the three QCs in terms of *commercial afforestation* in T35B, *agrarian practices* and *urbanisation* in T12A and S50E. *FITBs* were found to be less infested in T35B and T12A than in S50E when compared to NLC 2000. *Urban/built-up* are insignificantly present in T35B but densely seen in T12A and S50E. *Wetlands* were well pronounced in T35B in both NLC and ENLC 2000, while Tsomo River in close proximity to Ncora dam in S50E was still discernible in ENLC 2000. By 2014, half size of *FITBs* was reduced in T35B while no significant change was observed in T12A and S50E. *Forest plantation* was maximally intensified in T35B and intensely deforested in T12A and S50E. No significant change was seen in *urban/built-up* areas in T35B but civilisation and human development, in terms of *urban/built-up* areas, were made prominent in T12A and S50E. Conclusively, high degree of land cover change over a 14-year period between NLC 2000 and DLC 2014 appears to be exaggerated when compared to the transitional change between ENLC 2000 and DLC 2000. As a result, and because of the high accuracy of ENLC 2000, subsequent discussion on land use conversion and ET/NPP evaluation will solely reflect on the ENLC 2000 base reference set.

The period of 2000 – 2014, in ENLC 2000, the transformation in LULC initiated by both natural and human factors generally seemed to be marginal, but contributory in causing grassland degradation in the QCs. The grassland conversion to other land uses clearly occurred but persisted over the 14-year period. Waterbodies and wetlands persisted more in T35B as the dominant species of the catchments. While negligible, grassland intensification was observed in T35B. Degradation of grassland to alien plants and *FITBs* in T12A and S50E necessitates immediate rehabilitation to abate further degradation. Benini et al. (2010) found similar grassland increases and decreases in T35B and T12A/S50E respectively over the 14-year period within successive periods in the Lamone River basin. Although land cover for Lamone river basin is deciduous forest, the *Afforestation* activities that was seen to increase in Lamone River (Benini et al. 2010), also occurred in T35B where the *commercial plantation* nearly doubled the original size. The type of landscape tenure system existing in T12A and S50E infringed on the sustainability of commercial afforestation as no management system was in place to conserve the small areas of forest plantations present at the catchments. *Agrarian* and *urban intensification* were partially observed in T12A and S50E and such intensification barely occurred in T35B.

Degradation gradients for *deforestation, degradation* and *abandonment* were negligible in the three QCs. The conversion of classes, labelled *exceptionality,* can be characterised as a degradation gradient where an unexpected conversion took place. While such conversion requires immediate intervention, its occurrence in the QCs is insignificant. As established in the literature, invasive alien plants are known to have affected grassland veld types (Carbutt & Martindale 2014; Carbutt et al. 2011). Though incorporated as FITBs, its *persistence* and *intensification* are noticeable in T12A and S50E whereas the *reclamation* process, where FITBs are replaced by grasslands are more prominent in T35B.

Generally, the assumptions made from the transition analysis between edited reference and derived land cover shows that no significant changes were observed in terms of degradation except FITBs persistence and intensification at catchment scales. These FITBs infestation (including alien plants) were already prevalent prior to the reference year. Anthropogenic intensification may have occurred but at marginal scales. Moreover, rehabilitation strategies directed towards clearing of alien plants (FITBs) by WfW appears to yield no significant results as *reclamation* rates across the catchments does not equal the size of FITBs infested regions.

5.7 EVAPOTRANSPIRATION/NET PRIMARY PRODUCTIVITY REPLICATING REHABILITATION PROGRESS

By overlaying WfW clearing data on land-conversion maps and ET/NPP evaluation from 2000 to 2014, the success of WfW clearing efforts were demonstrated, though reversed by IAPs regrowth. In interpreting the cleared patches and level of rejuvenation, the assessment showed that land cover classification corresponded largely with the actual land use conversion (Indiarto & Sulistyawati 2014). Some conflicting misclassifications were encountered within the homogenous cover types (e.g. *forest plantation* and *FITBs*) that questioned the validity of land use conversion labels and WfW clearing data. Comparing land use conversion maps at 30 m resolution to demonstrate land feature productivity at a coarse cell size (1 km) with MODIS products, it was found that land use conversion maps were not completely efficient in characterising the complexity of vegetated and non-vegetated landscapes (Indiarto & Sulistyawati 2014). Despite possible classification error and reference data validity, some patches cleared in 2014 by WfW (centre of Figure 5.13) showed up as areas of *deforestation* (Plantation converted to other land uses) and had lower mean annual NPP in 2014 (Figure 5.15 legend entry [2003:2014]) which confirms the value of WfW clearing efforts. Areas where IAPs were completely felled and replaced by grasslands and bare soils (*reclamation*) were mostly seen in T35B (Figure 5.14). The conversion maps reflect land transformations from 2000 to 2014 based on finer resolution satellite imagery. These changes are corroborated in part by coarser resolution MODIS data. NPP and ET reveals the trends of clearing events and follow-ups over the same time period which assists in measuring the value of rehabilitation protocols of the WfW clearing programme.

According to Indiarto & Sulistyawati (2014), there was a strong correlation ($P < 0.01$) between NPP, precipitation and land surface temperature, which negated the land cover change as a non-determinant factor for NPP dynamics in Java Island. In this study, rainfall pattern showed no such correlation with ET or NPP ($Cc < 0.44$) but only differed significantly ($P < 0.05$) with ET/NPP. As a result, the land cover change promoted by WfW clearings is one important factor determining the ET/NPP dynamics on the clearing dates, but not on the cleared patches. While analytical linearity was done exclusively on the clearing dates, ET/NPP values for other years that were not the clearing dates correlated with the rainfall patterns as viewed in Figure 5.15 and Figure 5.16. This demonstrated that the ET/NPP trends might be primarily affected by rainfall rather than land cover alteration that was due to WfW clearing activities (Indiarto & Sulistyawati 2014). The unsustainability of WfW clearing program was shown by the ET/NPP modelling. Alien infestation is guaranteed to reoccur after clearing, if active restoration rather than passive restoration is adopted (See Chapter 1, paragraph six).

5.8 CONCLUSION AND RECOMMENDATIONS

The standard NLC 2000 dataset proved unsatisfactory to provide the actual base for transitional dynamism on the small area sizes of the QCs. Overall, the edited ENLC 2000 dataset with accuracy of about 85% demonstrated better land cover representations for the QCs. The GEOBIA approach was able to deal with the problem of salt-and-pepper effects, which is common with classification outcomes found in traditional per-pixel approaches (Blaschke 2010; Yu et al. 2006). The expert system applied to the 8-band Landsat provided robust land cover classifications for highly fragmented catchment-landscapes and precision in delineating boundaries of various vegetation types at an insufficiently coarse resolution (Blaschke 2010; Radoux & Defourny 2007). The multiresolution segmentation method employed proved useful in attaining the computation time and product accuracy as well as in segmenting the heterogeneous catchment-landscapes (Li et al. 2014). The LULC mapping accuracy of DLC 2014 of circa 85% and the 81% overall thematic agreement with the DEA land cover dataset 2013-14 SANLC, for the three QCs, demonstrated the efficiency of the classifiers and visual interpretation, using the rule-based expert system, in classifying remotely sensed imagery (Abd El-Kawy et al. 2011). Visual assessment was not only useful for enhancing classification accuracy, but assisted in outlining areas with similar spectral and textural properties to enable evaluating single-class impact that was done through mapping of FITBs, forest plantations and cultivated lands (Abd El-Kawy et al. 2011).

The clearing data obtained from the office of WfW in the Eastern Cape seemed adequate in monitoring the efforts of WfW activities toward grasslands rehabilitation after alien invasive trees eradication. The annual MOD17A3 NPP and MOD16A3 ET demonstrated acceptable trends for evaluating and monitoring reclamation progress of the cleared patches. The ET and rainfall clearly showed the degree of interaction between cleared patches and environmental factors.

The objectives and goals stipulated at the beginning of this chapter “towards land cover and land cover change at the QCs as well as the rehabilitation progress” have been described extensively. Difficulties were encountered mostly during image classification due to coarse Landsat data used. Recommendations for future studies or related research are listed below.

- Spectrally homogenous vegetation types were difficult to classify using 30 m resolution Landsat scenes. Hyperspectral or high resolution imagery such as IKONOS or WorldView should be explored in delineating and mapping different vegetation types present in the

QCs such as alien plants, forest indigenous, thickets and commercial plantation (Radoux & Defourny 2007).

- Sufficient ground truthing is required for definite mapping of alien plants and other cover classes as posited by Blaschke (2010) that rich-information base classification supersede the classification algorithms in OBIA.
- To minimise classification errors and uncertainties, high accuracy base reference datasets must be obtained to increase the chances of achieving realistic outputs from change-detection analyses.
- Using coarse 1 km resolution MODIS product to assess the ET/NPP of 30 m pixel-sized derived land-conversion maps for the cleared patches may be adequate for quantitative analyses. For qualitative studies, mathematically computed ET/NPP per pixel-size can provide exceptional guidelines for appropriate state of WfW clearing and rehabilitation efforts.
- To boost the ability to correctly evaluate the rehabilitation progress, comprehensive, valid and up-to-date WfW clearing data must be obtained.

CHAPTER 6: **INTEGRATING SOCIO-ECOLOGICAL SYSTEM INTO SUSTAINABLE SYSTEM**

A catchment is a drainage basin that feeds into a river system, while a quaternary catchment (QC) is the basic hydrological or principal water management areas (WMA) in South Africa (DWAF & WRC 1996). It is recognised that the level of national or societal development is directly linked to their ability to manage their water resources (Walmsley 2002). As mentioned in Section 1.2, water resources are limited natural resources in South Africa but a strong cornerstone for agricultural, industrial and commercial development (DWAF & WRC 1996). On the other hand, grassland, the second largest biome in South Africa was considered to be critically endangered and invaded mostly by Australian acacias (*Acacia mearnsii* and *A. dealbata*) (Coetzee, Rensburg & Robertson 2007; Van Wilgen, Forsyth & Le Maître 2008).

In the grassland biome, IAPs eradication is typically due to their impact on ecosystem services, water resources and biodiversity. However, the largest weighted impacts were observed on water resources and biodiversity (Van Wilgen, Forsyth & Le Maître 2008). Note that there are also social benefits and effects of IAPs in the rural settlements that are in proximity to the QCs (Palmer et al. 2015b) identified by the overarching project which will not be integrated as part of this study. The Eastern Cape region is a priority area for WfW due to its high rate of unemployment, since the WfW programme also provides short-term employment (Common Ground 2003). A preliminary assessment estimated that IAPs use about 5.58% of the mean annual rainfall (MAR) or 17% of the total water use in the Eastern Cape (Versfeld & Chapman 2000). In the study areas, these figurewas were estimated to be 13.26% (Secondary (S) catchment) and 2.94% (Tertiary (T) catchment) of the MAR (Versfeld & Chapman 2000). These figures were reassessed by Le Maître et al. (2013) to be 4.49% and 4.51% for the S and T catchments, and an overall figure of 2.9% of the naturalised MAR for the country. However, the authors stated that the values were conservative and believed to be underestimates of the actual impacts on surface flows. In Section 1.5, it was stated that efforts of WfW in clearing IAPs on their own is not a sufficient motivation to continue with Municipality and WfW programmes. This calls for the need to consider landscape sustainability when the activities of these programmes are completed (Palmer 2014).

To sustain the ecosystem health of the QCs, decision- and policy-makers require generic information on conditions of various facets of the catchment structures and forces acting on them (Hammond et al. 1995). Although sustainable development has been widely used for managing the interaction between environment and economic growth, there is often the practical problem of measurement and implementation (Alfieri, Hassan & Lange 2004; Walmsley 2002). Using a framework in developing and reporting on sustainable indicators in a logical pattern can aid in the easy identification and recapitulation of key issues. As described in Section 1.1, the DPSIR framework is a sustainable portfolio that identifies *driving forces* and *pressure* acting on a system *State*, quantifying the *Impact* degree and proffering a desired *response* to contain such impact. Integrated catchment management (ICM), an approach adopted by DWAF and WRC (1996), can be used for resource management by integrating existing environmental, ecological and socio-economic issues within a catchment into a holistic management philosophy, procedure and strategy, using a DPSIR framework. A similar approach will be used in integrating various aspects of the QCs under study into an optimal mix, by describing the degradation gradients and sustainable benefits gained in protecting the natural resources and ameliorating the socio-ecological consequences.

Preceding the simulation and evaluation of a sustainable protocol appropriate for the QC management, degradation gradients of the QC landscapes must be identified and reviewed. This final chapter will consolidate the generic objectives of this study and some part of the overarching project, in solving the problem statements (the aims) and addressing objective 6 of this study. In subsequent sections, factors affecting soil chemical properties, LULCC and WfW clearing efforts at the QCs are concisely summarised. Other pointers stemming from the contextualisation (and objectives) of the 'overarching project', having its focus on QC degradation and health are also discussed. These elements would represent the integral concepts that will be used to discuss the DPSIR framework suitable for the management of the catchments. The designed management protocol for policy- and decision-makers, to enable ecosystem services sustainability at the QCs, are also illustrated and described, followed by the concluding remarks.

6.1 REVIEW OF DEGRADATION GRADIENTS

The analytical soil experiments analysed in Chapter 4 showed that, although there was high soil pH for crop production in all the sampled sites – invaded, uninvaded and cleared –the soil pH in invaded sites appeared to be higher. Nutrients upsurge observed at the invaded sites, primarily caused by IAPs, might intensify IAPs infestations at the QCs due to their strong affinity for N content as well as phosphorus, magnesium and CEC (González-Muñoz, Costa-Tenorio & Espigares 2012). While phosphorus (P) is the only significant variable across the sampled patches, these nutrients upsurge and soil pH appeared to be acting principally on the degradation gradients of the soil system at the study sites (Lazzaro et al. 2014; Miles & Farina 2013; González-Muñoz, Costa-Tenorio & Espigares 2012). Detailed information on soil nutrient analyses, variations across patches, soil optimal conditions, results and discussion can be found in Chapter 4.

As observed from land cover classification and transition analysis done over a 10-year period, land modification and development was seen to have taken its root prior to the study years (2000 - 2014) in the rural SES. Agricultural practices, civilisation and infrastructural development were seen to increase marginally across the catchments. *FITBs* or alien plants prevailed persistently and intensified chiefly at the peripheral of river channels, agricultural areas and human inhabited regions. While some land cover classes such as grassland, waterbodies and wetlands maintained approximate states of persistence, slight land degradations were found to result from land use intensification and mainly from *FITBs* (alien plants) infestations.

WfW clearing of IAPs appeared to yield non-sustainable system, as regrowth of alien plants were easily seen after clearing when monitored with MOD17 and MOD16 ET/NPP products. While IAPs regrowth on cleared patches may be slightly dependent on rainfall, ET/NPP non-correlation with rainfall revealed other resilient factors such as soil nutrients (or soil moisture), which perhaps may have influenced IAPs rapid regrowth after clearing (Lazzaro et al. 2014; Miles & Farina 2013). According to the literature reviewed in Section 1.1, IAPs are known to impact on water resources and the South Africa government has spent considerable sums to increase water yield across the country through eradication (Hoffmann, Moran & Van Wilgen 2011; Van Wilgen et al. 2008; Gorgens & Van Wilgen 2004). Economic impact of about R3 to R5 million was accrued from WfW clearings of IAPs at the QCs (Table 5.12). More details on land cover classification and change analysis is presented in Chapter 5 of this thesis.

6.2 OVERARCHING PROJECT: AUXILIARY INDICATORS OF CATCHMENT HEALTH

Among many objectives of the overarching project listed in Section 1.3, livestock water productivity (LWP) (or water use efficiency (WUE)) and Reward for Ecosystem Sustainability (RES) are two processes that directly affect the ecosystem health at the QC. As prepared by Palmer et al. (2015b), defined LWP as the measure of agricultural outputs (goods and services) derived from livestock to the amount of water consumed in the process of producing these outputs. The benefits derived from water use are normally referred to as the productivity of water (Peden, Tadesse & Misra 2007). It models the ability of agricultural systems to convert water into food. LWP can be expressed in kilograms per cubic meter ($kg.m^{-3}$) of water, in litres per cubic meter ($L.m^{-3}$) of water or expressed on the monetary value per cubic metre ($ or $ZAR.m^{-3}$) of water if only milk or meat is considered.

Livestock and water interactions are crucial challenges, since livestock production utilizes huge amounts of water for feed production and fairly responsible for environmental degradation due to over grazing. Livestock and water managers face challenges of guaranteeing that livestock rearing minimizes water degradation, depletion and contamination of resources, while at the same time maximizing the outputs from livestock and other systems (Van Breugel et al. 2010). There is a need for improved understanding of livestock water productivity and its influences on water resources. This is because the concept is new and has been mostly neglected (Peden, Tadesse & Misra 2007; Peden, Taddese & Haileslassie 2009).

The latest growing attention to LWP has revealed that improvements in livestock water productivity are needed to meet the increased demands for animal products, without depleting and disturbing water scarcity. Additionally, strategies to improve livestock water productivity have only been identified theoretically. The goods and services derived from livestock have been focused on the monetary benefits, with real global assessment of the impacts of intervention on LWP not been identified. Analysis focusing on the LWP for a specific product still needs to be identified. The improved understanding of the livestock water interactions also needs to be inculcated in the livelihoods of communal farmers.

The primary requirement for assessing livestock water productivity at the study sites is estimating livestock related water inflow, depletion and storage. Peden, Tadesse & Misra (2007) developed a conceptual framework to analyse LWP adapted for a mixed-livestock operating system. One of the strategies for increasing LWP and conserving water described by Peden, Tadesse & Misra (2007), is the need to limit water loss through non-production depletion pathways. Such approaches include maintaining high vegetative ground cover, harvesting of water, improved soil-water holding capacity, decreasing extreme runoff and increasing infiltration as well as vegetated buffer zones around surface water bodies. This concept presumably will be adapted by the 'overarching project' in integrating water use in relation to livestock water interaction, hydrology, economics, conservation and production system for the mixed-farming systems prevalent in the study sites (Palmer 2015b).

Another objective of the 'overarching project' that influences catchment health is the need to examine the possibility of using a RES in rural rangelands as a possible solution for degradation and water issues (quantity and quality). RES, as one of a number of policy instruments, is a means of translating external, non-market values of ecosystem services, including water, into tangible incentives for local actors to benefit financially by providing ecosystem services (Engel, Pagiola & Wunder 2008; Turpie, Marais & Blignaut 2008). As a policy instrument, RES is described as particularly suitable for addressing environmental problems, which result from a situation where ecosystems are mismanaged because associated benefits are secondary from the perspective of ecosystem managers (Engel, Pagiola & Wunder 2008). In plain terms, as provided by Wunder (2005), RES describes a voluntary transaction between at least one willing buyer and one willing seller, where reward is conditional on the provision of service, although these arrangements may be structured in a number of other ways (see Engel, Pagiola & Wunder 2008 for a comprehensive review).

A RES structure for hydrological services is emerging in South Africa through the WfW Programme, under the auspices of DWS, which acts as a platform for the provision of environmental services (notably, water) through the eradication of invasive alien plants (IAPs) (Blignaut, Marais & Turpie 2007). Despite regulations of the Conservation of Agricultural Resources Act (Act of 43 of 1983, as amended), by which landowners are legally responsible for the management of IAPs on their land, landowners bear no cost for WfW activities on their properties. While this system constitutes a payment for an ecosystem service in a crude sense, it lacks the essential criteria that would qualify it as a RES approach according to Wunder's (2005) definition, which calls for a conditional transaction between willing suppliers and consumers.

More recently, as water benefits associated with the clearing of IAPs have become better established, a voluntary system of payments has begun to evolve, whereby water utilities and municipalities have contracted WfW to eradicate IAPs in catchments that affect their respective water supplies, with payment being conditional on service delivery (Turpie, Marais & Blignaut 2008). This comes closer to meeting Wunder's (2005) criteria, and represents a shift towards a payment system in the true sense. Although to date, despite 15 years of being in operation, examples are localised and represent only a small proportion of funds allocated to the programme. It is anticipated that this contribution will increase with growing water scarcity, since the water provision aspect of the WfW programme are in greater demand in the private sector and water utilities.

6.3 MANAGEMENT FRAMEWORK AT CATCHMENT SCALE

For effective catchment and water resource management, there is the need to define and assess the diverse and interacting components of catchment processes that impact on catchment resources (DWAF & WRC 1996). The three basic strategic approaches involved are: analysing the catchment system that affects catchment health and water resource use; assessing the existing environmental and socio-economic value in relation to the value arising from beneficial utilisation of the catchment services, water resources and the allied impacts of the management actions; and monitoring the environmental conditions and associated socio-economic factors. These are the basic information used for the development of the QC DPSIR management system (Walmsley 2002).

The designed DPSIR concept for the QCs was able to identify the indicators, reflect their cause-and-effect interactions, allow separability between categories of issues, enable analytical and usage flexibility and improve systematic monitoring (Walmsley 2002). As described in Section 1.2, the five indicators in the DPSIR framework including *driving forces* (or *Drivers*), *pressure*, *state*, *impact* and *response*, were used for developing the QC sustainable indicators. These sustainable indicators (or indicator system) analyses the catchment systems by assessing the current situation, which can be used as a model for short- and long-term monitoring once developed (Walmsley 2002). According to Walmsley (2002), this has not been applied at a catchment scale. This approach was used to summarise and consolidate events at the QCs, vis-a-vis interspersed landscapes, agricultural practises, and management systems, into an optimal mix of DPSIR framework for the benefits of the policy-makers. A flow diagram showing the conceptual connections and cause-and-effect relationships of DPSIR indicators for the QC categories is shown Figure 6.1 DPSIR framework of agricultural, invasive alien plants and other land use changes at the three quartenary catchment scalesFigure 6.1.

At the catchment scale, the main natural *driving force* is often the *climate*, which directly impacts on the water availability of a system. High or low precipitation will affect water stored as surface water in reservoirs, dams, river, lakes, wetlands, estuaries, and as groundwater in aquifers. High or low precipitation also determines the productivity of agriculture (Figure 6.1). The amount of available surface water is predetermined by the MAR, which measures the volume of water flow into rivers after soil absorption and evaporation. In other words, high precipitation and low evaporation is directly proportional to water. Man-made induced *drivers*, comprising *agricultural and other land use changes* were mostly pressured by the need for *agricultural landscape management*, while land use modification and development were often triggered by *LULC management practises* (Figure 6.1). Other *pressure indicators* acting on the systems include *cultivation, commercial afforestation, livestock production and overgrazing, soil tillage and dung depositions, FITBs/IAPs infestation, civilisation* and *infrastructural development*.

While the functionality of the SES structural properties have been largely pressured by IAPs invasion and farming, it also interferes with the LULC *states* and stability, which include, *grassland cover and revegetation*, *soil structure and composition*, and *water availability* (Figure 6.1). *Grassland cover, land cover and revegetation* is critically important for continuous livestock production and functional ecosystem sustainability at the catchments. Soil quality, on the other hand, affects the vegetation types and growth, thus defined by soil lithology and morphology (*structure and composition*). The term *water availability* refers to the amount of water required for all the water use sectors at the QCs vis-a-vis livestock rearing, cultivation practises, grassland productivity, alien plants and FITBs, industry, domestic and environmental sectors. *Water availability* in the QCs are measured in terms of both water quantity and quality as both are essential for ecosystem integrity and use value The impairment of fresh waterbodies in the QCs can emanate from various sources such as agriculture, domestic, mining and industrial practises. These pollutions can be in form of salinization, eutrophication and sedimentation, toxic organic and inorganic substances, infectious organisms and oxygen-demanding wastes. It is impractical to monitor all forms of pollution acting on the water quality, but can be narrowed to the highlighted pressure indicators at the QCs (Walmsley 2002).

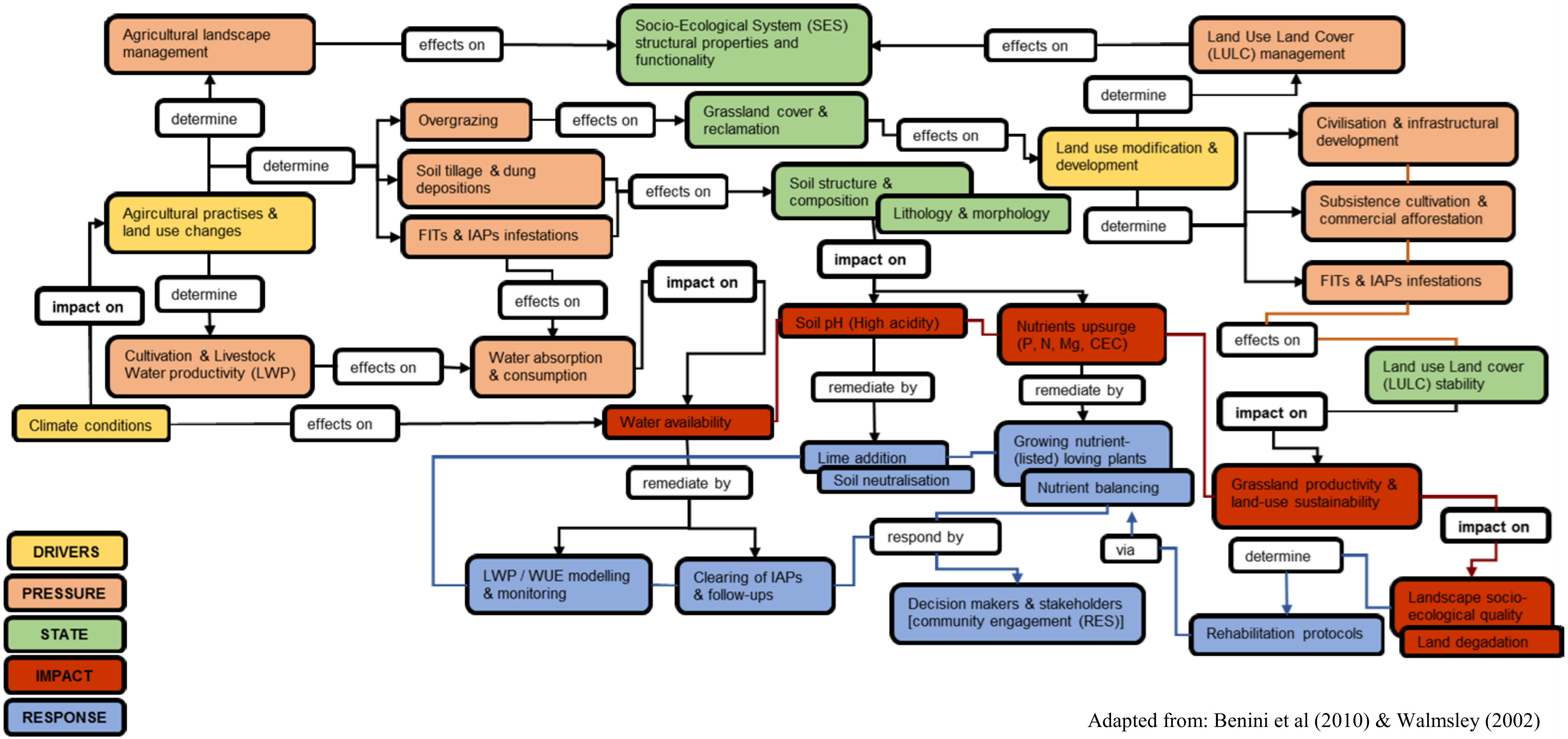


Figure 6.1 DPSIR framework of agricultural, invasive alien plants and other land use changes at the three quartenary catchment scales.

In addressing the query posited in section 5.4.3 on whether the land use conversions could have a detrimental influence on the natural systems, three important systems appropriate for rehabilitation were represented as the *impact indicators*. These systems are simultaneously impacted by diverse events in form of *driving forces* and *pressure indicators*, and include *ecosystem integrity and use value*, *grassland productivity and land use sustainability*, and *soil quality* (Figure 6.1). Anthropogenic-mediated changes on a natural system usually have negative impacts on the functional integrity of a system (Walmsley 2002). This took the form of IAPs invasion, mediated by communal form of agrarian practises affecting resources and reclamation.

Ecosystem integrity and use value, which have a cause and effect interaction, are the basic elements that moderate the sustainability of any system. As already established in this thesis, the water availability are prevalent issues, directly or indirectly utilised by various components of the QCs such as cultivation, livestock farming, carbon capture and human development (Figure 6.1). If the resource is to be conserved for the purpose of agriculture and human development on a sustainable basis, then the use of the resources should not decline. The *use value* of a system is directly related to *ecosystem integrity,* i.e. if the ecosystem is not functioning properly, this will have a direct effect on *use value* (Walmsley 2002). For instance, the addition of lime for neutralising soil acidity will lead to eutrophication, which creates an imbalance in the system causing algal bloom, which decreases the use value for LWP that requires clean water and for domestic purposes. In both cases, treatment costs would rise, adversely affecting the economic value of the water in the system (Walmsley 2002). However, the financial costs may or may not be pinned on the declining rate of the use value (Walmsley 2002).

Grassland productivity and land use sustainability are considerably important to drive the mutualistic relationships existing between environmental and human subsystems in terms of provisioning of ecosystem services. As natural species of the QCs, grasslands have been transformed and widespread displacement of these native species by IAPs, agricultural, civilisation and industrial development has been poorly revegetated (or reclaimed). This generated to landscape degradation, impacting on the socio-ecological quality (Figure 6.1

Soil quality has been affected by various land use forms in the study areas such as alien plants and FITBs infestation, livestock overgrazing and trampling, agrarian intensification etc. Soil compositions are found to contain very high acidity and N content that tend to promote rapid spread and infestations of alien invasive trees. This in turn, affects the water availability already insufficient for the sustainability of other water use sectors in the system (Figure 6.1). Generically, these land use conversions evidently affect the *SES*, not to mention the use-value decline, economic costs of remediation, rehabilitation and management. The effects of these acting forces on the *impact indicators* convincingly addressed the question stated above, which pertains to the impacts of land use conversions on the SES of these QCs.

In the contextual framework of the DPSIR, the *responses* often apply to mostly long-term management actions, rather than emergency measures. Such long-term actions may comprise policy development in the form of international treaties, national and local statute, and catchment management plans. The indirect response commonly taken is always in the form of knowledge base expansion via research and monitoring. *Responses* can be separately applied on any segment in the causal chain outlined in Figure 6.1. *Responses* are aimed at mitigating the impacts of anthropogenic pressures caused by development and are often unable to make an impact on the driving forces. Actions (*response indicators*) required to restore the *impact systems* to sustainable *states* are listed in Figure 6.1.

It has been documented by Descheemaeker, Amede & Haileslassie (2009) and Peden, Tadesse & Misra (2007) that the main water use in livestock system was related to transpiration of water for feed production, which is about 50–100 times the amount of water needed for livestock drinking. LWP modelling will monitor the amount of water channelled to livestock production in terms of livestock servicing (rearing & feed production) and drinking, while clearing of IAPs, either by WfW or by using the RES tool, will attempt to restore the QCs to sustainable *states*. However, clearing of the IAPs is not sufficient motivation for the WfW efforts to continue saving water, considering that the soil quality has already been significantly impacted by IAPs novelty in up-surging soil nutrients and acidity. As a result, soil remediation through nutrient balancing and soil neutralisation is needed to limit the availability and accessibility of nutrients that promote IAPs regrowth and continuous spread (Figure 6.1). Decision-makers need to therefore, structure a novel rehabilitation strategy according to the stipulated *responses*, and this must involve the stakeholders' commitment if sustainable grassland and water availability can be sustained in these rural settlements in the Eastern Cape.

6.4 CONCLUDING REMARKS

According to Walmsley (2002), South Africa introduced a National Water Act (No. 36 of 1998) whose founding feature was for ensuring integrated water resource management for specified catchments by the catchment management agencies (CMAs). One of such bodies is WfW, established in 1995, and has been managing the negative impacts of IAPs on water resources and ecosystem services, using labour-intensive methods which contribute towards poverty alleviation (Macdonald 2004). Since the inception of WfW, large areas located primarily in the rural areas, have undergone clearing and follow-up treatment. However, an evaluation after 14 years of WfW operation at the QCs revealed that after IAPs control were done on small areas of large invaded areas, there were secondary invasions of the same invaders after clearing (Van Wilgen et al. 2012). The authors recommended a change of strategy to a more focused approach, which can be extracted from the key indicators outlined in the DPSIR framework developed for the QCs, which enclosed in itself:

- The crucial information required for the management of these QCs and the ability to compare between catchments and time.
- The ease of understanding while remaining analytically sound, scientifically valid and readily available to use (Walmsley 2002).
- All elements of sustainability, including social, economic and biophysical aspects of the catchment systems (Walmsley 2002).

Walmsley (2002) mentioned that indicators could be generically, developed for the management of catchments in South Africa, but the framework has the relevance for developing indicators for a single catchment. This single catchment management approach for the QCs, using a specific DPSIR framework design, captured the natural systems and forces acting on its sustainability. In conclusion, the framework covers the generic elements directly linked to this study (and some part of the overarching project), that are affecting the QCs health and further ensured that the management issues resulting from land use, water resource and soil quality are taken care of. A novel management scheme is expected to be developed from the framework, and integrated with the QCs management and sustainability. When strategically and duly implemented, the new management plan is ascertained to lower the degradation rate and speed up the system sustainability at landscape scales.

Nonetheless, the aim and objectives for this research were well attained, and the results obtained would support the efforts of the WFW and the overarching project. The research problem, which queried the success of various methods and methodologies selected in investigating the rangeland degradation, can as well be confirmed by the positive outcomes generated towards sustainability using DPSIR framework. The critical reflection must be directed to the extent of IAPs impacts (as well as anthropogenic impacts) that affected the ecosystem functionality of the study sites. Also, the high pH concentrations were noted to affect grassland reclamation and will affect any selected future land use option(s), as high pH contents were noted on both cleared and farm lands. And the development of the DPSIR framework, with its main purpose of proffering solutions to these problems, brings insights that sustainability can be achieved. The livelihoods of the farmers and the rural communities can be improved when strategized measures are put in place and well implemented. This, however, will certainly generate a management system where both the stakeholders and the decision-makers will be actively involved. As expected, the outcomes of this research will be employed by the policy- and decision-makers (WfW programme) in rehabilitating the grassland biome in the Eastern Cape and good results are envisaged to come out of the process. Lastly, this research will support aspiring researchers and scientists in their future works, in relation to any form of natural or man-made degradation in any region, worldwide.

Word Count: 41 219

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PERSONAL COMMUNICATIONS

Muller J 2015. Staff, Centre for Geographical Analysis (CGA), Stellenbosch University. Discussion on 15 February on OBIA classification and rule sets development.

Münch Z 2015. Lecturer (Supervisor), Department of geography and environmental studies, Stellenbosch University. Meeting on 12 March about land cover mapping and classification.

Ras B 2014. Soil analyst, Dohne agricultural development Institute. Stutterheim. Email on 14 November on status of soil analysis (WRC 3, 8, 9, 10).

APPENDICES

Appendix N	Indicator based approach for land cover conversion for the three QCs using NLC 2000
Appendix O	Indicator based approach for land cover conversion for the three QCs using ENLC 2000
Appendix P	Raw data on land cover areas (ha) filtered from the Reference State (NLC 2000) and Edited version (ENLC) for 2014 DLC

APPENDIX A

Soil sampling field datasheet & field report of soil sampling at
QC T35B and QC T12A

Table A. 1 Soil sampling field data sheet

Samplers	Signatures

Quaternary catchment	Site description/no	Date	Time of arrival	Time of departure

Photograph no	Vegetation type	Weather

Sample name	Time (GMT)	Depth	Tube material	Soil form	Topsoil clay %	Core no	GPS coordinates

Management system and comments
Non-personnel on-site and reason

METHOD /Non-standard equipment used	Deviations from intended scope of work
Additional notes	**Sketch of sampling location (include north arrows and sample names)**

(Sample name include codes/ names of quaternary catchment, site no, vegetation type and core no, e. g. T12A-1-C10-1)

Table A. 2 Field report of soil sampling at QC T35B cleared in 2005

Quaternary Catchment: T35B						
Site No: WRC03		**Clearing Date: 2005**				
Sample Name	**Site Status**	**Vegetation Type**	**Depth**	**Core No**	**Longitude**	**Latitude**
W031A	Cleared	A. dealbata/Grass	10cm	1A	-3101675	2814145
W031B	Cleared	A. dealbata/Grass	20cm	1B	-3101675	2814145
W032A	Cleared	A. dealbata/Grass	10cm	2A	-3101710	2814149
W032B	Cleared	A. dealbata/Grass	20cm	2B	-3101710	2814149
W033A	Cleared	A. dealbata/Grass	10cm	3A	-3101761	2814152
W033B	Cleared	A. dealbata/Grass	20cm	3B	-3101761	2814152
W034A	Invaded	A. dealbata/Grass	10cm	4A	-3101520	2814124
W034B	Invaded	A. dealbata/Grass	20cm	4B	-3101520	2814124
W035A	Invaded	A. dealbata/Grass	10cm	5A	-3101493	2814125
W035B	Invaded	A. dealbata/Grass	20cm	5B	-3101493	2814125
W036A	Invaded	A. dealbata/Grass	10cm	6A	-3101452	2814116
W036B	Invaded	A. dealbata/Grass	20cm	6B	-3101452	2814116
W037A	Uninvaded	Grass	10cm	7A	-3101457	2814158
W037B	Uninvaded	Grass	20cm	7B	-3101457	2814158
W038A	Uninvaded	Grass	10cm	8A	-3101482	2814166
W038B	Uninvaded	Grass	20cm	8B	-3101482	2814166
W039A	Uninvaded	Grass	10cm	9A	-3101524	2814187
W039B	Uninvaded	Grass	20cm	9B	-3101524	2814187

Cleared: Large expanse of cleared land with sloppy landscape, sampled at the strip of the catchment between stumps, adjacent to burnt and un-cleared areas but surrounded by natural grassland

- *Acacia dealbata* invaded, cleared in 2005, clearing debris undisposed, fenced catchment, presence of cow dungs
- Burnt stumps of felled IAPs with emerging grass cover, however natural attenuation taking place

Invaded: Dealbata canopy, fenced and presence of cow dungs (grazing)

Uninvaded: Flat plain natural grassland (predominant grasses in all catchments include *Sporobius africana*, *Eragiostus curvula*, *Themeda triandra*, *Heteropogon contortus, etc*).

- Fenced, presence of a graveyard, a small dam, horses, cows but no overgrazing and farming

Table A. 3 Field report n soil sampling at QC T35B cleared in 2004

Quaternary Catchment: T35B						
Site No: WRC08		**Clearing Date: 2004**				
Sample Name	**Site Status**	**Vegetation Type**	**Depth**	**Core No**	**Longitude**	**Latitude**
W081A	Cleared	A. mearnsii/Grass	10cm	1A	-310426	2817393
W081B	Cleared	A. mearnsii/Grass	20cm	1B	-310426	2817393
W082A	Cleared	A. mearnsii/Grass	10cm	2A	-3104243	2817377
W082B	Cleared	A. mearnsii/Grass	20cm	2B	-3104243	2817377
W083A	Cleared	A. mearnsii/Grass	10cm	3A	-3104231	2817357
W083B	Cleared	A. mearnsii/Grass	20cm	3B	-3104231	2817357
W084A	Invaded	A. mearnsii	10cm	4A	-310437	281665
W084B	Invaded	A. mearnsii	20cm	4B	-310437	281665
W085A	Invaded	A. mearnsii	10cm	5A	-3104376	2816664
W085B	Invaded	A. mearnsii	20cm	5B	-3104376	2816664
W086A	Invaded	A. mearnsii	10cm	6A	-310439	281669
W086B	Invaded	A. mearnsii	20cm	6B	-310439	281669
W087A	Uninvaded	Grass	10cm	7A	-310442	281672
W087B	Uninvaded	Grass	20cm	7B	-310442	281672
W088A	Uninvaded	Grass	10cm	8A	-31044	281672
W088B	Uninvaded	Grass	20cm	8B	-31044	281672
W089A	Uninvaded	Grass	10cm	9A	-3104381	2816724
W089B	Uninvaded	Grass	20cm	9B	-3104381	2816724

Cleared: *Acacia mearnsii* invaded, cleared in 2004, flat plain, high grass cover, grazing, cow dungs and stumps

Invaded: *A. mearnsii* invaded with thick understorey, 6m tree height, and low grass cover, no grazing, fenced

Uninvaded: Sloppy rangeland surrounded by burnt areas; cow dungs and grazing, no farming

Table A. 4 Filed report on soil at QCT12A cleared in

Quaternary Catchment: T12A						
Site No: WRC09		**Clearing Date: not confirmed**				
Sample Name	**Site Status**	**Vegetation Type**	**Depth**	**Core No**	**Longitude**	**Latitude**
W091A	Cleared	A. mearnsii/Grass	10cm	1A	-3131553	2746220
W091B	Cleared	A. mearnsii/Grass	20cm	1B	-3131553	2746220
W092A	Cleared	A. mearnsii/Grass	10cm	2A	-3131548	2746228
W092B	Cleared	A. mearnsii/Grass	20cm	2B	-3131548	2746228
W093A	Cleared	A. mearnsii/Grass	10cm	3A	-3131552	2746239
W093B	Cleared	A. mearnsii/Grass	20cm	3B	-3131552	2746239
W094A	Invaded	A. mearnsii	10cm	4A	-3131593	2746195
W094B	Invaded	A. mearnsii	20cm	4B	-3131593	2746195
W095A	Invaded	A. mearnsii	10cm	5A	-3131595	2746194
W095B	Invaded	A. mearnsii	20cm	5B	-3131595	2746194
W096A	Invaded	A. mearnsii	10cm	6A	-3131602	2746190
W096B	Invaded	A. mearnsii	20cm	6B	-3131602	2746190
W097A	Uninvaded	Grass	10cm	7A	-3131569	2746232
W097B	Uninvaded	Grass	20cm	7B	-3131569	2746232
W098A	Uninvaded	Grass	10cm	8A	-3131572	2746239
W098B	Uninvaded	Grass	20cm	8B	-3131572	2746239
W099A	Uninvaded	Grass	10cm	9A	-3131577	2746250
W099B	Uninvaded	Grass	20cm	9B	-3131577	2746250

Cleared: *A. mearnsii* invaded, cleared but regrowth of *A. mearnsii*; excluded, presence of stumps and grazing

Invaded: *A. mearnsii* invaded, no understorey, little or no grass cover, no grazing
Uninvaded: Close proximity to the 'invaded', no grazing, no farming, excluded

Table A. 5 Field report on soil sampling at QC T12A cleared in

Quaternary Catchment: T12A

Site No: WRC10		Clearing Date: not confirmed				
Sample Name	**Site Status**	**Vegetation Type**	**Depth**	**Core No**	**Longitude**	**Latitude**
W101A	Cleared	A. mearnsii/Grass	10cm	1A	-3131446	2745735
W101B	Cleared	A. mearnsii/Grass	20cm	1B	-3131446	2745735
W102A	Cleared	A. mearnsii/Grass	10cm	2A	-3131460	2745751
W102B	Cleared	A. mearnsii/Grass	20cm	2B	-3131460	2745751
W103A	Cleared	A. mearnsii/Grass	10cm	3A	-3131464	2745768
W103B	Cleared	A. mearnsii/Grass	20cm	3B	-3131464	2745768
W104A	Invaded	A. mearnsii	10cm	4A	-3131380	2745664
W104B	Invaded	A. mearnsii	20cm	4B	-3131380	2745664
W105A	Invaded	A. mearnsii	10cm	5A	-3131364	2745656
W105B	Invaded	A. mearnsii	20cm	5B	-3131364	2745656
W106A	Invaded	A. mearnsii	10cm	6A	-3131353	2745654
W106B	Invaded	A. mearnsii	20cm	6B	-3131353	2745654
W107A	Uninvaded	Grass/Cultivated	10cm	7A	-3131459	2745584
W107B	Uninvaded	Grass/Cultivated	20cm	7B	-3131459	2745584
W108A	Uninvaded	Grass/Cultivated	10cm	8A	-3131450	2745590
W108B	Uninvaded	Grass/Cultivated	20cm	8B	-3131450	2745590
W109A	Uninvaded	Grass/Cultivated	10cm	9A	-3131438	2745590
W109B	Uninvaded	Grass/Cultivated	20cm	9B	-3131438	2745590

Cleared: *A. mearnsii invaded,* cleared, high grass cover, small degree of reinvasion, close to a school.
Invaded: Thick understorey of *A. mearnsii* with some clearing, close to 'cleared'
Uninvaded: Grassland, no farming, surrounded by *A. mearnsii,* no much grazing, old cultivated land

APPENDIX B

Soil analytical results

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Date: 09 February 2015

WO31A	D1211	1.04	16	231	572	28	3.54	7.22	49	3.78	1.4	0.21
WO31B	D1212	1.11	9	132	364	10	4.17	6.4	65	3.6	0.5	0.14
WO32A	D1213	1.1	19	144	470	15	3.65	6.48	56	3.68	1.9	0.19
WO32B	D1214	1.12	11	95	302	0	3.83	5.58	69	3.5	1.2	0.16
WO33A	D1215	1.15	25	125	162	0	5.02	6.14	82	3.5	0.7	0.16
WO33B	D1216	1.15	7	62	189	0	4.41	5.5	80	3.53	0.8	0.20
WO34A	D1217	1.24	18	228	196	0	3.91	5.47	71	3.59	0.5	0.23
WO34B	D1218	1.2	3	100	106	0	3.19	3.97	80	3.82	0.1	0.13
WO35A	D1219	1.23	26	176	410	54	2.91	5.84	50	3.66	1	0.21
WO35B	D1220	1.26	5	74	201	31	2.94	4.39	67	3.77	0	0.17

WO36A	D1221	1.16	14	119	184	0	3.73	4.94	75	3.51	1	0.23
WO36B	D1222	1.2	2	37	54	0	3.51	3.87	91	3.67	0	0.12
WO37A	D1223	1.23	16	106	260	0	1.84	3.41	54	3.99	1.3	0.15
WO37B	D1224	1.21	7	15	316	0	1.84	3.46	53	4.06	0.1	0.13
WO38A	D1225	1.2	19	196	330	9	1.89	4.1	46	4.04	1.1	0.15
WO38B	D1226	1.21	12	88	206	0	2.5	3.75	67	3.9	0.1	0.12
WO39A	D1227	1.13	9	215	479	120	0.71	4.64	15	4.2	0.1	0.19
WO39B	D1228	1.08	3	151	242	44	1.6	3.56	45	4.09	0	0.15
WO81A	D1229	1.12	6	25	105	0	3.82	4.41	87	3.76	0	0.12
WO81B	D1230	1.15	1	18	71	0	2.9	3.3	88	4.02	0	0.12
WO82A	D1231	1.11	22	32	199	0	4.41	5.47	80	3.71	0	0.16
WO82B	D1232	1.12	4	15	82	0	3.94	4.39	90	3.9	0	0.14
WO83A	D1233	1.1	16	110	224	0	3.12	4.52	69	3.83	0	0.22
WO83B	D1234	1.2	3	48	54	0	3.3	3.69	89	3.96	0	0.12
WO84A	D1235	9.5	22	105	151	0	5.85	6.86	85	3.61	0	0.20
WO84B	D1236	1.02	6	25	82	0	4.72	5.19	91	3.79	0	0.20
WO85A	D1237	9.2	31	124	168	0	5.41	6.57	82	3.64	0	0.30
WO85B	D1238	1.03	8	37	80	0	4.64	5.13	90	3.78	0	0.17
WO86A	D1239	1.02	26	144	274	0	5.39	7.13	76	3.63	0	0.24
WO86B	D1240	1.03	4	118	69	0	5.47	6.13	89	3.74	0	0.24
WO87A	D1241	1.01	7	120	311	57	2.78	5.11	54	3.99	0	0.23
WO87B	D1242	9.9	7	79	212	15	3.12	4.5	69	3.94	0	0.20
WO88A	D1243	1.01	9	221	889	101	1.52	7.35	21	4.26	1.2	0.24
WO88B	D1244	1.03	4	147	572	58	2.2	5.91	37	4.22	6.7	0.19
WO89A	D1245	9.8	7	240	625	86	2.44	6.88	35	4.09	1.2	0.28
WO89B	D1246	1.04	4	165	411	43	3.16	5.99	53	4.05	1.7	0.24
WO91A	D1247	1.23	3	78	390	50	1.82	4.38	42	4	2.1	0.19
W091B	D1248	1.22	4	48	289	29	2.76	4.56	60	3.84	0.9	0.17
WO92A	D1249	1.18	6	74	645	126	1.38	5.82	24	4.07	1.9	0.23
WO92B	D1250	1.22	5	71	272	23	2.79	4.52	62	3.88	3.4	0.19
WO93A	D1251	1.17	4	80	528	54	1.5	4.78	31	3.93	3.2	0.22

WO93B	D1252	1.22	3	54	297	14	2.47	4.2	59	3.89	2.5	0.17
WO94A	D1253	1.15	6	278	845	159	0.84	7.08	12	4.11	2.8	0.28
WO94B	D1254	1.18	3	151	380	120	2.26	5.53	41	3.82	1.3	0.19
WO95A	D1255	1.24	9	162	576	51	3.83	7.53	51	3.68	1.9	0.26
WO95B	D1256	1.23	5	199	471	248	2.68	7.58	35	3.92	1.2	0.21
WO96A	D1257	1.2	16	215	300	41	3.04	5.42	56	3.6	1.6	0.23
WO96B	D1258	1.24	3	88	261	125	2.28	4.84	47	3.85	1.3	0.21
WO97A	D1259	1.21	4	86	311	43	2.22	4.35	51	3.96	1	0.18
WO97B	D1260	1.19	3	96	464	109	1.63	5.09	32	4.08	2.1	0.20
WO98A	D1261	1.24	4	60	326	39	4.07	6.17	66	3.67	1.3	0.16
WO98B	D1262	1.24	3	58	318	39	4	6.06	66	3.55	1.1	0.15
WO99A	D1263	1.21	8	70	362	69	3.37	5.92	57	3.62	1.9	0.18
WO99B	D1264	1.26	5	58	258	28	4.32	5.99	72	3.47	0.7	0.16
WO101A	D1265	1.21	25	125	319	33	4.93	7.1	69	3.33	2.6	0.25
WO101B	D1266	1.21	3	161	544	85	4.11	7.94	52	3.5	2.6	0.18
WO102A	D1267	1.17	22	171	453	43	4.68	7.73	61	3.37	2.7	0.27
WO102B	D1268	1.23	28	132	312	42	4.01	6.25	64	3.38	2.6	0.19
WO103A	D1269	1.17	28	119	265	23	5	6.82	73	3.31	2.3	0.27
WO103B	D1270	1.29	7	146	769	127	2.56	7.82	33	3.59	4.4	0.18
WO104A	D1271	1.24	23	198	1164	143	1.11	8.59	13	4.14	13.4	0.27
WO104B	D1272	1.35	13	181	573	93	1.76	5.85	30	3.89	9.3	0.19
WO105A	D1273	1.38	122	95	213	24	4.83	6.32	76	3.39	7.8	0.20
WO105B	D1274	1.37	151	63	227	27	5.25	6.76	78	3.35	13.7	0.18
WO106A	D1275	1.38	26	129	311	46	4.78	7.04	68	3.49	25.7	0.20
WO106B	D1276	1.34	4	133	239	34	3.28	5.09	64	6.55	2.7	0.14
WO107A	D1277	1.29	23	101	284	66	3.84	6.06	63	3.54	15.6	0.18
WO107B	D1278	1.26	3	84	363	61	2.57	5.09	50	3.77	1.8	0.13
WO108A	D1279	1.36	5	214	331	68	2.28	5.04	45	3.78	19.5	0.14
WO108B	D1280	1.28	3	100	224	28	2.47	4.06	61	3.71	6.7	0.13
WO109A	D1281	1.33	3	157	413	60	1.45	4.4	33	3.92	5.9	0.16
WO109B	D1282	1.3	3	154	528	98	1.53	5.36	28	3.88	5.1	0.15

APPENDIX C

WRC-site 3: Nutrient variations across treatments and depths with the mean values visible by the boxplots

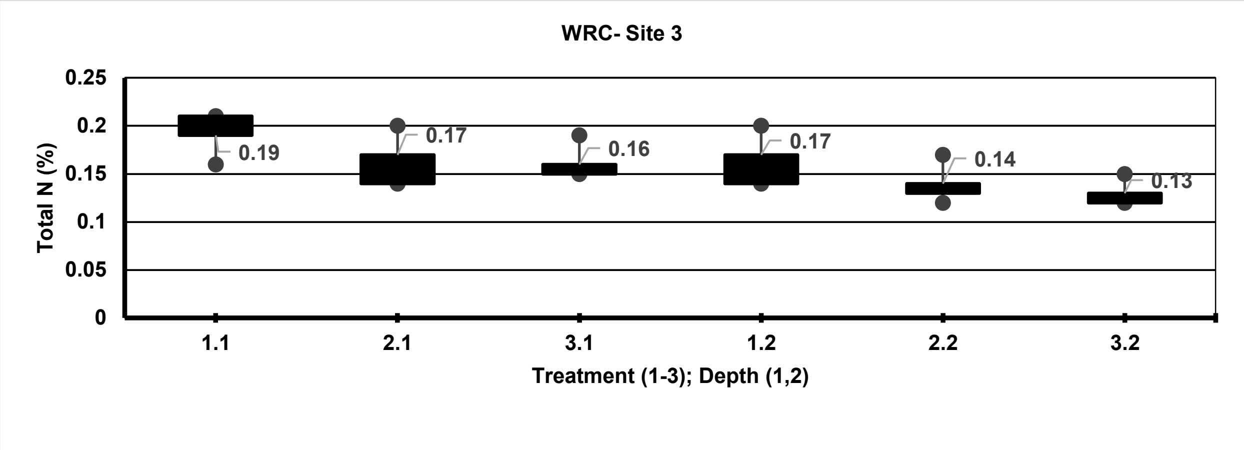

Figure C. 1Total nitrogen (N) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths at WRC– Site 3

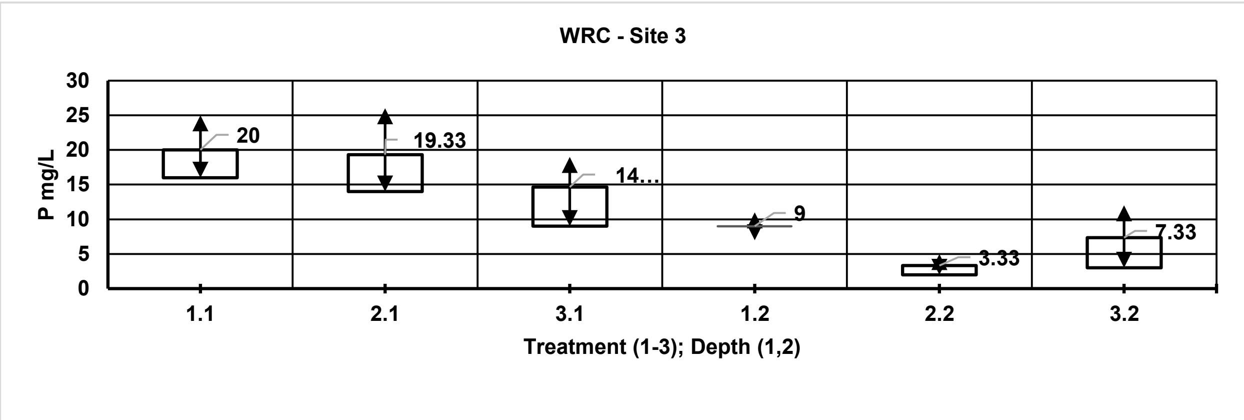

Figure C. 2 Phosphorus (P) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3

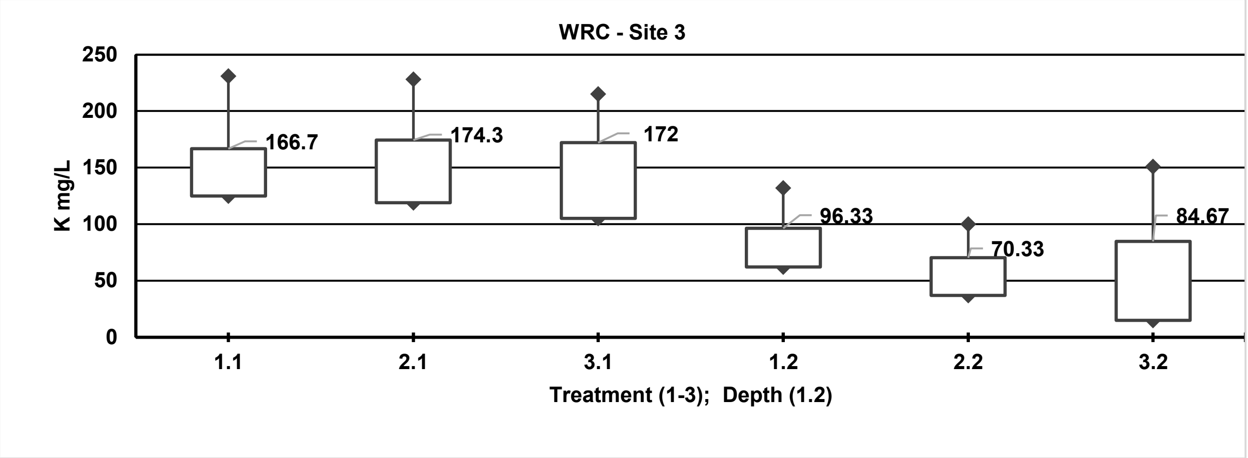

Figure C. 3 Potassium (K) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3

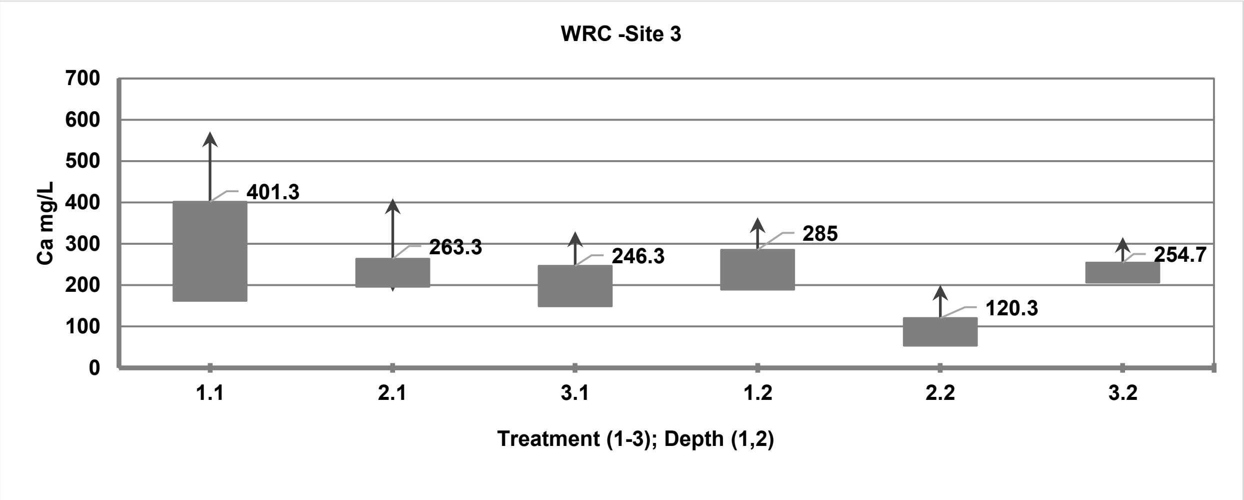

Figure C. 4 Calcium (Ca) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3

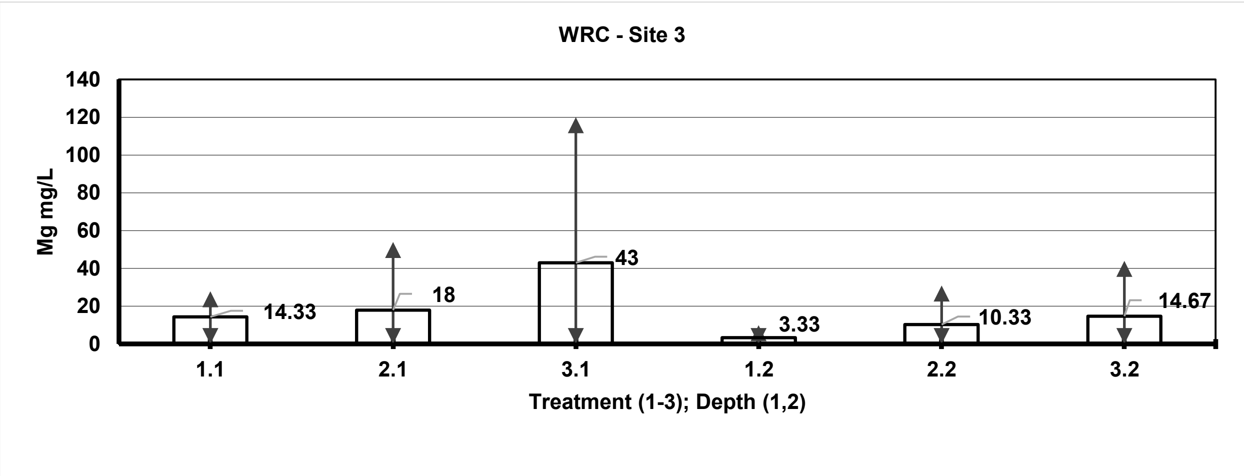

Figure C. 5 Magnesium (Mg) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC–Site 3

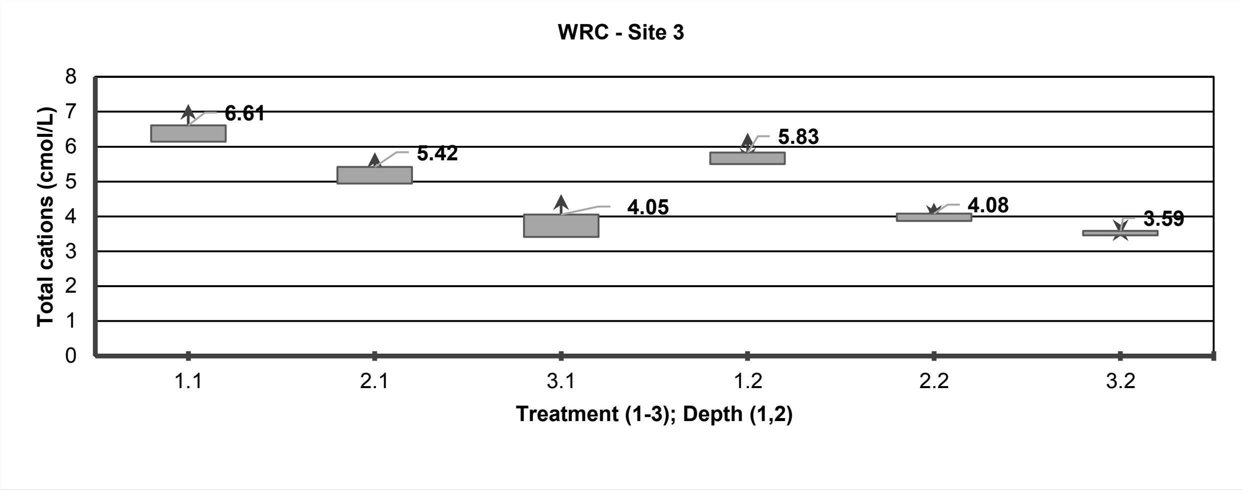

Figure C. 6 Total cations variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

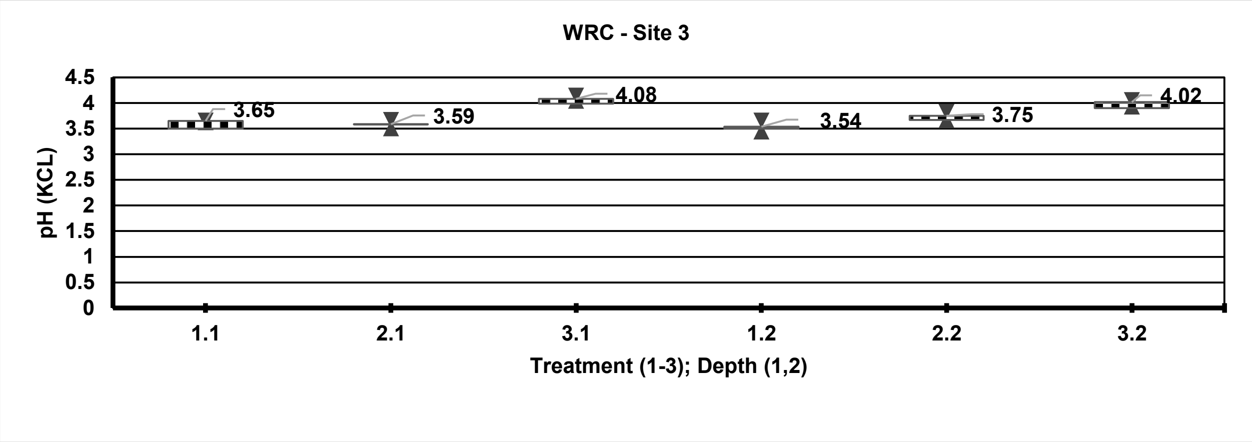

Figure C. 7 Soil pH variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

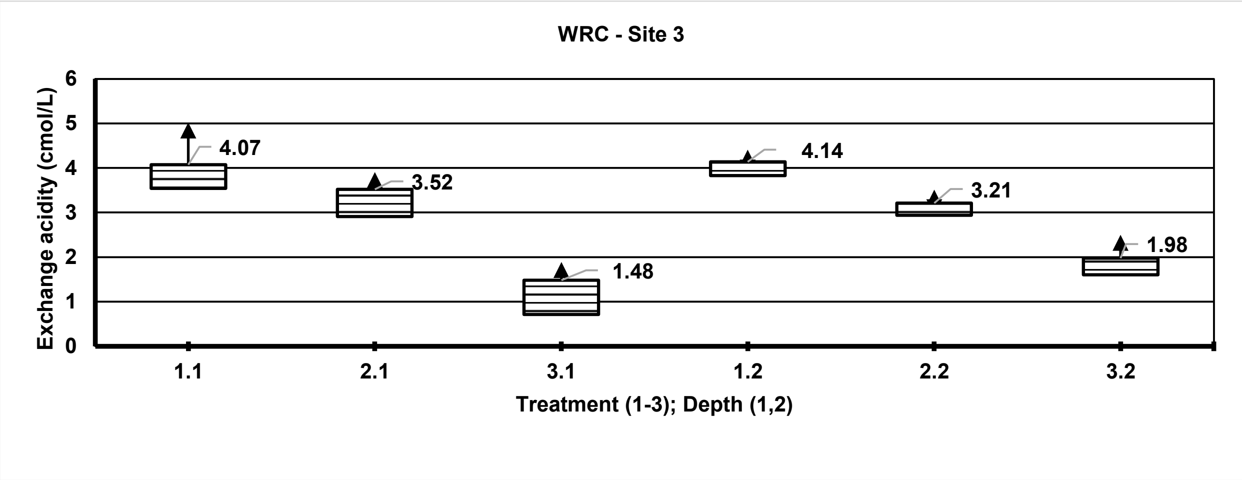

Figure C. 8 Exchange acidity variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

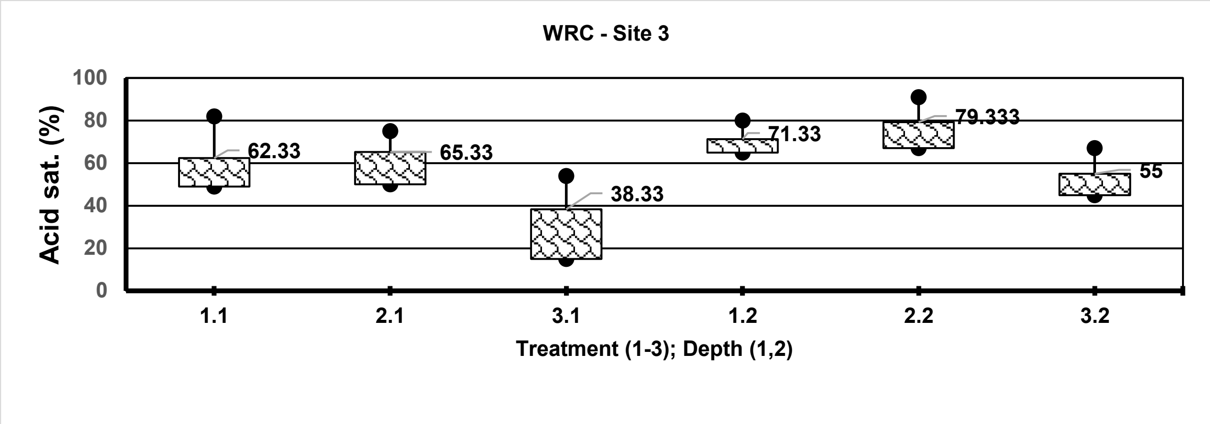

Figure C. 9 Acid saturation variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

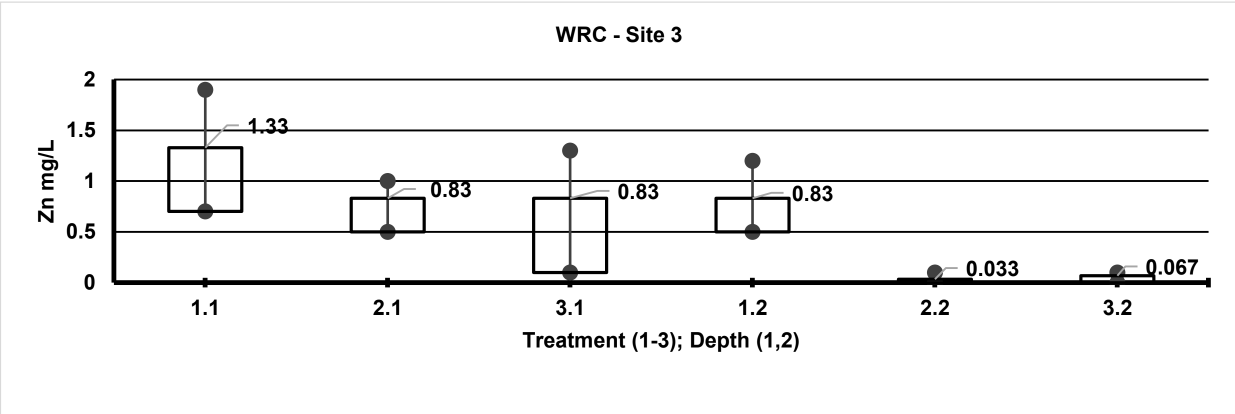

Figure C. 10 Zinc (Zn) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

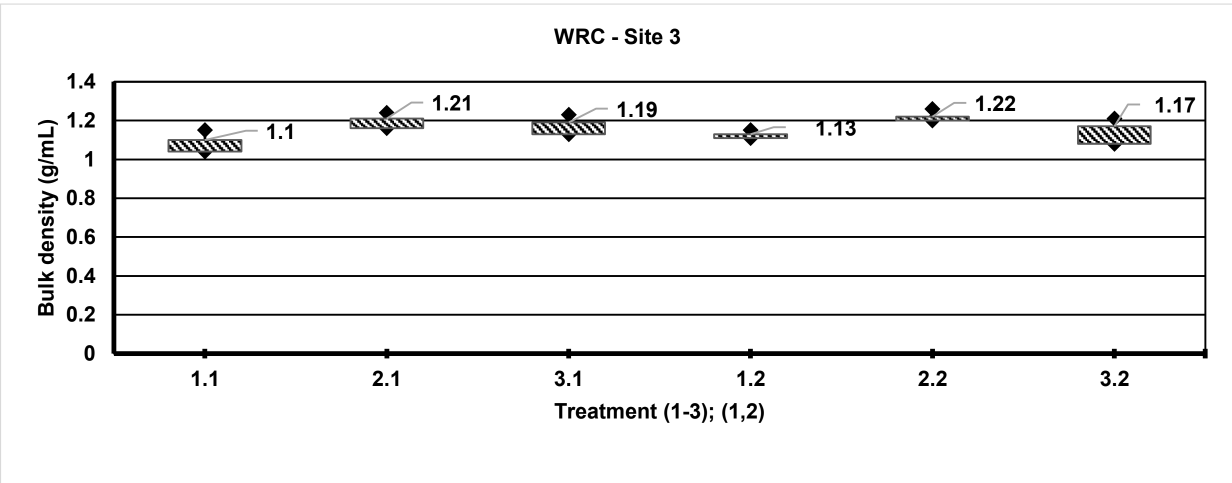

Figure C. 11Bulk density Variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 3.

Table C 1 Exploratory summary of the statistical variability of nutrients across treatments and depths showing the mean, standard error, significance value, maximum and minimum values in WRC-site 3

Variable	1.1 Cleared A			2.1 Invaded B			3.1 Uninvaded C			1.2 Cleared D			2.2 Invaded E			3.2 Uninvaded F			P-value
	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	
Macronutrients																			
Nitrogen	0.17 ± 0.014	0.21	0.16	0.17±0.018	0.21	0.14	0.16 ±0.014	0.21	0.14	0.17±0.018	0.2	0.14	0.14±0.016	0.17	0.12	0.13±0.0089	0.15	0.12	P>0.05
Phosphorus	20±2.65^{a}	25	16	19.3±3.52^{b}	26	14	14.7±2.97	19	9	9±1.15	11	7	3.33±0.88^{ab}	5	2	7.33±2.60	12	3	P<0.001
Potassium	166.7±32.63	231	125	174.3±31.4	228	119	172±33.9	215	105	96.3±20.21	132	62	70.33±18.28	100	37	84.67±29.30	151	15	p>0.05
Calcium	401.3±123.24	572	162	263.3±73.42	410	184	246.3±52.70	330	149	285±51.23	364	189	120.3±43.04	201	54	254.7±32.38	316	206	P>0.05
Magnesium	14.33±8.09	28	0	18±18	54	0	43±38.59	120	0	3.33±3.33	10	0	10.33±10.33	31	0	14.67±14.67	44	0	P>0.05
Micronutrient																			
Zinc	1.33±0.35^{ab}	1.9	0.7	0.83±0.17	1	0.5	0.83±0.37	1.3	0.1	0.83±0.20	1.2	0.5	0.033±0.033^{a}	0.1	0	0.067±0.033^{b}	0.1	0	P<0.01
Other variables																			
pH	3.65±0.082^{fg}	3.78	3.5	3.59±0.04^{de}	3.66	3.51	4.077±0.06^{bcdf}	4.2	3.99	3.54±0.030^{ac}	3.6	3.5	3.75±0.044^{b}	3.82	3.67	4.02±0.059^{aeg}	4.09	3.9	P<0
Total cations	6.61±0.32^{efg}	7.22	6.14	5.42±0.26^{d}	5.84	4.94	4.05±0.36^{ce}	4.64	3.41	5.83±0.29^{abc}	6.4	5.5	4.08±0.16^{be}	4.39	3.87	3.59±0.085^{adf}	3.75	3.46	P<0
Exchange acidity	4.07±0.48^{ef}	5.02	3.54	3.52±0.31^{d}	3.91	2.91	1.48±0.39^{bcde}	1.89	0.71	4.14±0.17^{ab}	4.41	3.83	3.21±0.16^{c}	3.51	2.94	1.98±0.27^{af}	2.5	1.6	P<0
Acid saturation	62.33±10.03	82	49	65.33±7.75	75	50	38.33±11.89	54	15	71.33±4.48	80	65	79.33±6.94	91	67	55±6.43	67	45	P>0.05
Sample density	1.097±0.032	1.15	1.04	1.21±0.025	1.24	1.16	1.17±0.030	1.23	1.13	1.13±0.012	1.15	1.11	1.22±0.02	1.26	1.2	1.17±0.043	1.21	1.08	p>0.05

APPENDIX D

WRC-site 8: Nutrient variations across treatments and depths with the mean values visible by the boxplots

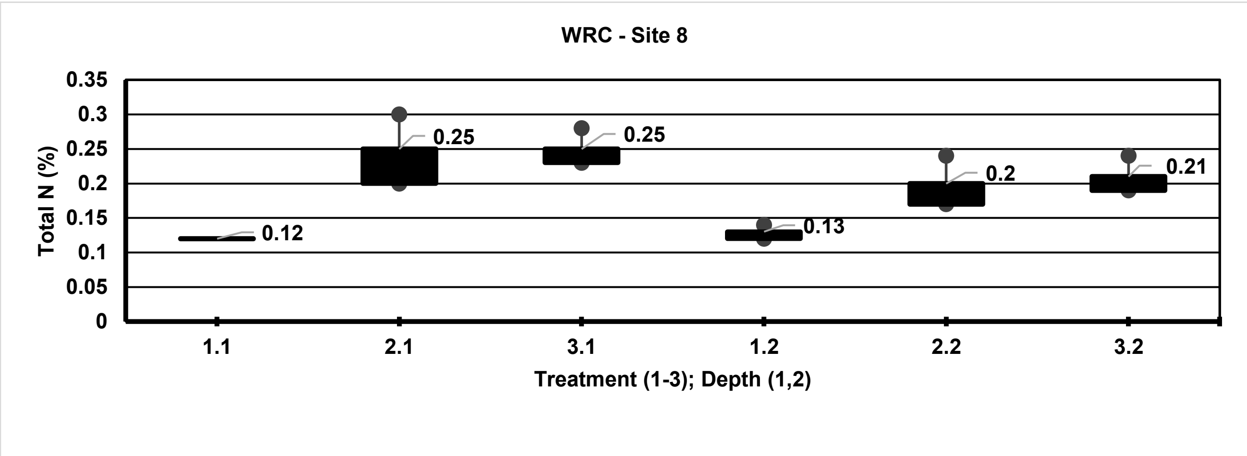

Figure D. 1Total nitrogen (N) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

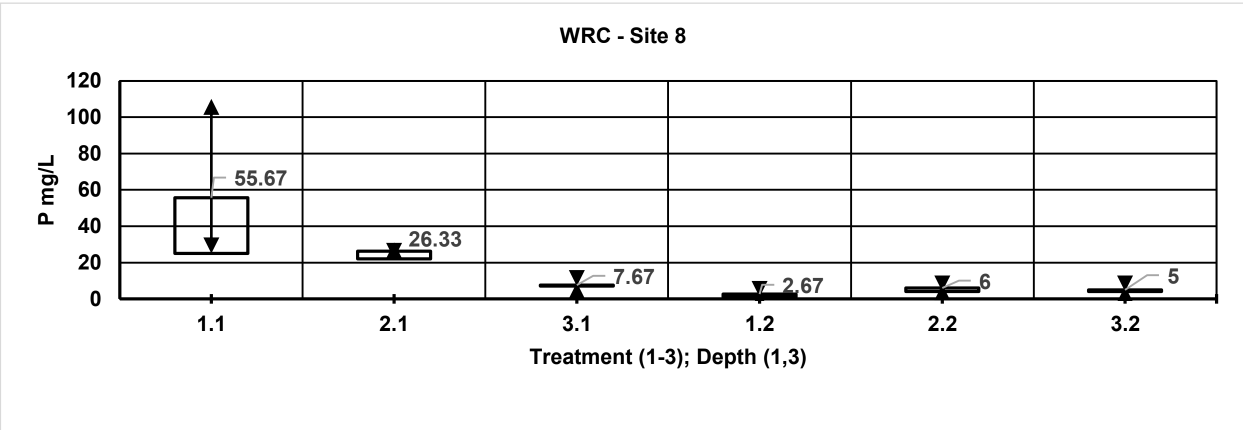

Figure D. 2 Phosphorus (P) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8

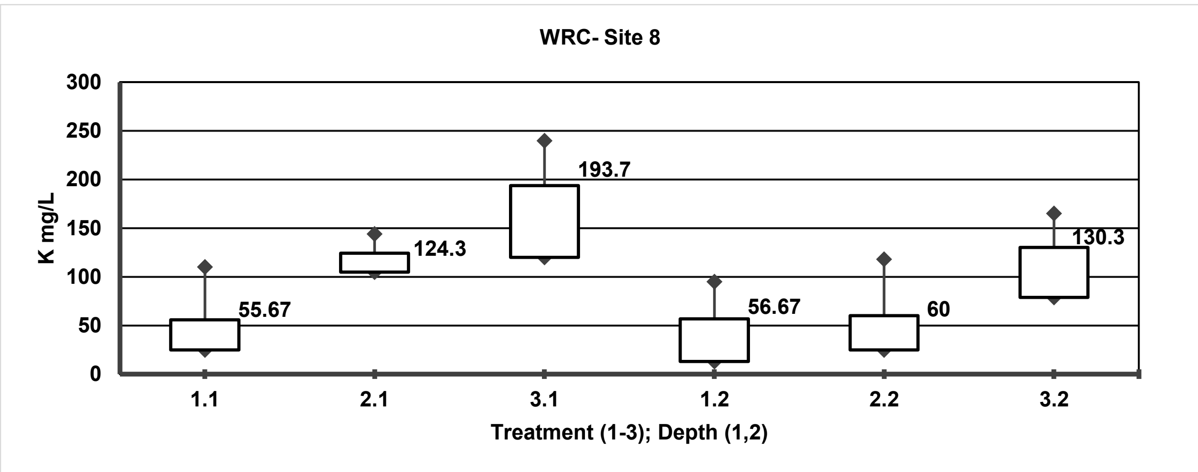

Figure D. 3 Potassium (K) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

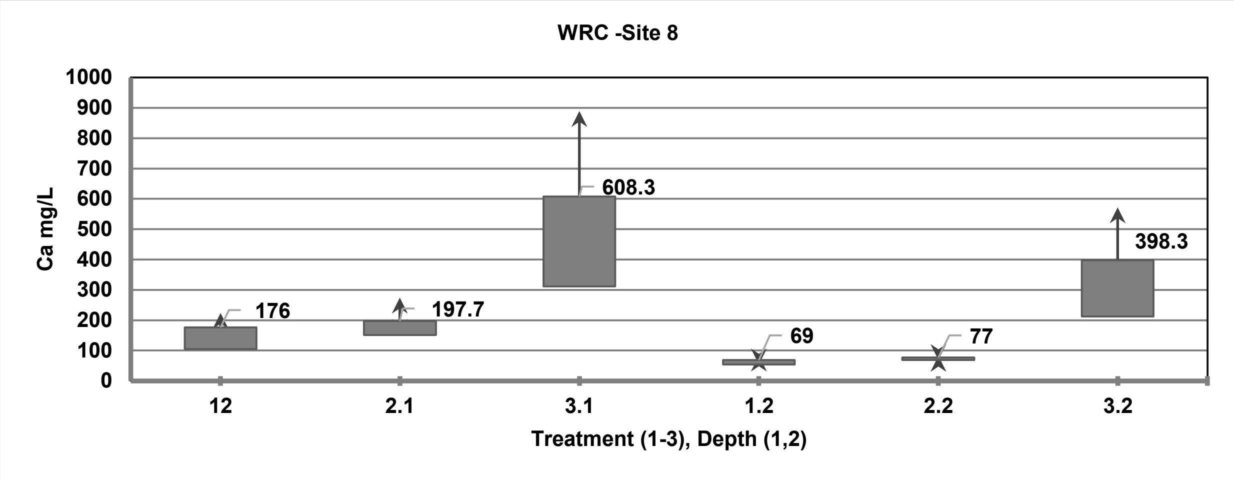

Figure D. 4 Calcium (Ca) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

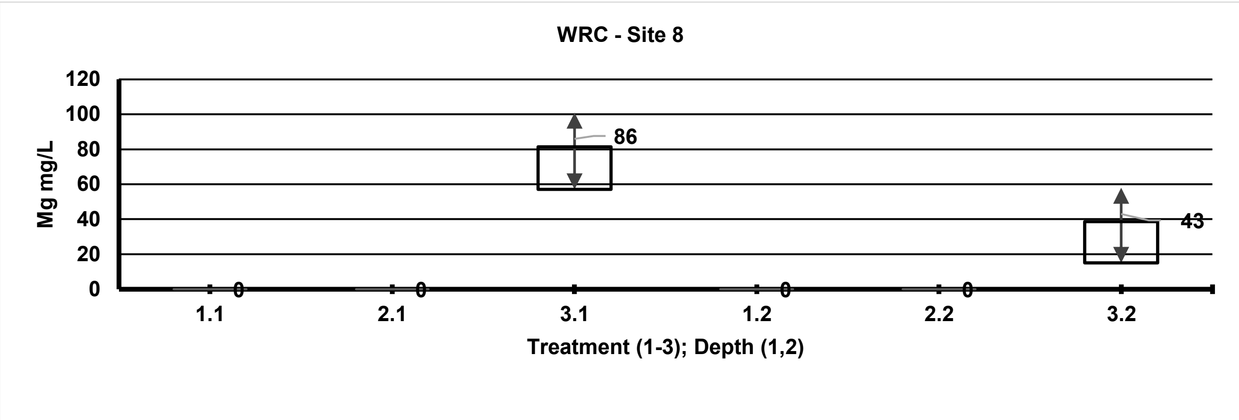

Figure D. 5 Magnesium (Mg) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC–Site 8

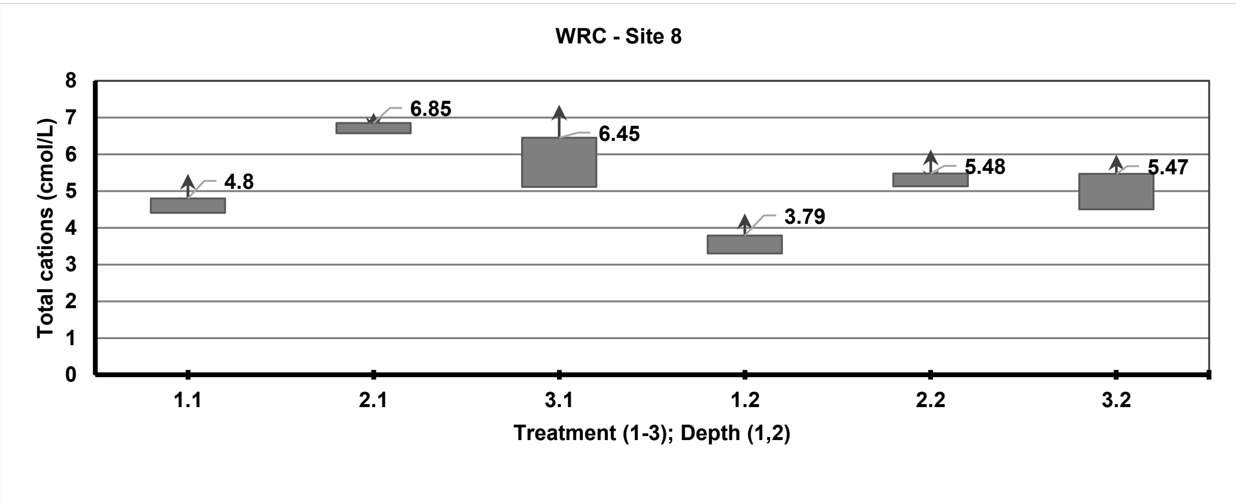

Figure D. 6 Total cations variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

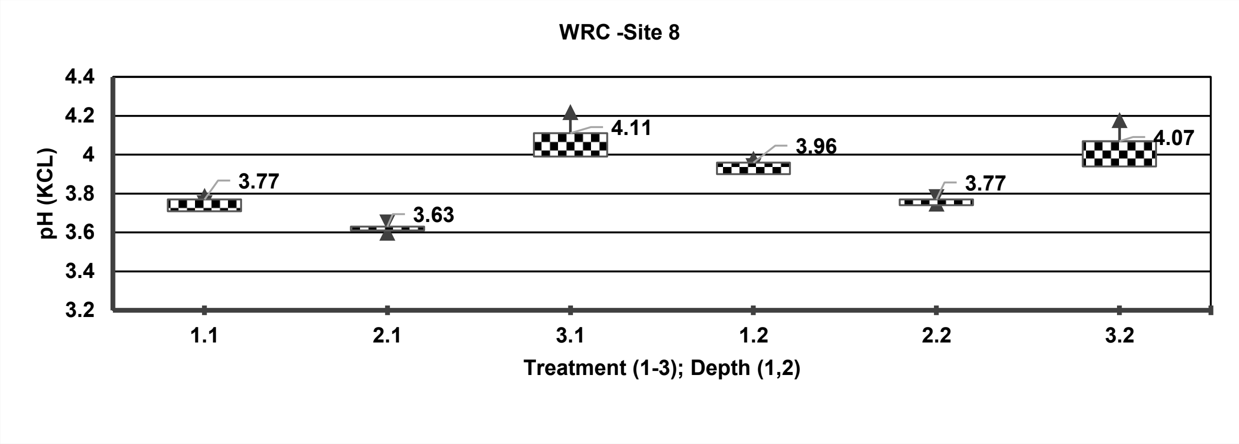

Figure D. 7 Soil pH variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

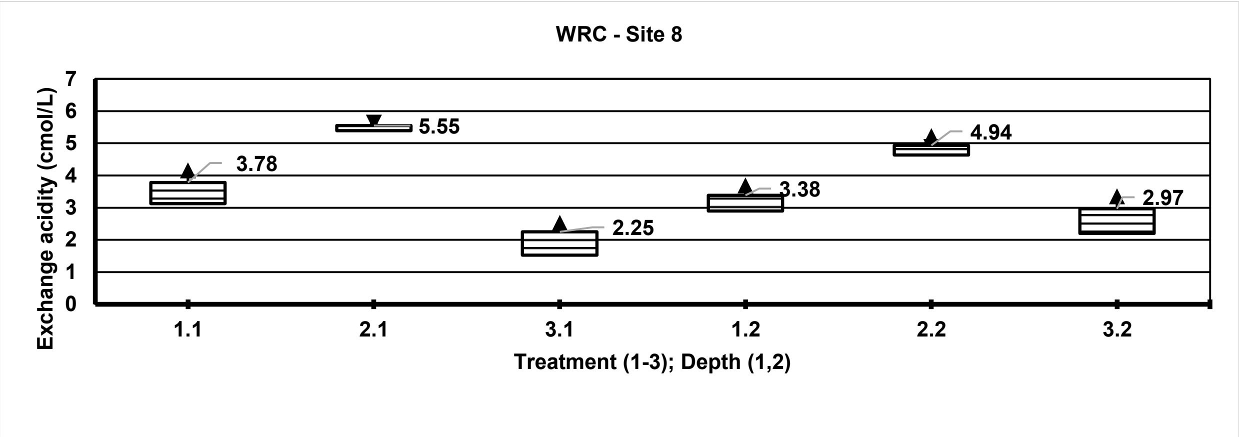

Figure D. 8 Exchange acidity variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

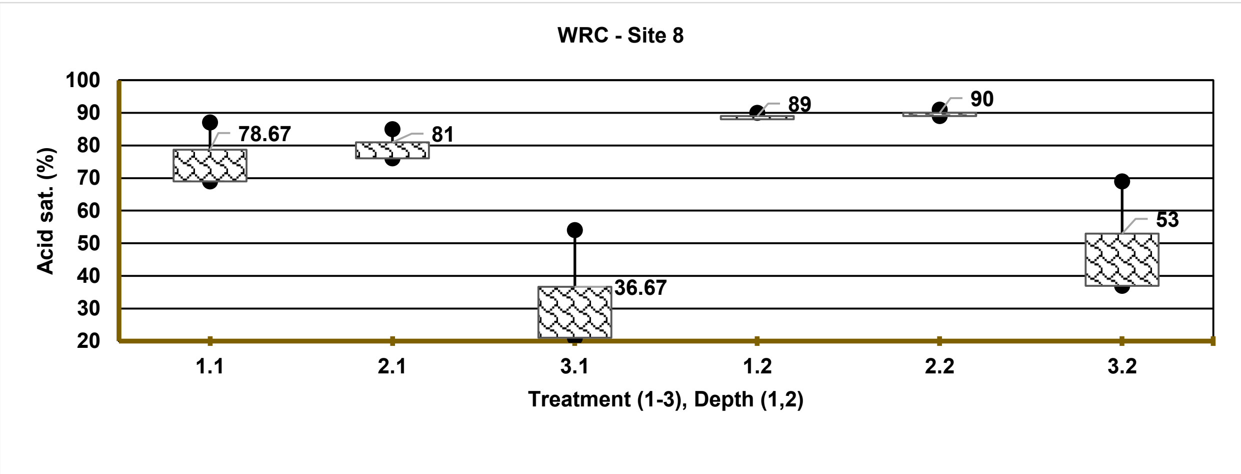

Figure D. 9 Acid saturation variability on cleared, invaded and uninvaded treatments with 10 cm and 20 cm depths in WRC– Site 8.

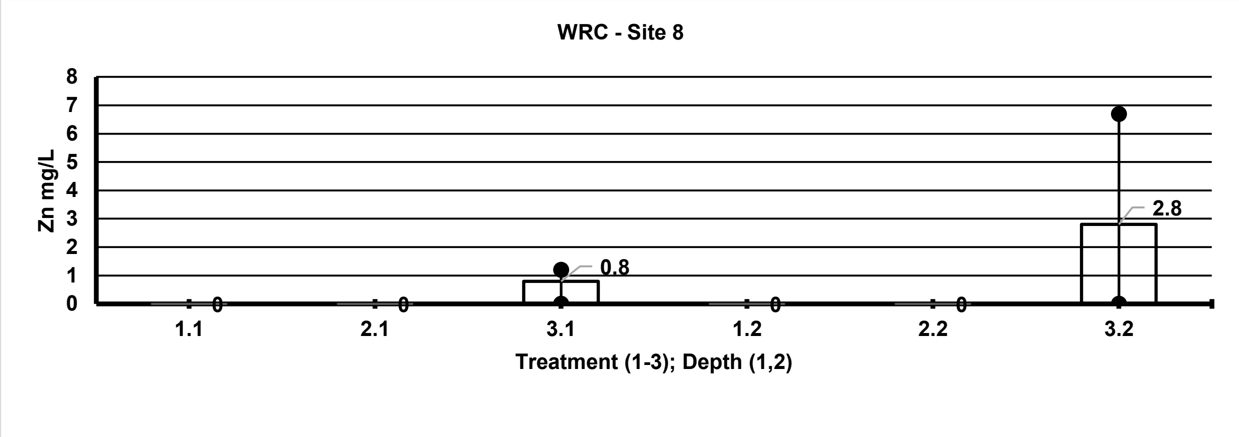

Figure D. 10 Zinc (Zn) variability on cleared, invaded and uninvaded treatments at10 cm and 20 cm depths in WRC– Site 8.

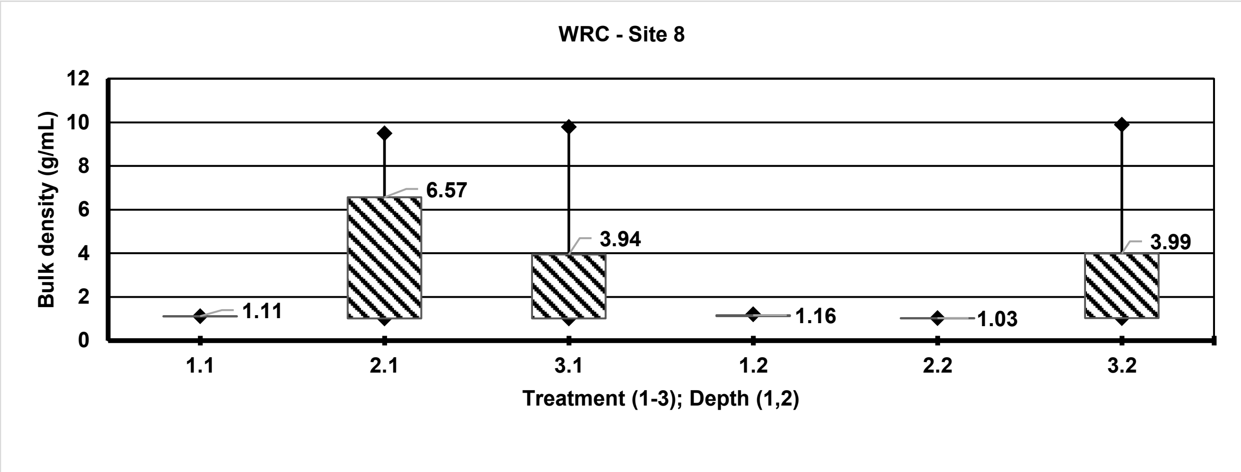

Figure D. 11 Bulk density variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 8.

Table D 1 Exploratory summary of the statistical variability of nutrients across treatments and depths showing the mean, standard error, significance value, maximum and minimum values in WRC-site 8

Treatment = 1-3; Depth = 1(A-C), 2 (D-F)

Variable	**1.1 Cleared A**			**2.1 Invaded B**			**3.1 Uninvaded C**			**1.2 Cleared D**			**2.2 Invaded E**			**3.2 Uninvaded F**			**P-value**
	Mean ±S.E	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	**Mean ±S.E**	**Max**	**Min**	
Macronutrients																			
Nitrogen	0.12±0^{cde}	0.12	0.12	0.25±0.029^{bc}	0.3	0.2	0.25±0.015^{ad}	0.28	0.23	0.13±0.007^{ab}	0.14	0.12	0.20±0.020	0.24	0.17	0.21±0.015^{e}	0.24	0.19	P<0
Phosphorus	55.67±27.24^{a}	110	25	26.33±2.60	31	22	7.67±0.67	9	7	2.67±0.88^{a}	4	1	6±1.15	8	4	5±1	7	4	P<0.05
Potassium	55.67±27.24^{b}	110	25	124.3±11.26	144	105	193.7±37.24^{ab}	240	120	56.67±23.82^{a}	95	13	60±29.21	118	25	130.3±26.19	165	79	P<0.05
Calcium	176±36.23^{a}	224	105	197.7±38.48	274	151	608.3±167.1^{abc}	889	311	311±8.14^{b}	82	54	77±4.04^{c}	82	69	398.3±104.1	572	212	P<0.01
Magnesium	0±0^{hi}	0	0	0±0^{fg}	0	0	81.33±12.91^{cdefh}	101	57	0±0^{bc}	0	0	0±0^{ad}	0	0	38.67±12.60^{abegi}	58	15	P<0
Micronutrient																			
Zinc	0±0	0	0	0±0	0	0	0.8±0.4	1.2	0	0±0	0	0	0±0	0	0	2.8±2.01	6.7	0	P>0.05
Other variables																			
pH	3.77±0.035^{fg}	3.83	3.71	3.63±0.009^{cde}	3.64	3.61	4.11±0.079^{bcf}	4.26	3.99	3.96±0.035^{d}	4.02	3.9	3.77±0.015^{a}	3.79	3.74	4.07±0.081^{abeg}	4.22	3.94	P<0
Total cations	4.8±0.34	5.47	4.41	6.85±0.16^{b}	7.13	6.57	6.45±0.68^{a}	7.35	5.11	3.79±0.32^{ab}	4.39	3.3	5.48±0.32	6.13	5.13	5.47±0.48	5.99	4.5	P<0.01
Exchange acidity	3.78±0.37^{c}	4.41	3.12	5.55±0.15^{b}	5.85	5.39	2.25±0.38	2.78	1.52	3.38±0.30^{a}	3.94	2.9	4.94±0.26	5.47	4.64	2.97±0.41^{abc}	3.6	2.2	P<0
Acid saturation	78.67±5.24^{f}	87	69	81±2.65^{e}	85	76	36.67±9.56^{cdef}	54	21	89±0.58^{bc}	90	88	90±0.58^{a}	91	89	53±9.24^{afdb}	69	37	P<0
Sample density	1.11±0.006	1.12	1.1	6.57±2.78	9.5	1.02	3.94±2.93	9.8	1.01	1.16±0.023	1.2	1.12	1.027±0.003	1.03	1.02	3.99±2.96	9.9	1.03	P>0.05

Similar letters indicate means that are significantly different (P<0, 0.001, 0.01, 0.05)

P<0, P<0.001, P<0.01	= highly significant difference
P<0.05	=significance difference
P>0.05	= no significance difference

APPENDIX E

WRC-site 9: Nutrient variations across treatments and depths with the mean values visible by the boxplots

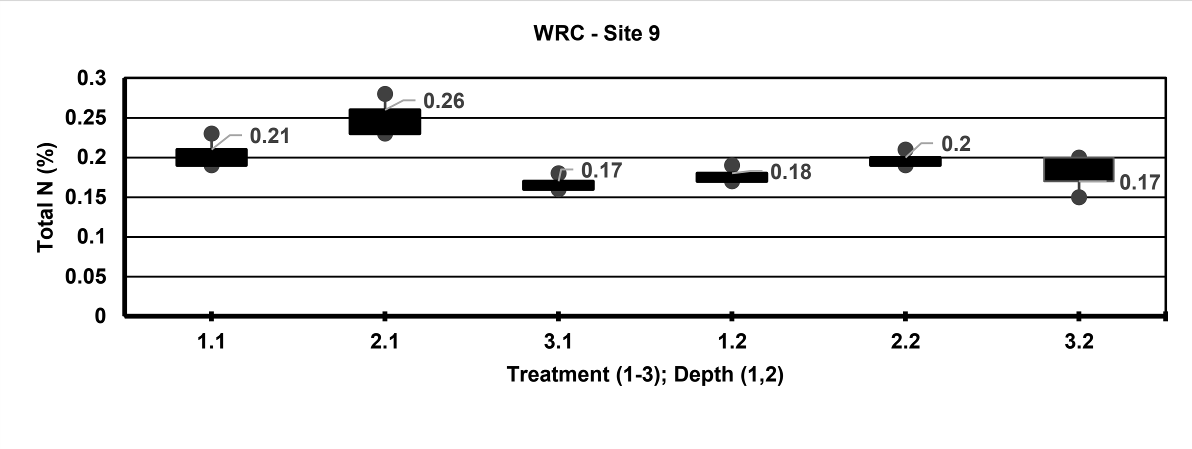

Figure E 1Total nitrogen (N) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

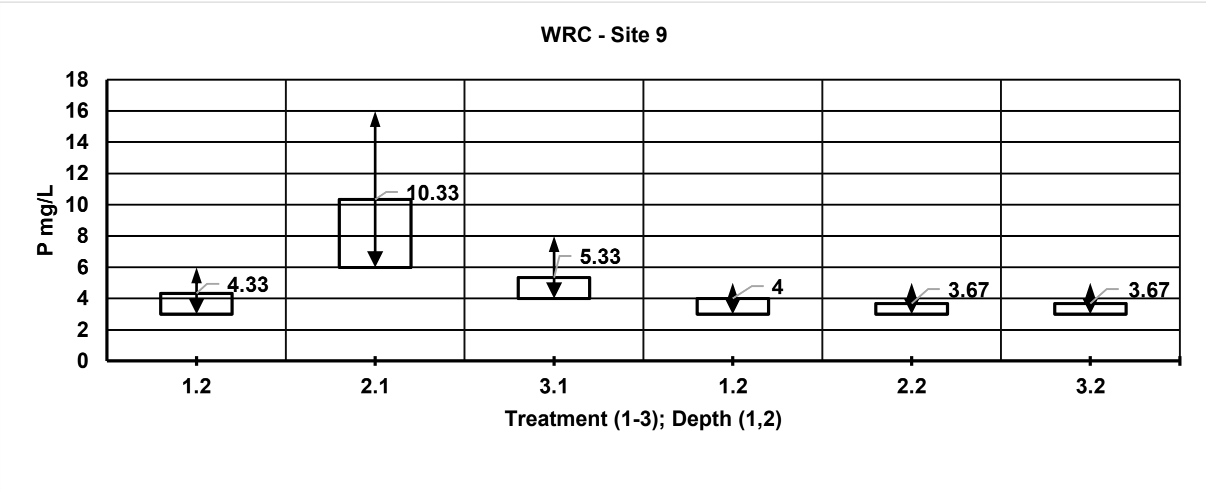

Figure E 2 Phosphorus (P) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9.

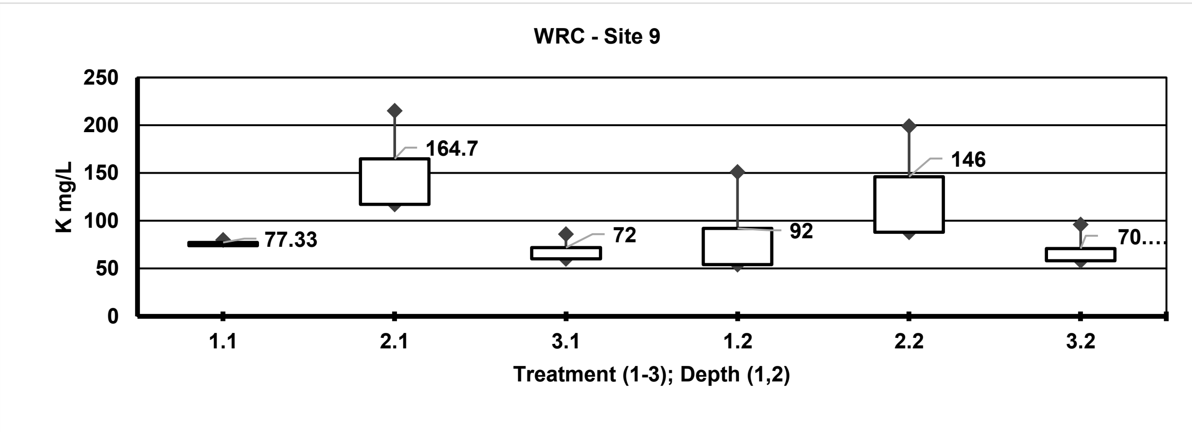

Figure E 3 Potassium (K) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9.

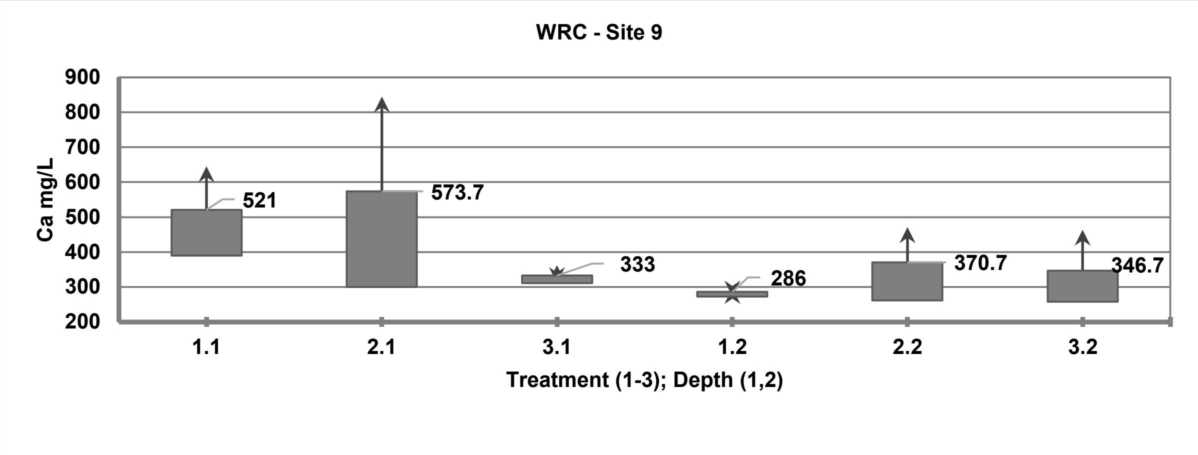

Figure E 4 Calcium (Ca) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

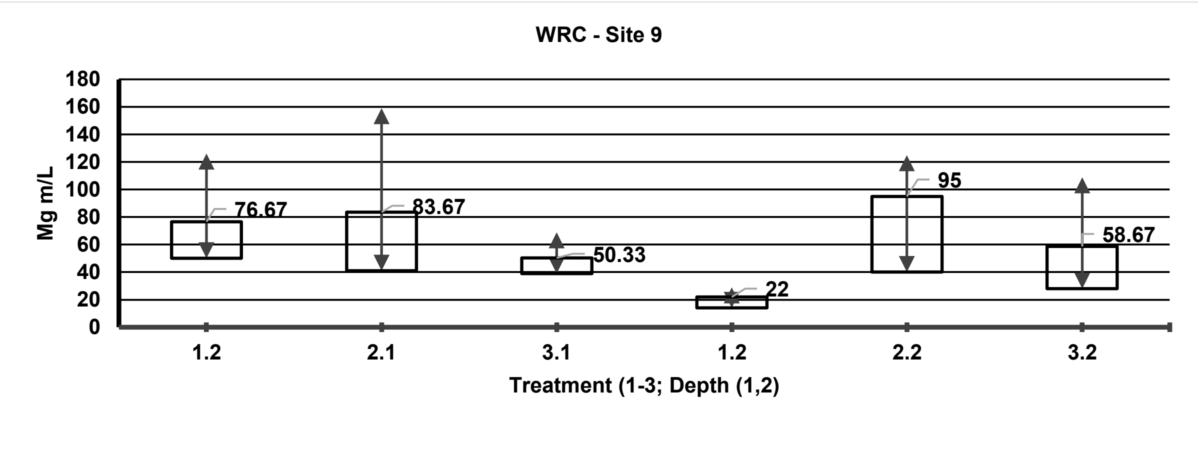

Figure E 5 Magnesium (Mg) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

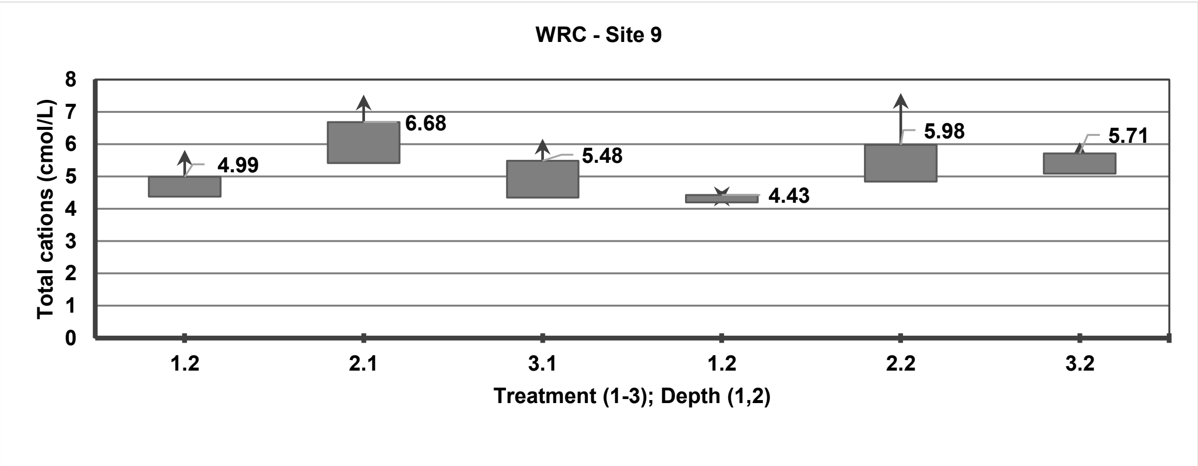

Figure E 6 Total cations variability on cleared, invaded and uninvaded treatments at10 cm and 20 cm depths in WRC– Site 9

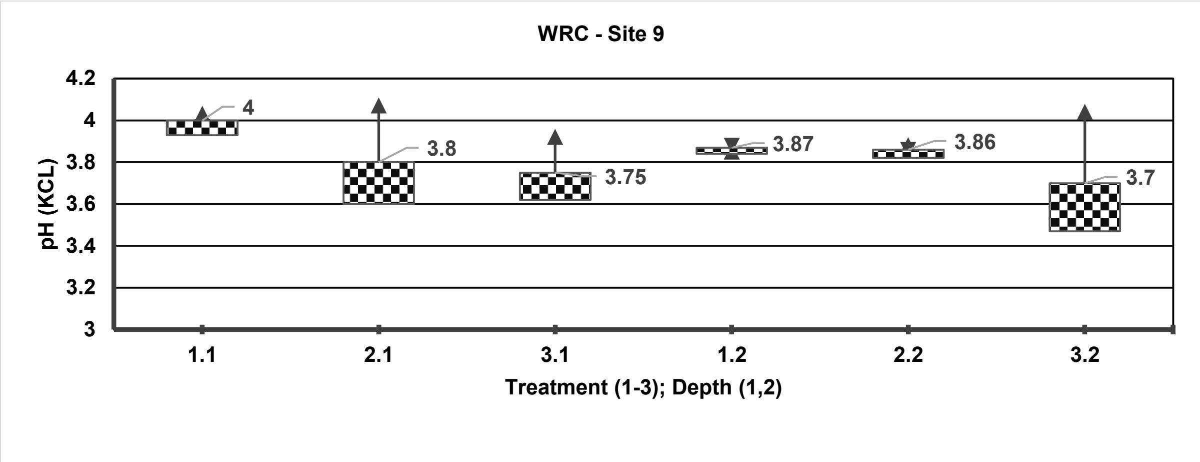

Figure E 7 Soil pH variability on cleared, invaded and uninvaded treatments at10 cm and 20 cm depths in WRC–Site 9

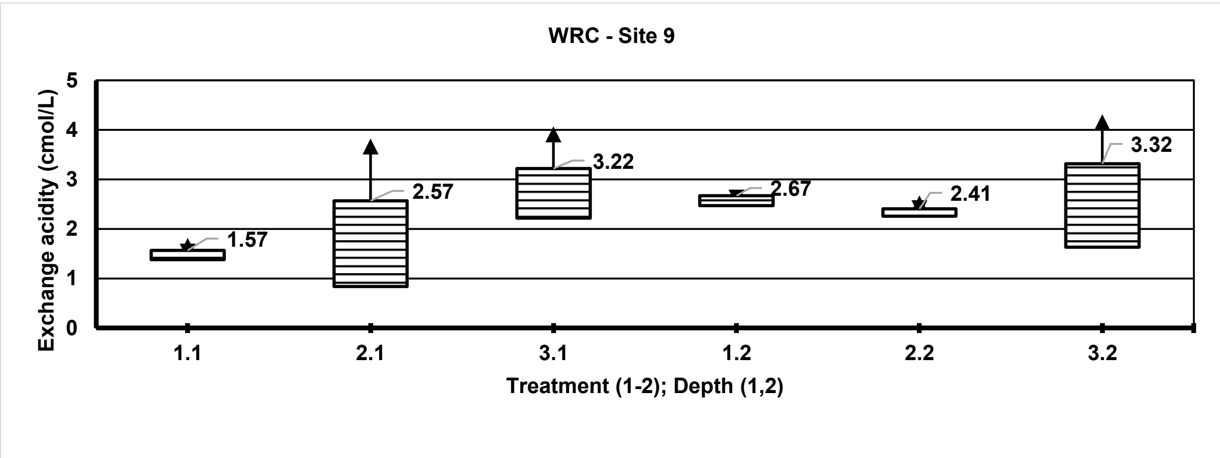

Figure E 8 Exchange acidity variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

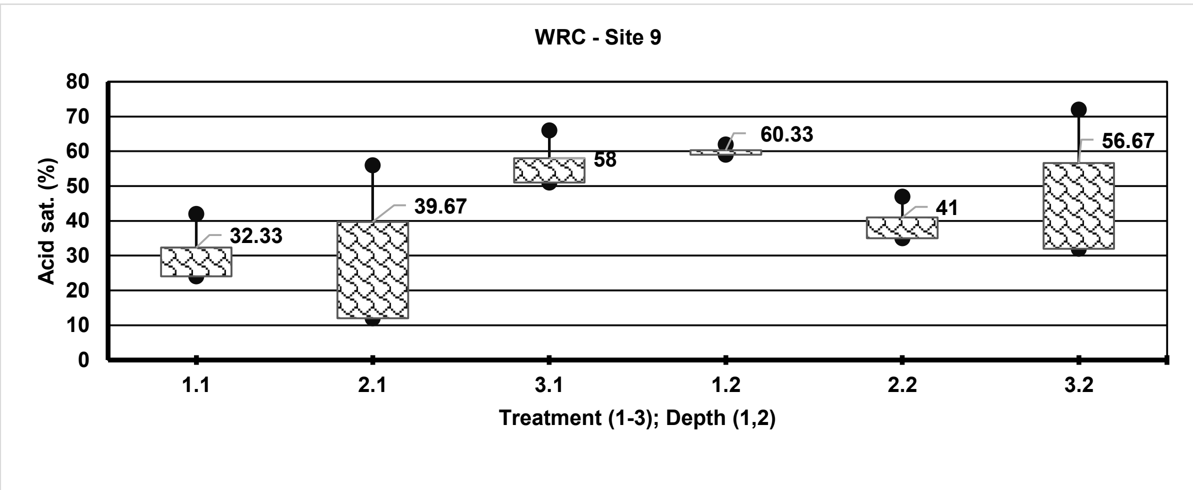

Figure E 9 Acid saturation variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

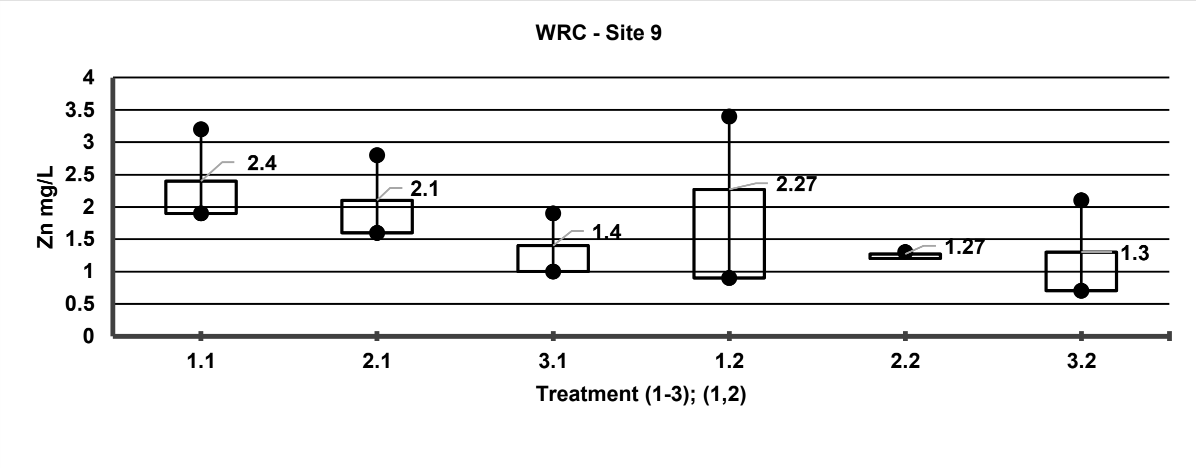

Figure E 10 Zinc (Zn) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9

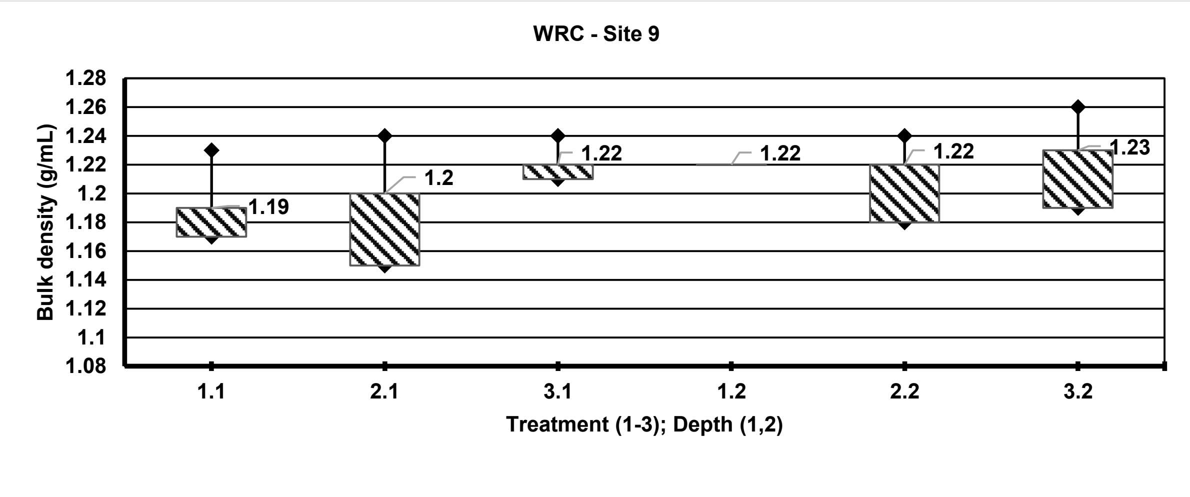

Figure E 11Bulk density variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 9.

Table E 1 Exploratory summary of the statistical variability of nutrients across treatments and depths showing the mean, standard error, significance value, maximum and minimum values in WRC-site 9

Note:

Variable	1.1 - Cleared A			2.1 - Invaded B			3.1 - Uninvaded C			1.2 - Cleared D			2.2 - Invaded E			3.2 - Uninvaded F			P-value
	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	
Macronutrients																			
Nitrogen	0.21±0.012	0.23	0.19	0.26±0.014[abc]	0.28	0.23	0.17±0.007[a]	0.18	0.16	0.18±0.007[b]	0.19	0.17	0.20±0.007	0.21	0.19	0.17±0.015[c]	0.2	0.15	P<0
Phosphorus	4.33±0.88	6	6	10.33±2.97[ab]	16	6	5.33±1.33	8	4	4±0.58	5	3	3.67±0.67[a]	5	3	3.67±0.67[b]	5	3	p<0.05
Potassium	55.67±27.24	110	25	124.3±11.26[ab]	144	105	193.7±37.24[a]	240	120	56.67±23.82	95	13	60±29.21	118	25	130.3±26.19[b]	165	79	P<0.05
Calcium	521±73.70	645	390	573.7±157.3	845	300	333±15.13	362	311	286±7.37	297	272	370.7±60.80	471	261	346.7±61.17	464	258	P>0.05
Magnesium	76.67±24.69	126	50	83.67±37.78	159	41	50.33±9.40	69	39	22±4.36	29	14	95±27.54	125	40	58.67±25.37	109	28	P>0.05
Micronutrient																			
Zinc	2.4±0.40	3.2	1.9	2.1±0.36	2.8	1.6	1.4±0.26	1.9	1	2.27±0.73	3.4	0.9	1.27±0.03	1.3	1.2	1.3±0.42	2.1	0.7	P>0.05
Other variables																			
pH	4±0.04	4.07	3.93	3.80±0.16	4.11	3.6	3.75±0.11	3.96	3.62	3.87±0.015	3.89	3.84	3.86±0.030	3.92	3.82	3.7±0.19	4.08	3.47	P>0.05
Total cations	4.10±0.43	5.82	4.38	6.68±0.6	7.53	5.42	5.48±0.57	6.17	4.35	4.43±0.11	4.56	4.2	5.98±0.82	7.58	4.84	5.71±0.31	6.06	5.09	P>0.05
Exchange acidity	1.57±0.13	1.82	1.38	2.57±0.89	3.83	0.84	3.22±054	4.07	2.22	2.67±0.10	2.79	2.47	2.41±0.14	2.68	2.26	3.32±0.85	4.32	1.63	P>0.05
Acid saturation	32.33±5.24	42	24	39.67±13.91	56	12	58±4.36	66	51	60.33±0.88	62	59	41±3.46	47	35	56.67±12.45	72	32	P>0.05
Sample density	1.19±0.019	1.23	1.17	1.20±0.026	1.24	1.15	1.22±0.01	1.24	1.21	1.22±0	1.22	1.22	1.22±0.019	1.24	1.18	1.23±0.021	1.26	1.19	P>0.05

Treatment = 1-3; Depth = 1(A-C), 2 (D-F)

Similar letters indicate means that are significantly different (P<0, 0.001, 0.01, 0.05)

P<0, P<0.001, P<0.01	= highly significant difference
P<0.05	=significance difference
P>0.05	= no significance difference

APPENDIX F

WRC-site 10: Nutrient variations across treatments and depths with the mean values visible by the boxplots

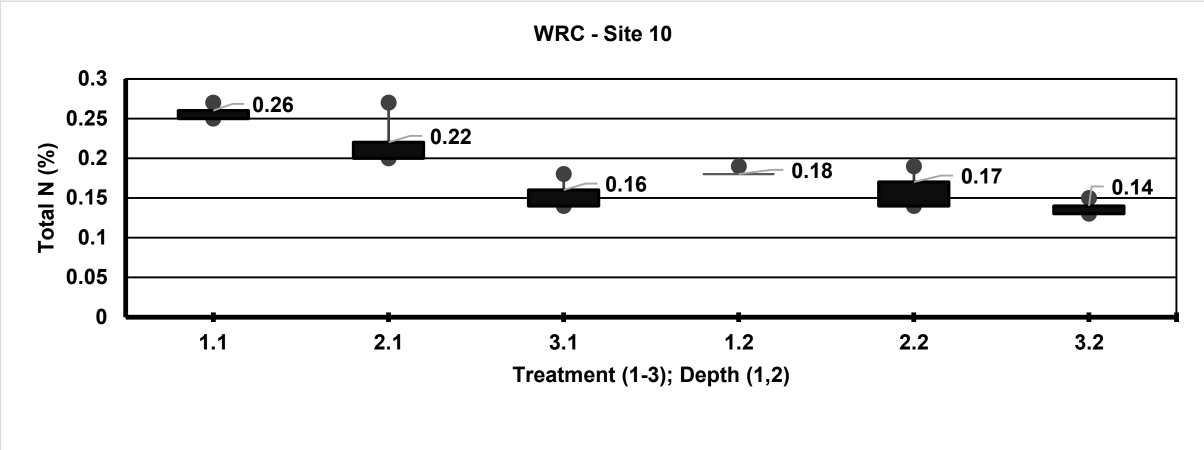

Figure F 1Total nitrogen (N) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC–Site 10.

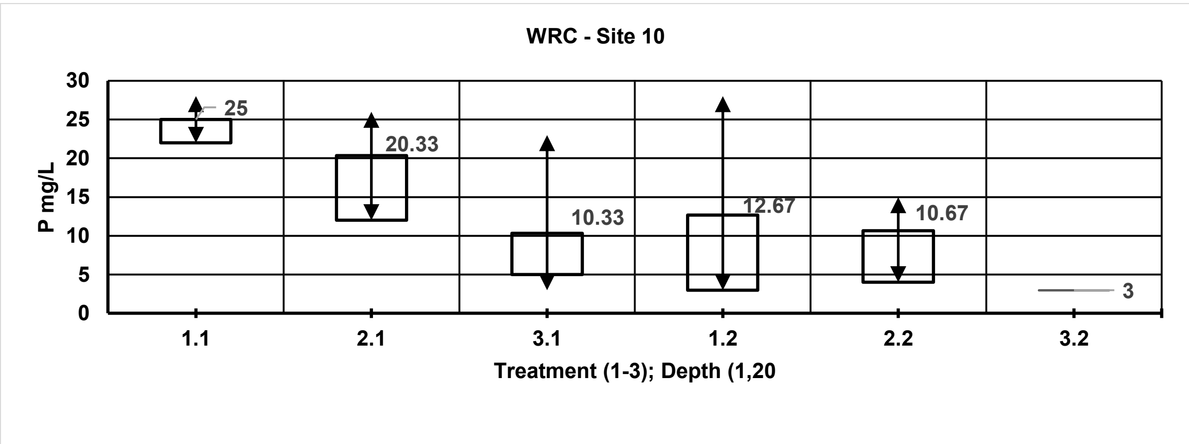

Figure F 2 Phosphorus (P) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10..

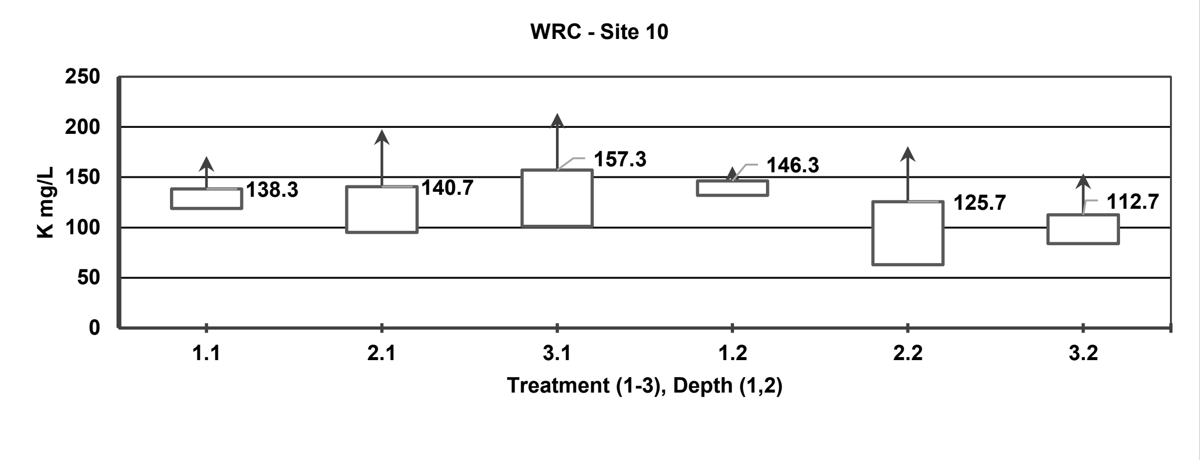

Figure F 3 Potassium (K) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

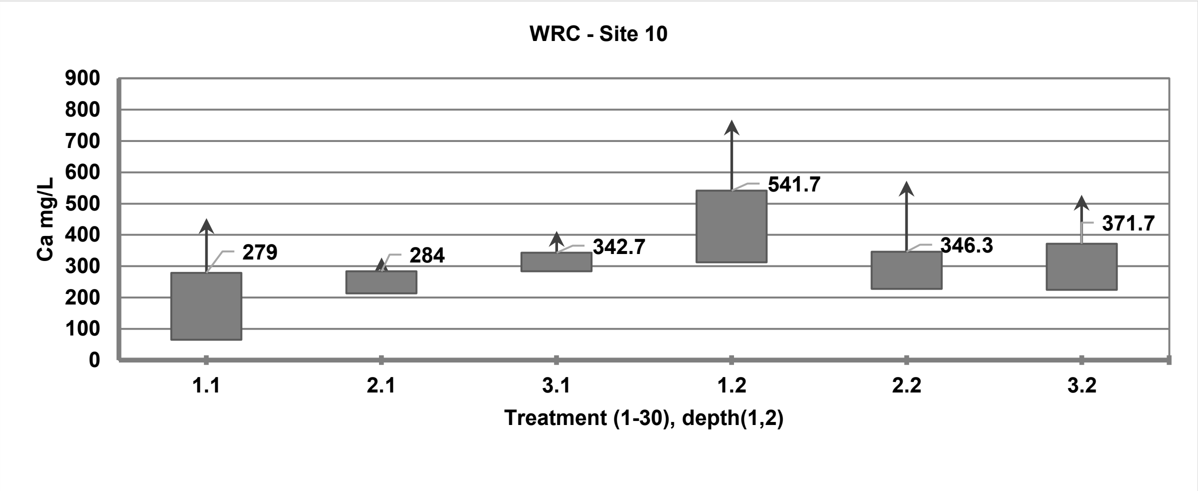

Figure F 4 Calcium (Ca) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

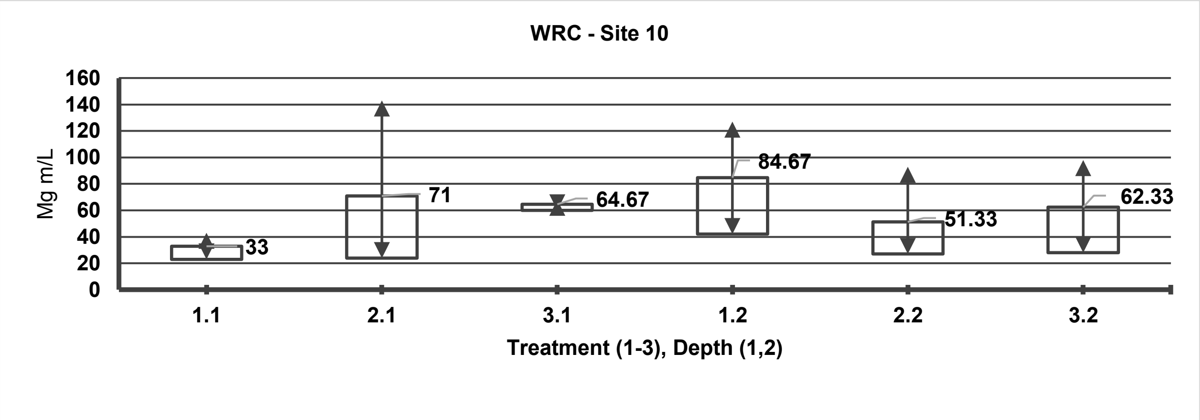

Figure F 5 Magnesium (Mg) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10

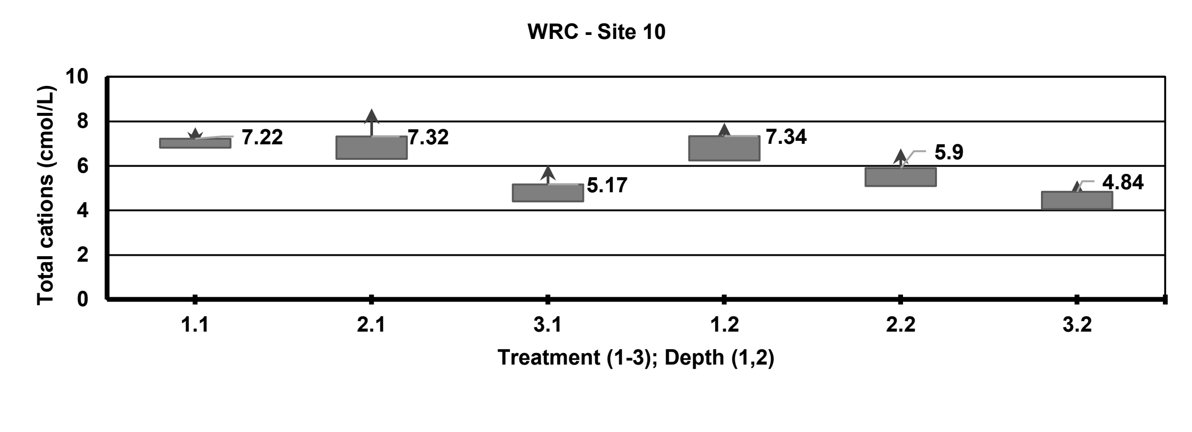

Figure F 6 Total cations variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

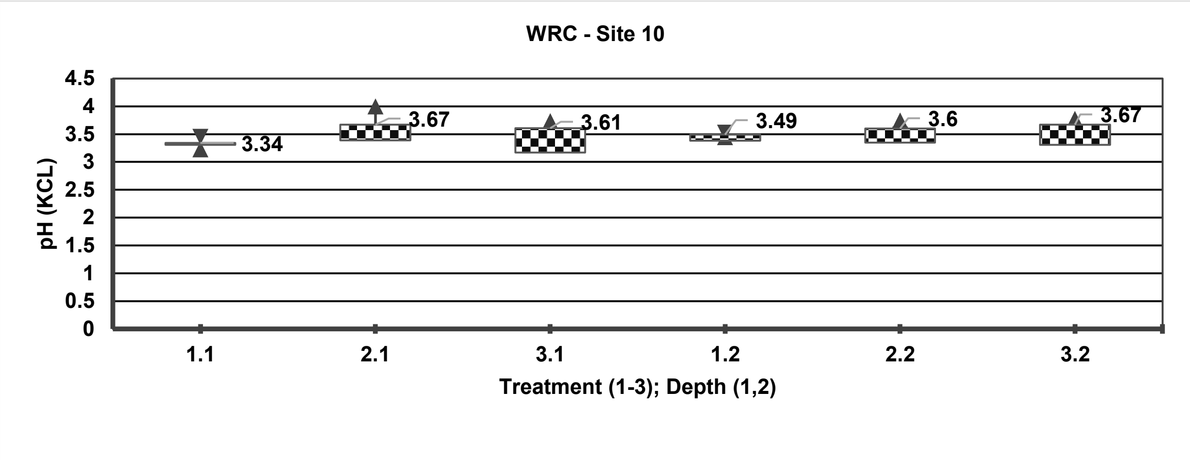

Figure F 7 Soil pH variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

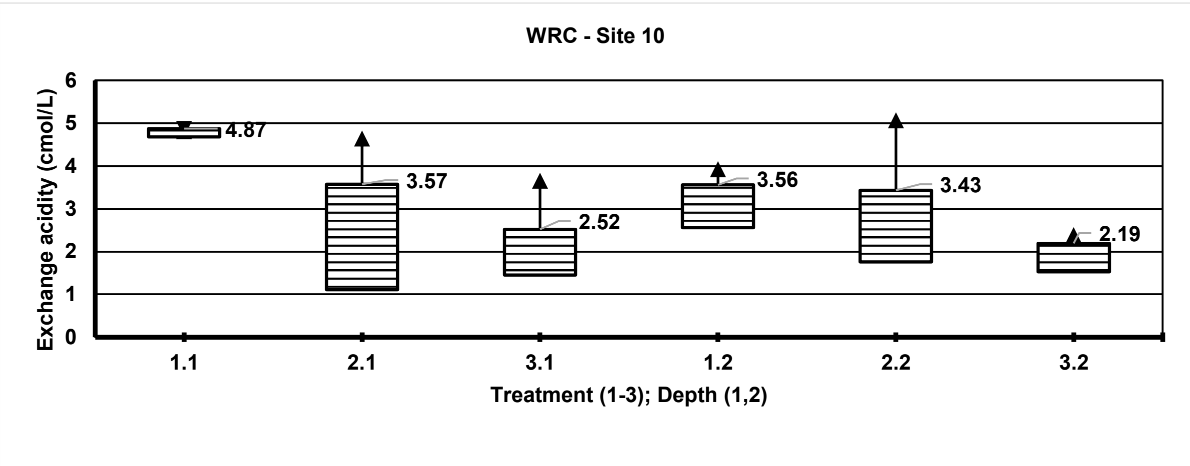

Figure F 8 Exchange acidity variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

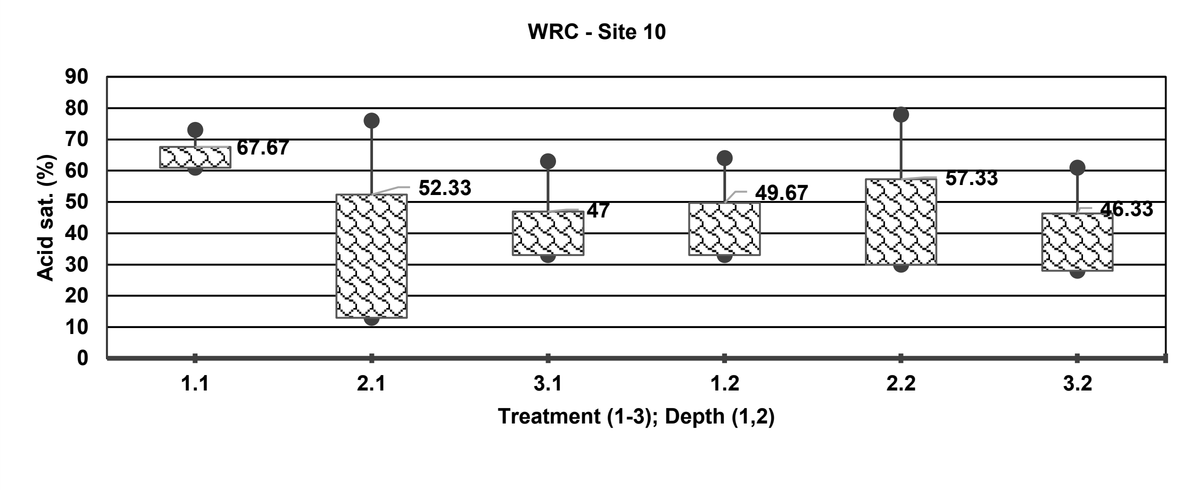

Figure F 9 Acid saturation variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

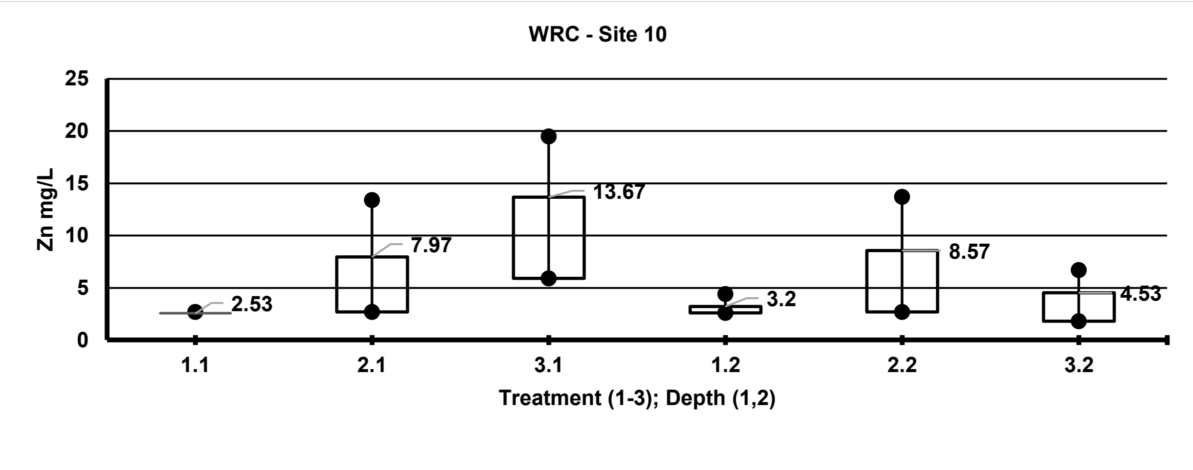

Figure F 10 Zinc (Zn) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

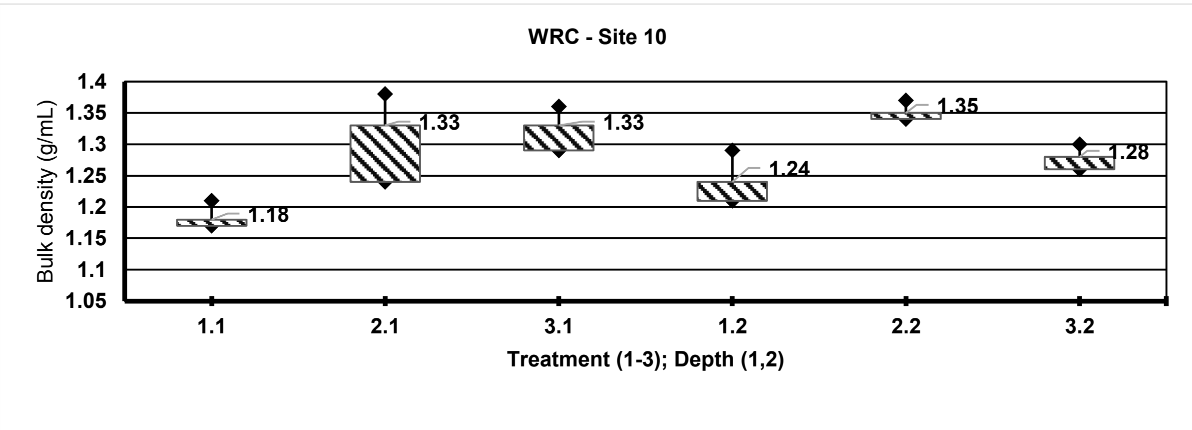

Figure F 11 Bulk density variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths in WRC– Site 10.

Table F 1 Exploratory summary of the statistical variability of nutrients across treatments and depths showing the mean, standard error, significance value, maximum and minimum values in WRC-site 10

Note:

Variable	1.1 - Cleared A			2.1 - Invaded B			3.1 - Uninvaded C			1.2 - Cleared D			2.2 - Invaded E			3.2 - Uninvaded F			P-value
	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	Mean ±S.E	Max	Min	
Macronutrients																			
Nitrogen	0.26±0.007^{bcde}	0.27	0.25	0.22±0.023^{a}	0.27	0.2	0.16±0.012 b	0.18	0.14	0.18±0.003^{c}	0.19	0.18	0.17±0.015^{d}	0.19	0.14	0.14±0.007^{ae}	0.15	0.13	P<0
Phosphorus	25±1.73	28	22	20.33±4.26	26	12	10.33±6034	23	3	12.67±7.75	28	3	10.67±3.38	15	4	3±0	3	3	P>0.05
Potassium	138.3±16.42	171	119	140.67±30.30	198	95	157.33±32.62	214	101	146.3±8.37	161	132	125.7±34.26	181	63	112.7±21.18	154	84	P>0.05
Calcium	279±113.8	453	65	284±35.84	328	213	342.7±37.69	413	284	541.7±131.9	769	312	346.3±113.4	573	227	371.7±87.86	528	224	P>0.05
Magnesium	33±5.77	43	23	71±36.56	143	24	64.67±2.40	68	60	84.67±24.24	127	127	51.33±20.93	93	27	62.33±20.22	98	28	P>0.05
Micronutrient																			
Zinc	2.53±0.12	2.7	2.3	7.10±3.09	13.4	2.7	13.67±4.04	19.5	5.9	3.2±0.6	4.4	2.6	8.57±3.20	13.7	2.7	4.53±1.44	6.7	1.8	P>0.05
Other variables																			
pH	3.34±0.018	3.37	3.31	3.67±0.24	4.14	3.39	3.61±0.22	3.88	3.17	3.49±0.061	3.59	3.38	3.60±0.16	3.89	3.35	3.67±0.18	3.92	3.31	P>0.05
Total cations	7.22±0.27^{c}	7.73	6.82	7.32±0.67^{b}	8.59	6.32	5.17±0.48	6.06	4.4	7.34±0.54^{a}	7.94	6.25	5.9±0.48	6.76	5.09	4.84±0.40^{abc}	5.36	4.06	P<0.01
Exchange acidity	4.87±0.097	5	4.68	3.57±1.23	4.83	1.11	2.52±0.70	3.84	1.45	3.56±0.50	4.11	2.56	3.43±1.01	5.25	1.76	2.19±0.33	2.57	1.53	P>0.05
Acid saturation	67.67±3.53	73	61	52.33±19.80	76	13	47±8.72	63	33	49.67±9.02	64	33	57.33±14.25	78	30	46.33±9.70	61	28	P>0.05
Sample density	1.18±0.013	1.21	1.17	1.33±0.047	1.38	1.24	1.33±0.020	1.36	1.29	1.24±0.024	1.29	1.21	1.35±0.009	1.37	1.34	1.28±0.012	1.3	1.26	P>0.05

Treatment = 1-3; Depth = 1(A-C), 2 (D-F)

Similar letters indicate means that are significantly different (P<0, 0.001, 0.01, 0.05)

P<0, P<0.001, P<0.01 = highly significant difference

P<0.05 =significance difference

P>0.05 = no significance difference

APPENDIX G

Assessment of nutrient variations on 'all sites' across treatments and depths with the mean values visible by the boxplots

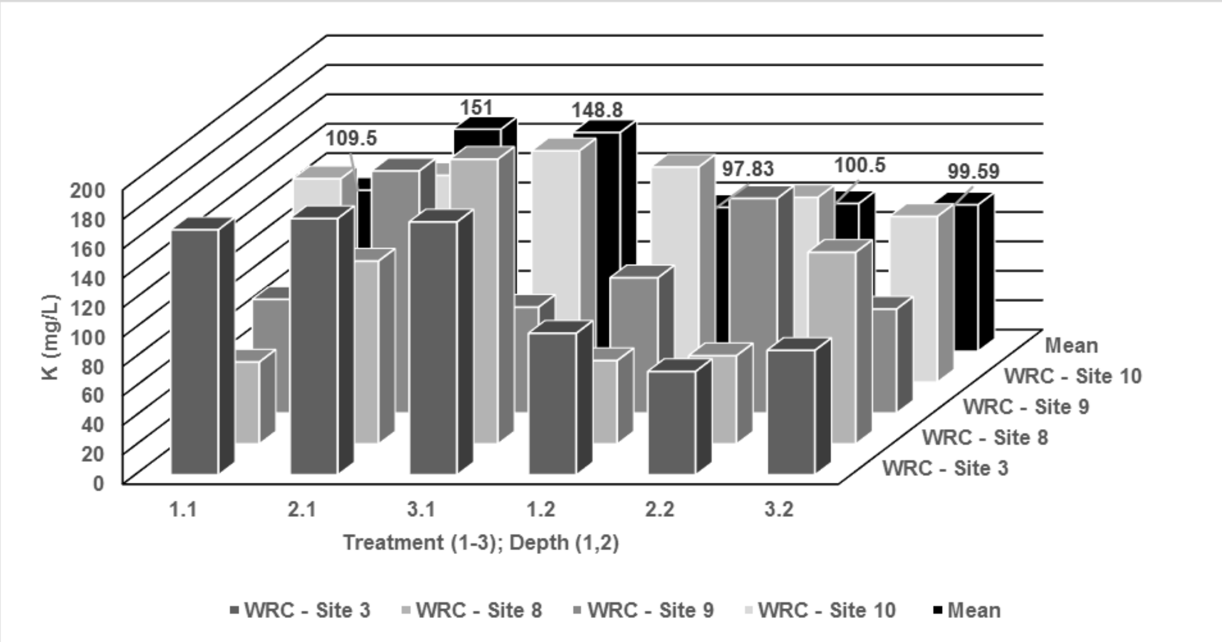

Figure G 1 Potassium (K) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on 'all sites'.

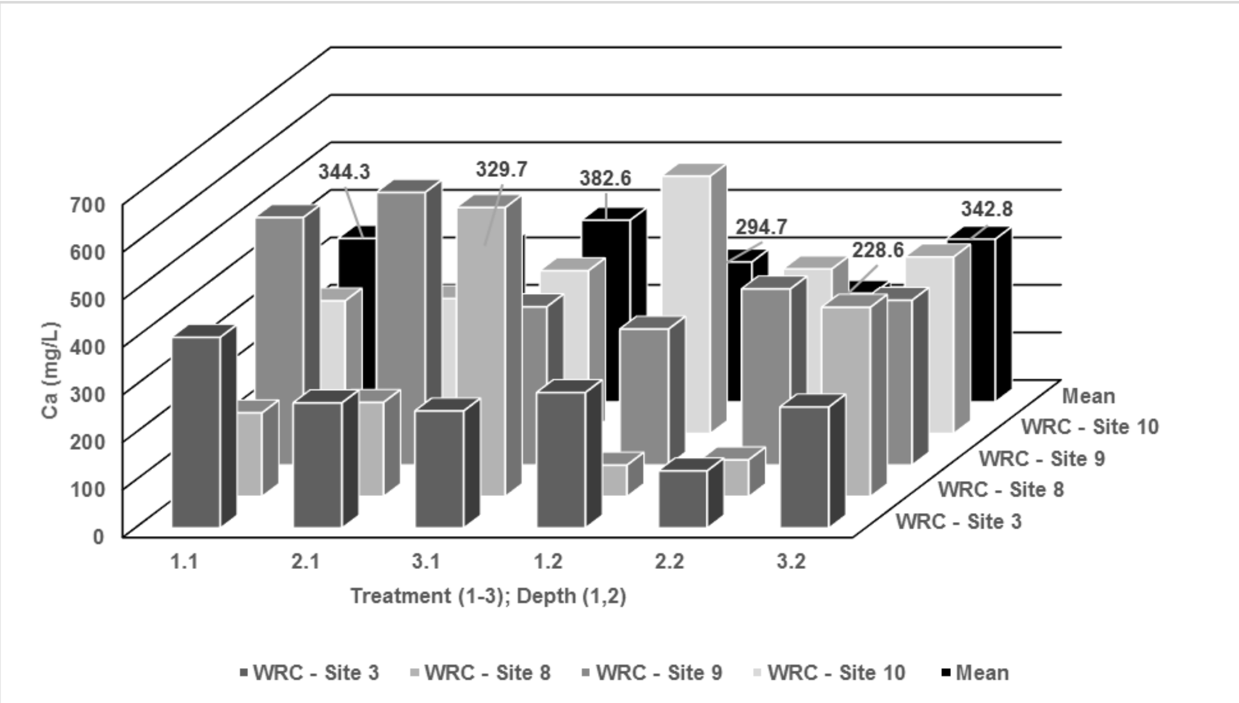

Figure G 2 Calcium (Ca) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on 'all sites'.

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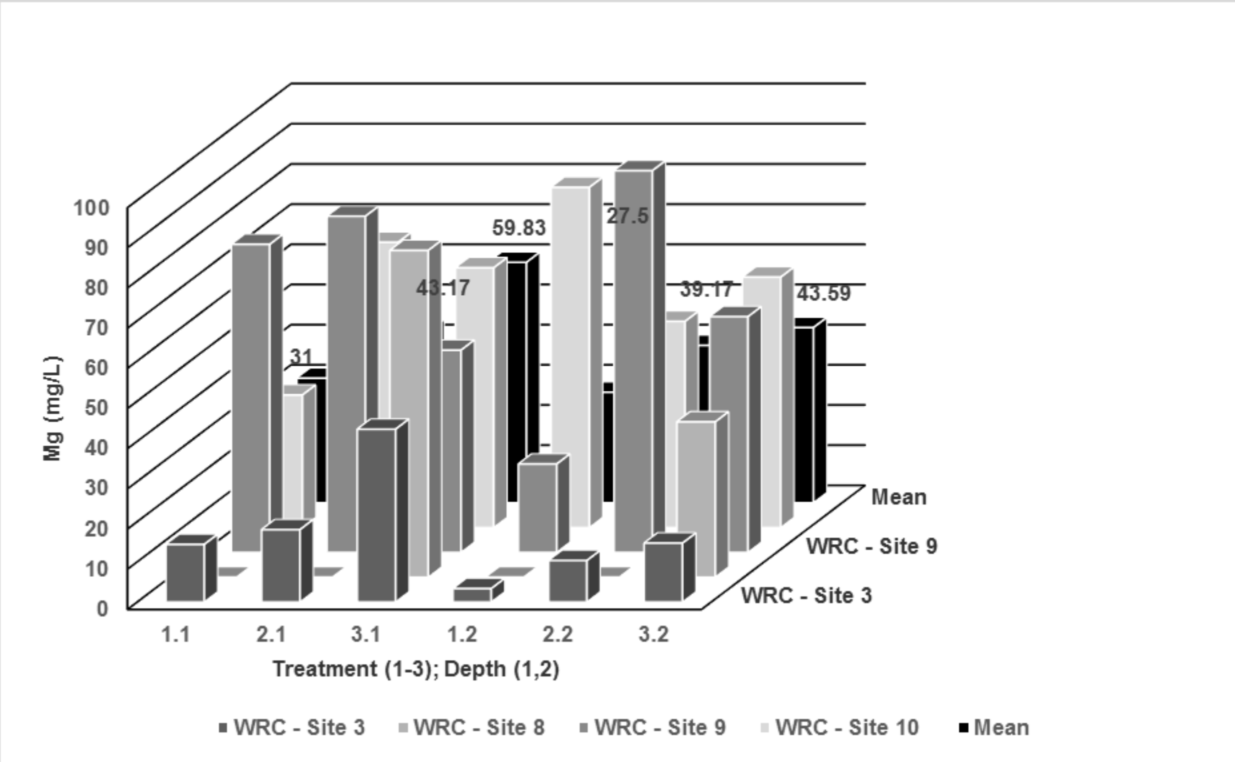


Figure G 3 Magnesium (Mg) variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on 'all sites'.

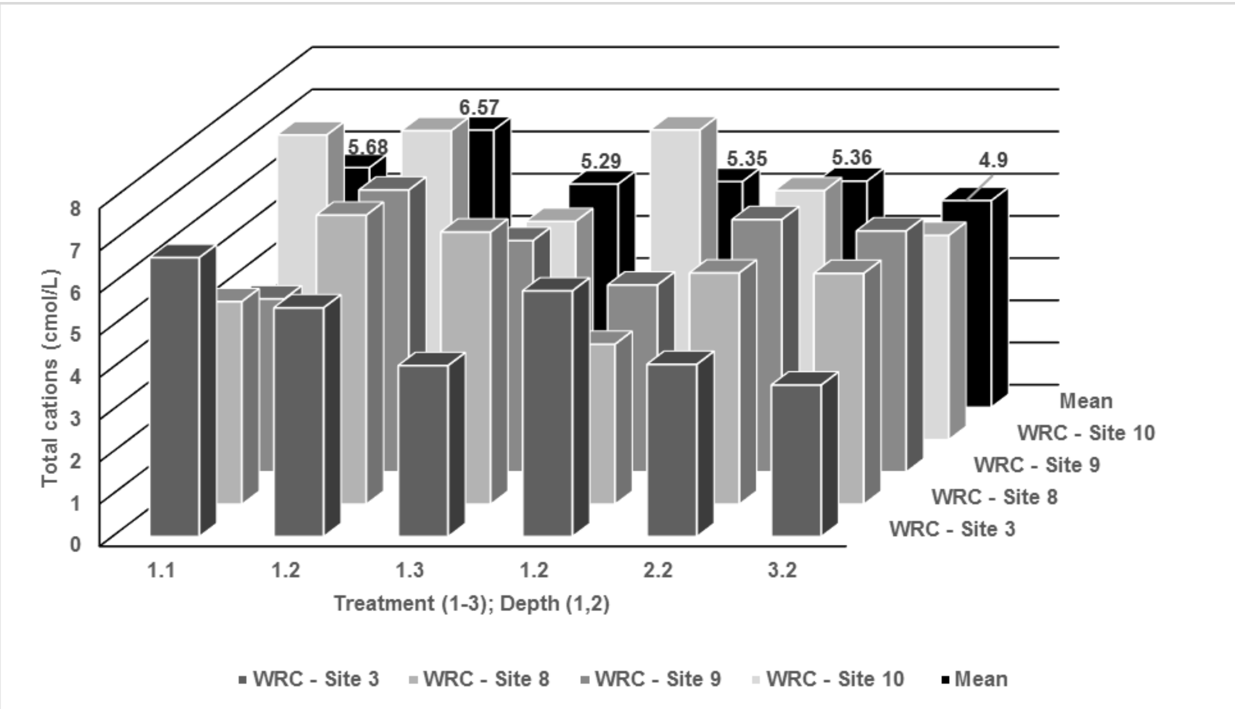


Figure G 4 Total cations variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on 'all sites'.

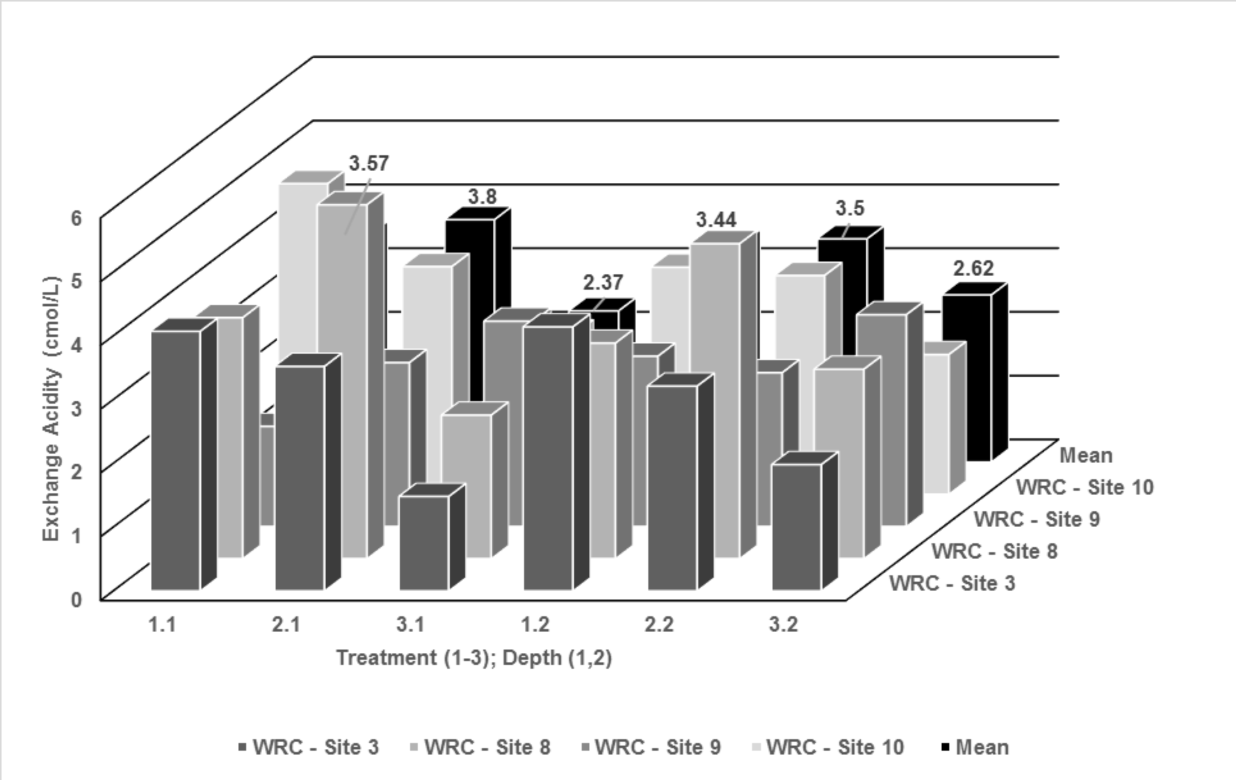


Figure G 5 Exchange acidity variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on ‘all site’

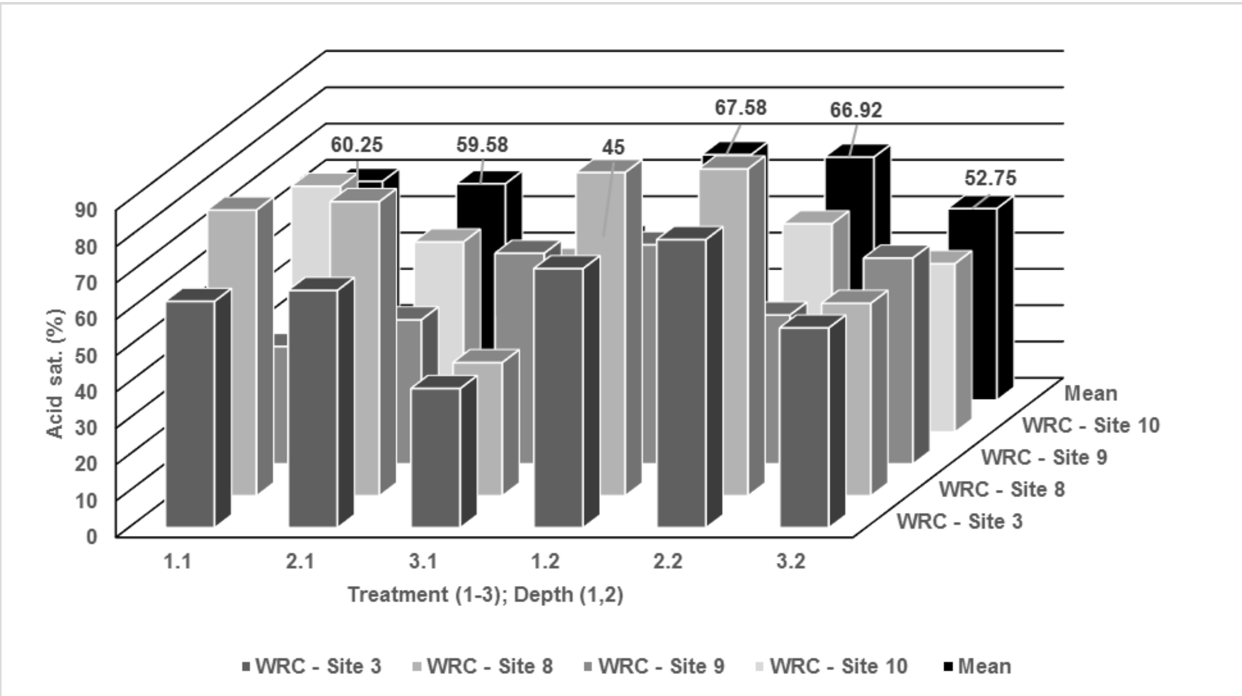


Figure G 6 Acid saturation variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on ‘all site’.

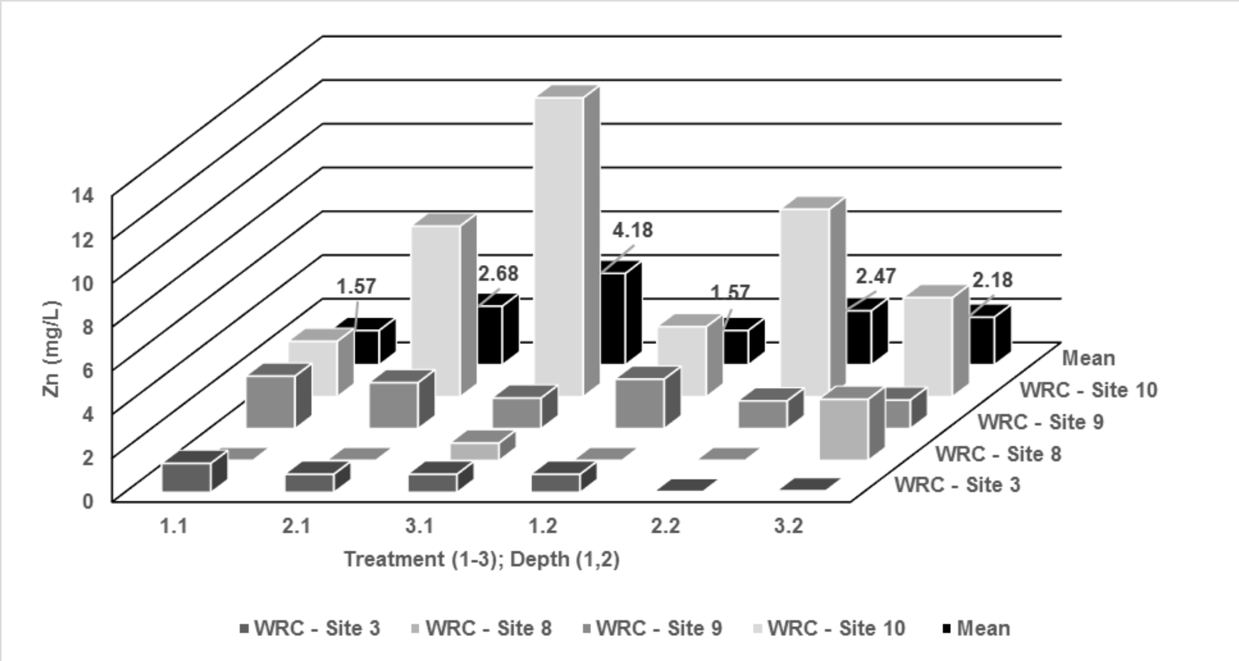


Figure G 7 Zinc (Zn) variability along cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on ’all sites’.

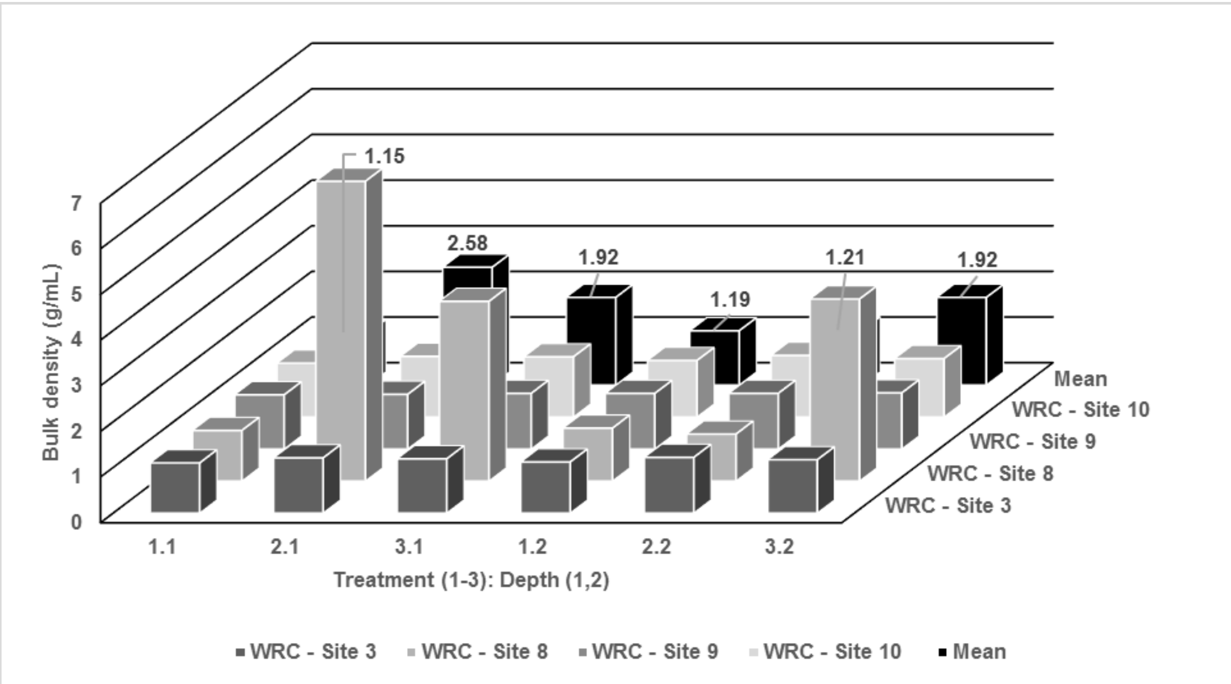
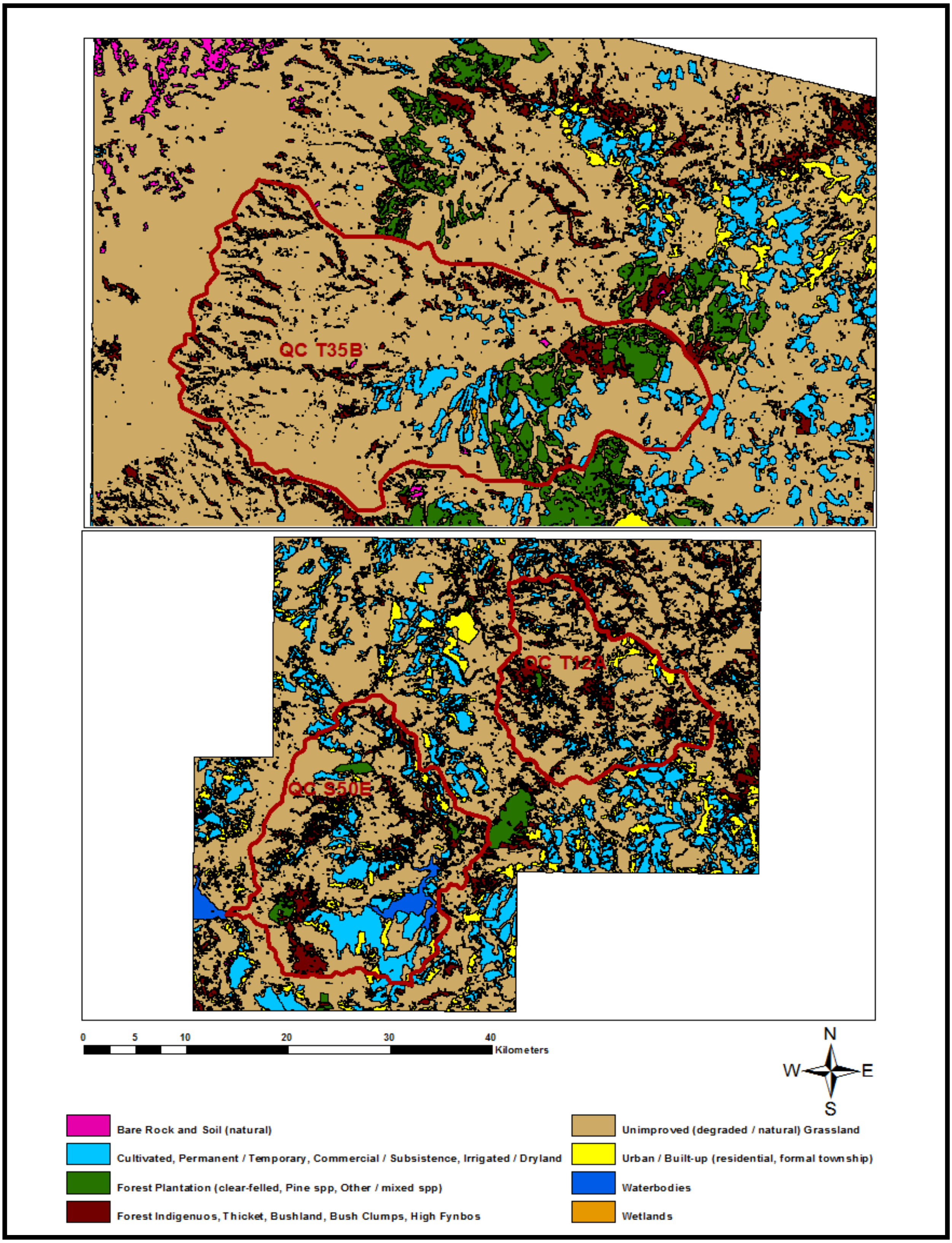


Figure G 8 Bulk density variability on cleared, invaded and uninvaded treatments at 10 cm and 20 cm depths on ’all sites’.

APPENDIX H

Derived land cover (DLC) map (2014) of the QCs landmass showing the feature-outlines of the three QCs.



APPENDIX I

Details of accuracy assessment for derived land cover (DLC) 2014 for QC T35B.

Table I 1 Details of accuracy assessment for derived land cover (DLC) 2014 for QC T35B

	CLASSIFICATION (2014)									
		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WI	Total
REFERENCE (NLC 2000)	BRS	13				6				19
	CLs	1	400			15				416
	FITBs		8	167		158		2	6	341
	FPs				186	12			2	200
	UGd/n	2	17	28	14	1255	2		15	1333
	UrBu		2			1	6			9
	Wb		1			2		39	17	59
	WI		17	1		95		6	63	182
	Total	**16**	**445**	**196**	**200**	**1544**	**8**	**47**	**103**	**2559**
	Sum diagonal									**2129**

		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WI	Total
REFERENCE (NLC 2000)	BRS	304	8455	3724	3800	29336	152	893	1957	48621
	CLs	6656	185120	81536	83200	642304	3328	19552	42848	1064544
	FITBs	5456	151745	66836	68200	526504	2728	16027	35123	872619
	FPs	3200	89000	39200	40000	308800	1600	9400	20600	511800
	UGd/n	21328	593185	261268	266600	2058152	10664	62651	137299	3411147
	UrBu	144	4005	1764	1800	13896	72	423	927	23031
	Wb	944	26255	11564	11800	91096	472	2773	6077	150981
	WI	2912	80990	35672	36400	281008	1456	8554	18746	465738
	Total	**40944**	**1138755**	**501564**	**511800**	**3951096**	**20472**	**120273**	**263577**	**6548481**
	Sum diagonals									**349012**

Table I 2 Details of accuracy assessment for derived land cover (DLC) 2014 for QC T12A

	CLASSIFICATION (2014)									
		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WI	Total
REFERENCE (NLC 2000)	BRS	4	6	0	0	2	0	0	0	12
	CLs	0	192	1	0	10	5	0	0	208
	FITBs	0	8	290	0	68	2	0	0	368
	FPs	0	0	0	11	0	0	0	0	11
	UGd/n	0	54	20	0	766	28	4	8	880
	UrBu	1	17	0	0	21	178	0	0	217
	Wb	0	0	0	0	2	0	9	0	11
	WI	0	0	0	0	2	0	0	53	55
	Total	**5**	**277**	**311**	**11**	**871**	**213**	**13**	**61**	**1762**
	Sum diagonal									**1503**

REFERENCE (NLC 2000)

	BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WI	Total
BRS	60	3324	3732	132	10452	2556	156	732	21144
CLs	1040	57616	64688	2288	181168	44304	2704	12688	366496
FITBs	1840	101936	114448	4048	320528	78384	4784	22448	648416
FPs	55	3047	3421	121	9581	2343	143	671	19382
UGd/n	4400	243760	273680	9680	766480	187440	11440	53680	1550560
UrBu	1085	60109	67487	2387	189007	46221	2821	13237	382354
Wb	55	3047	3421	121	9581	2343	143	671	19382
WI	275	15235	17105	605	47905	11715	715	3355	96910
Total	**8810**	**488074**	**547982**	**19382**	**1534702**	**375306**	**22906**	**107482**	**3104644**
Sum diagonals									**988444**

Table I 3 Details of accuracy assessment for derived land cover (DLC) 2014 for QC S50E

REFERENCE (NLC 2000)

	CLASSIFICATION (2014)								
	BRS	**CLs**	**FITBs**	**FPs**	**UGd/n**	**UrBu**	**Wb**	**WI**	**Total**
BRS	7								7
CLs		985	8		39				1032
FITBs	1	16	1018	2	137	4			1178
FPs			37	344					381
UGd/n	3	20	27	1	1261	9		3	1324
UrBu		6		3	20	209			238
Wb		3	1		12		125		141
WI		18			73	2		5	98
Total	**11**	**1048**	**1091**	**350**	**1542**	**224**	**125**	**8**	**4399**
Sum diagonal									**3954**

REFERENCE (NLC 2000)

	BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WI	Total
BRS	77	7336	7637	2450	10794	1568	875	56	30793
CLs	11352	1081536	1125912	361200	1591344	231168	129000	8256	4539768
FITBs	12958	1234544	1285198	412300	1816476	263872	147250	9424	5182022
FPs	4191	399288	415671	133350	587502	85344	47625	3048	1676019
UGd/n	14564	1387552	1444484	463400	2041608	296576	165500	10592	5824276
UrBu	2618	249424	259658	83300	366996	53312	29750	1904	1046962
Wb	1551	147768	153831	49350	217422	31584	17625	1128	620259
WI	1078	102704	106918	34300	151116	21952	12250	784	431102
Total	**48389**	**4610152**	**4799309**	**1539650**	**6783258**	**985376**	**549875**	**35192**	**19351201**
Sum diagonals									**4613490**

APPENDIX J

Details of accuracy assessment for edited national land cover (ENLC) 2000 for the three QCs.

Table J 1 Details of accuracy assessment for edited national land cover (ENLC) 2000 for QC T35B

	CLASSIFICATION 2014									
REFERENCE (ENLC 2000)		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WL	Total
	BRS					39				39
	CLs		421	12	1	37	3	1	51	526
	FITBs		18	202	6	105	5			336
	FPs		15	2	501	67			22	607
	UGd/n		19	39	11	1171			26	1266
	UrBu						10			10
	Wb					1		15	1	17
	WL		17		2	25			129	173
	Total	0	**490**	**255**	**521**	**1445**	**18**	**16**	**229**	**2974**
	Sum diagonal									2449

REFERENCE (ENLC 2000)		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WL	Total
	BRS	0	19110	9945	20319	56355	702	624	8931	115986
	CLs	0	257740	134130	274046	760070	9468	8416	120454	1564324
	FITBs	0	164640	85680	175056	485520	6048	5376	76944	999264
	FPs	0	297430	154785	316247	877115	10926	9712	139003	1805218
	UGd/n	0	620340	322830	659586	1829370	22788	20256	289914	3765084
	UrBu	0	4900	2550	5210	14450	180	160	2290	29740
	Wb	0	8330	4335	8857	24565	306	272	3893	50558
	WL	0	84770	44115	90133	249985	3114	2768	39617	514502
	Total	**0**	**1457260**	**758370**	**1549454**	**4297430**	**53532**	**47584**	**681046**	**8844676**
	Sum diagonal									2529106

Table J 2 Details of accuracy assessment for edited national land cover (ENLC) 2000 for QC T12A

	CLASSIFICATION 2014									
REFERENCE (ENLC 2000)		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WL	Total
	BRS			2		4				6
	CLs		230	6		24	13			273
	FITBs		3	561	97	61	3			725
	FPs			1	30					31
	UGd/n		15	23	1	1088	35	1	13	1176
	UrBu		13			27	185			225
	Wb					2		3		5
	WL					4			2	6
	Total	0	261	593	128	1210	236	4	15	2447
	Sum diagonal									2099

		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WL	Total
REFERENCE (ENLC 2000)	**BRS**	0	1566	3558	768	7260	1416	24	90	14682
	CLs	0	71253	161889	34944	330330	64428	1092	4095	668031
	FITBs	0	189225	429925	92800	877250	171100	2900	10875	1774075
	FPs	0	8091	18383	3968	37510	7316	124	465	75857
	UGd/n	0	306936	697368	150528	1422960	277536	4704	17640	2877672
	UrBu	0	58725	133425	28800	272250	53100	900	3375	550575
	Wb	0	1305	2965	640	6050	1180	20	75	12235
	WL	0	1566	3558	768	7260	1416	24	90	14682
	Total	0	638667	1451071	313216	2960870	577492	9788	36705	5987809
	Sum diagonals									1981316

Table J 3 Details of accuracy assessment for edited national land cover (ENLC) 2000 for QC S50E

	CLASSIFICATION 2014									
		BRS	**CLs**	**FITBs**	**FPs**	**UGd/n**	**UrBu**	**Wb**	**WL**	**Total**
REFERENCE (ENLC 2000)	**BRS**					13				13
	CLs		837	8		128	32	2	10	1017
	FITBs		12	603	87	104	3			809
	FPs			29	655	4	1			689
	UGd/n	1	45	28	1	1289	30		2	1396
	UrBu		8		1	33	235			277
	Wb		1	6		10		431		448
	WL					48	1		25	74
	Total	**1**	**903**	**674**	**744**	**1629**	**302**	**433**	**37**	**4723**
	Sum diagonal									4075

		BRS	CLs	FITBs	FPs	UGd/n	UrBu	Wb	WL	Total
REFERENCE (ENLC 2000)	**BRS**	13	11739	8762	9672	21177	3926	5629	481	61399
	CLs	1017	918351	685458	756648	1656693	307134	440361	37629	4803291
	FITBs	809	730527	545266	601896	1317861	244318	350297	29933	3820907
	FPs	689	622167	464386	512616	1122381	208078	298337	25493	3254147
	UGd/n	1396	1260588	940904	1038624	2274084	421592	604468	51652	6593308
	UrBu	277	250131	186698	206088	451233	83654	119941	10249	1308271
	Wb	448	404544	301952	333312	729792	135296	193984	16576	2115904
	WL	74	66822	49876	55056	120546	22348	32042	2738	349502
	Total	**4723**	**4264869**	**3183302**	**3513912**	**7693767**	**1426346**	**2045059**	**174751**	**22306729**
	Sum diagonal									4530706

APPENDIX K

National land cover (NLC) / Edited national land cover (ENLC) 2000 and Derived land cover (DLC) 2014 for T35B.

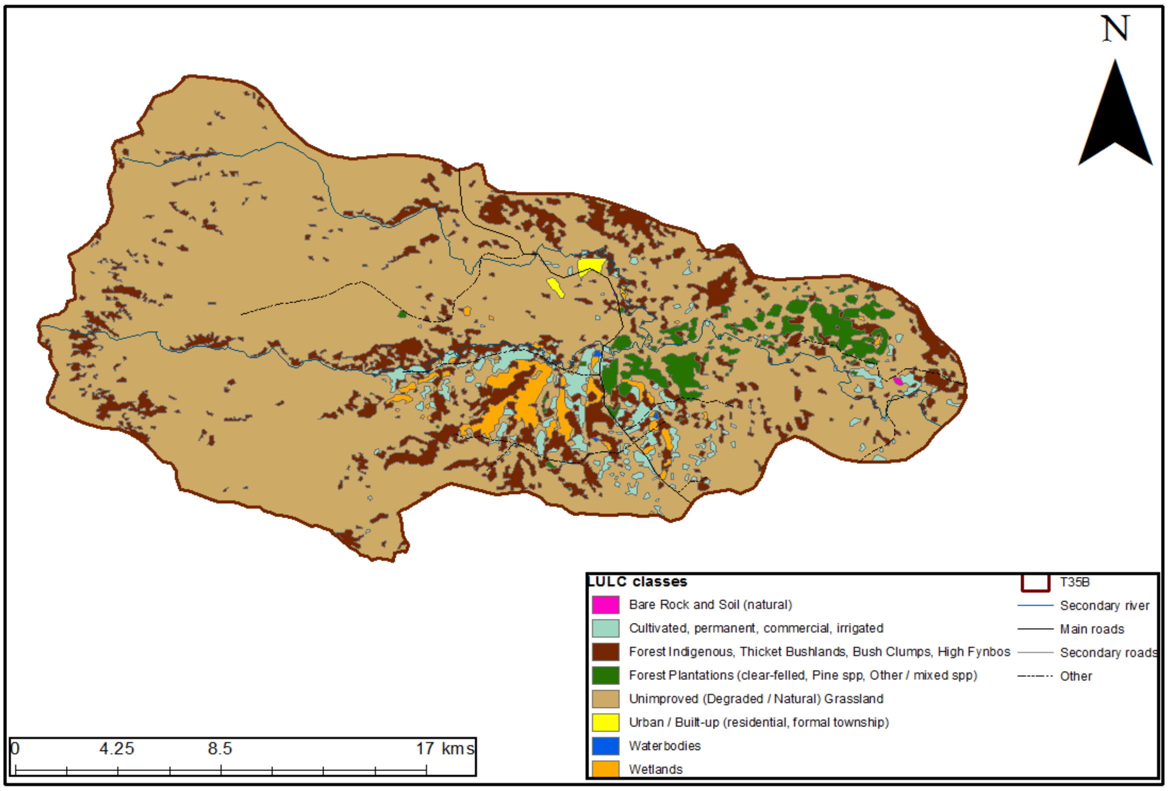


Figure K 1 National land cover (NLC) for the QC T35B.

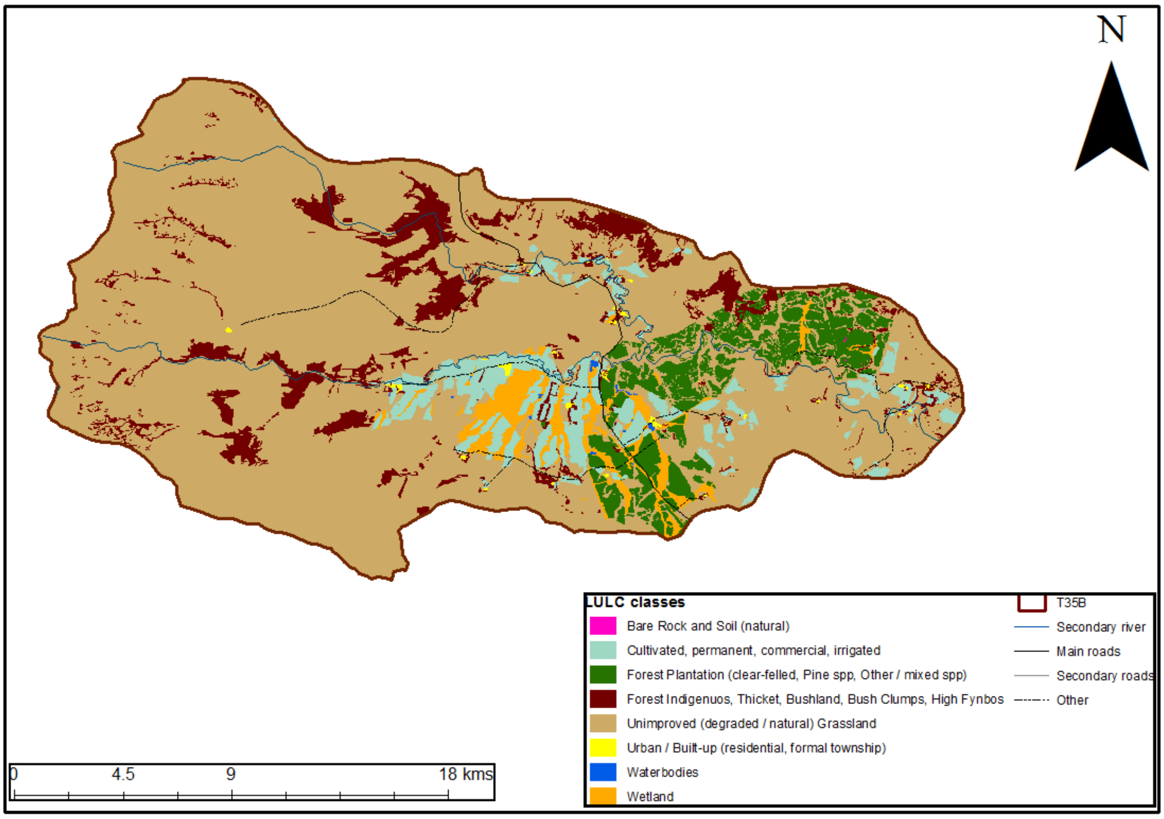


Figure K 2 Edited national land cover (ENLC) 2000 for the QC T35B.

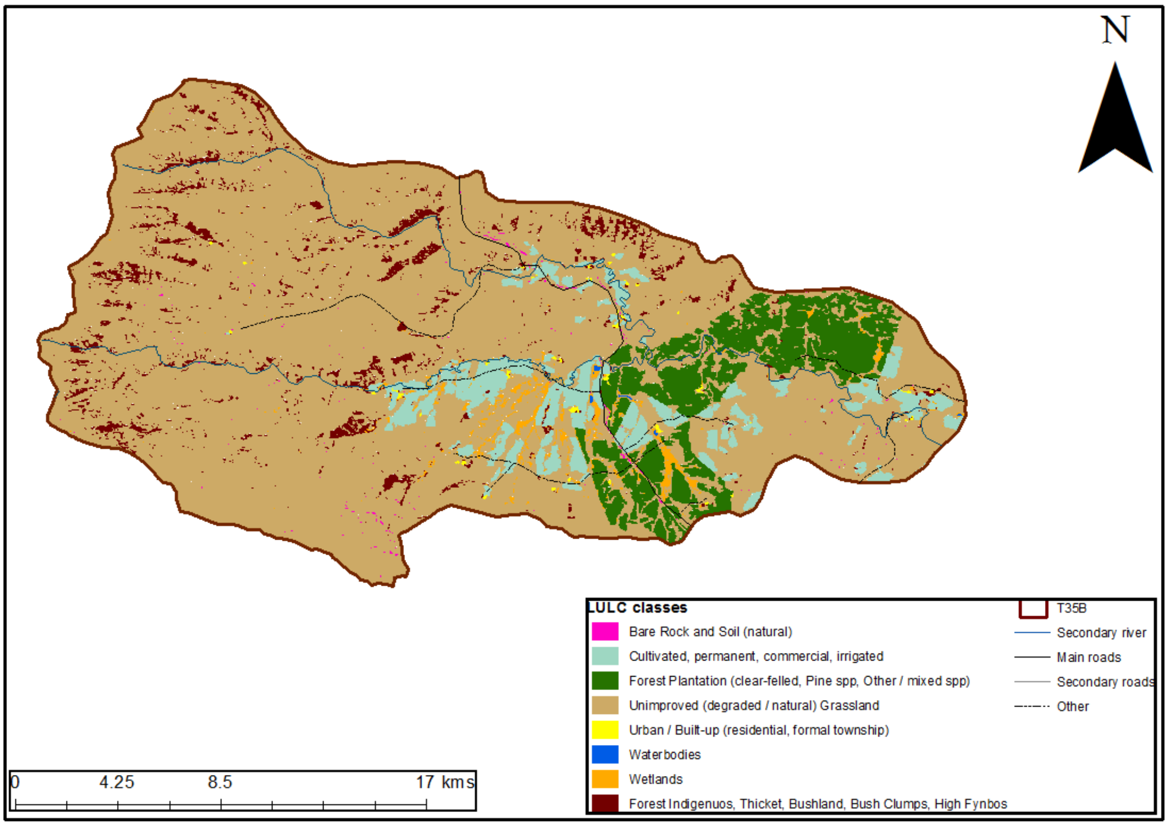


Figure K 3 Derived land cover (DLC) 2014 for the QC T35B.

APPENDIX L

National land cover (NLC)/Edited National land cover (ENLC) 2000 and Derived land cover (DLC) 2014 for the QC T12A.

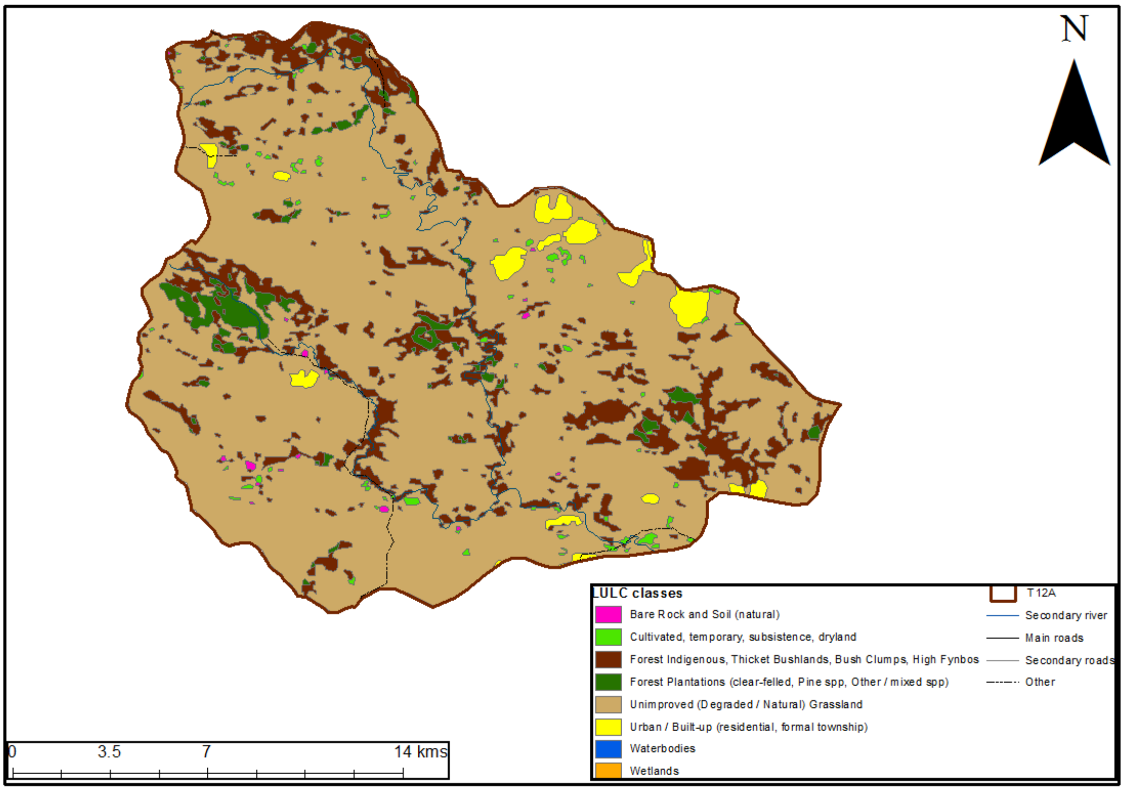


Figure L 1 National land cover (NLC) for the QC T12A.

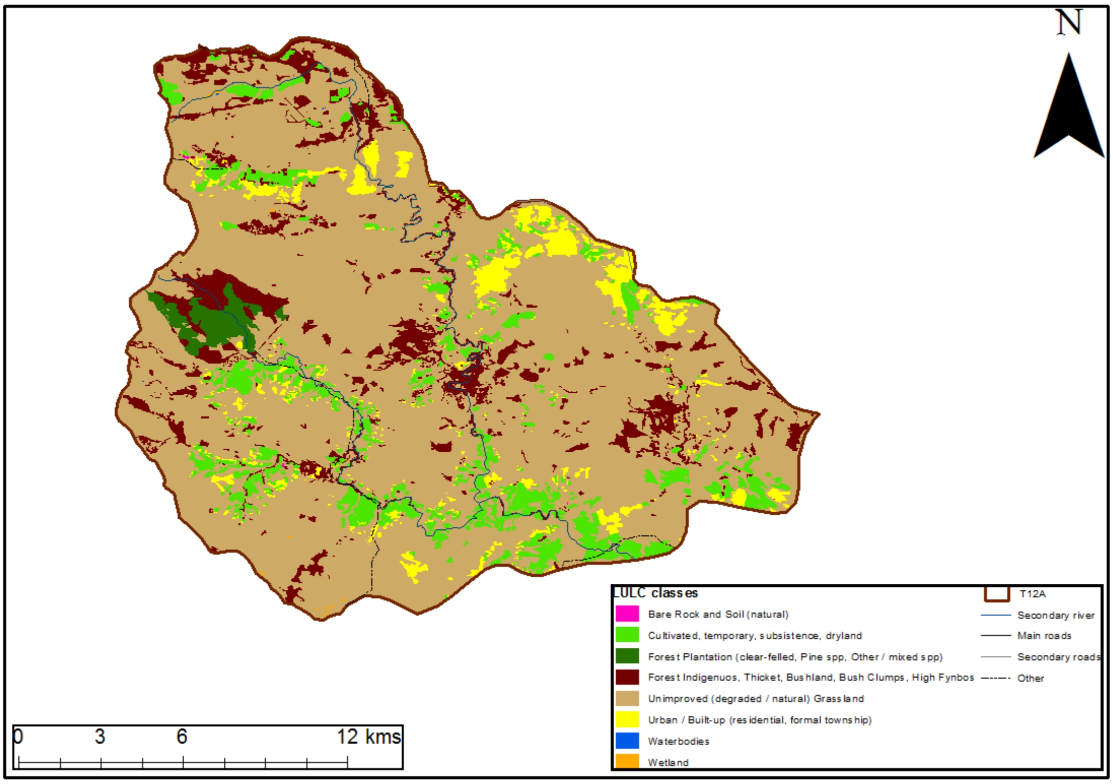


Figure L 2 Edited national land cover (ENLC) 2000 for the QC T12A.

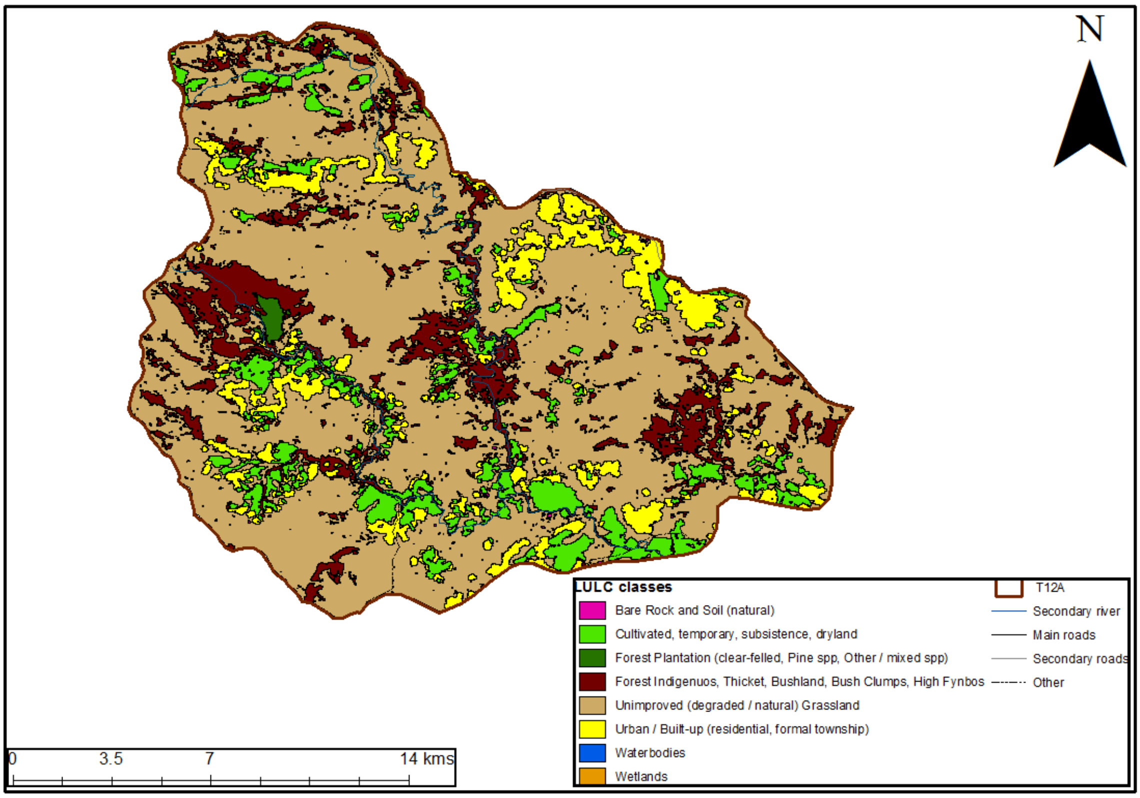


Figure L 3 Derived land cover (DLC) 2014 for the QC T12A.

APPENDIX M

National land cover (NLC)/Edited national land cover (ENLC) 2000 and Derived land cover (DLC) 2014 for the QC S50E

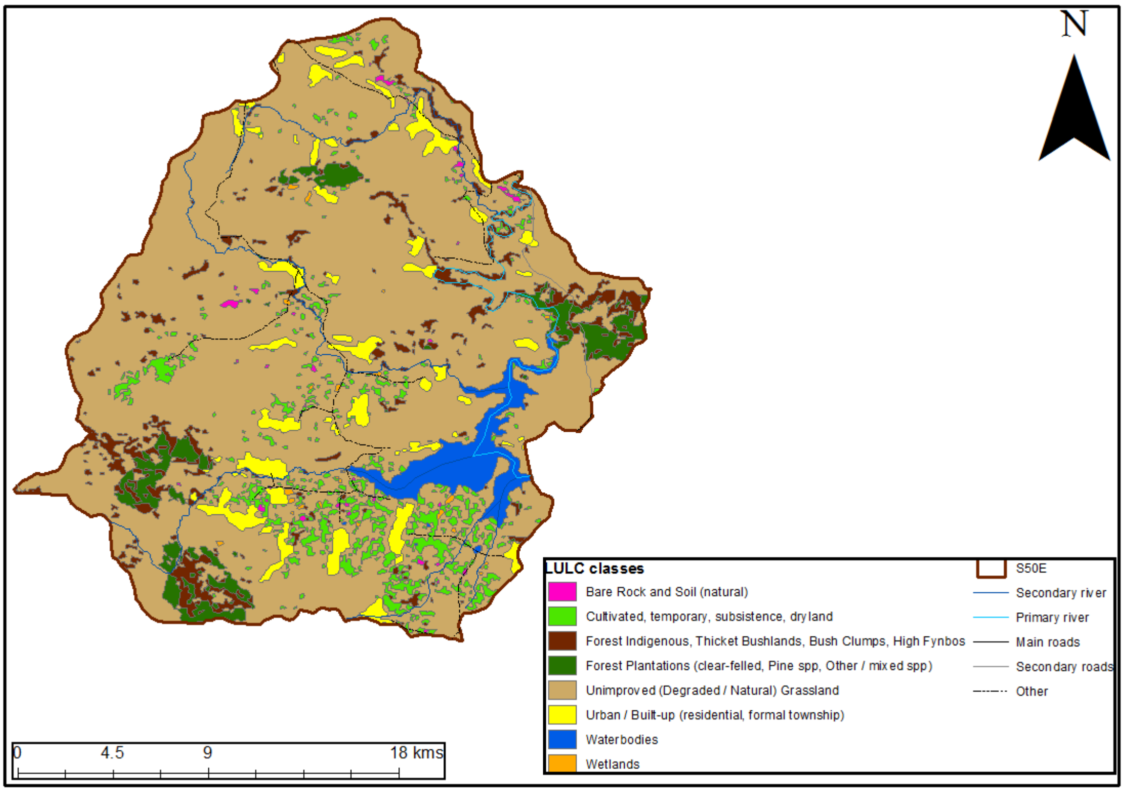


Figure M 1 National land cover (NLC) for the QC S50E.

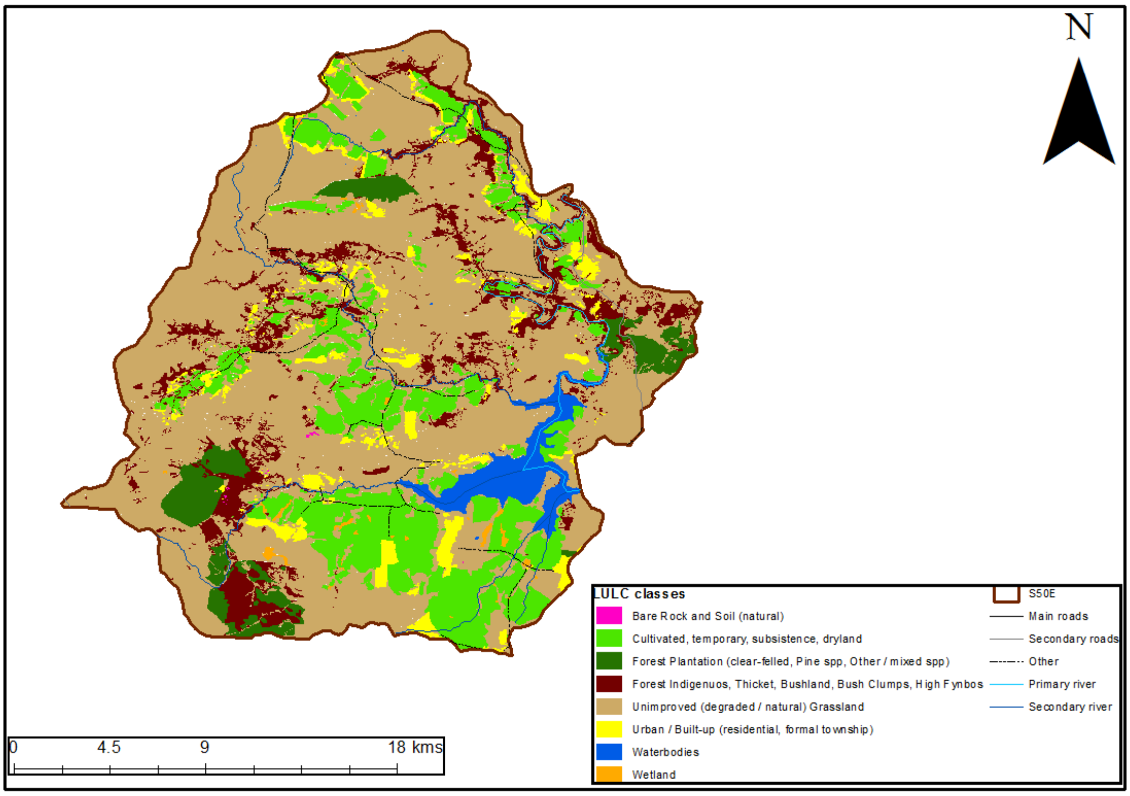


Figure M 2 Edited National land cover (ENLC) 2000 for the QC S50E.

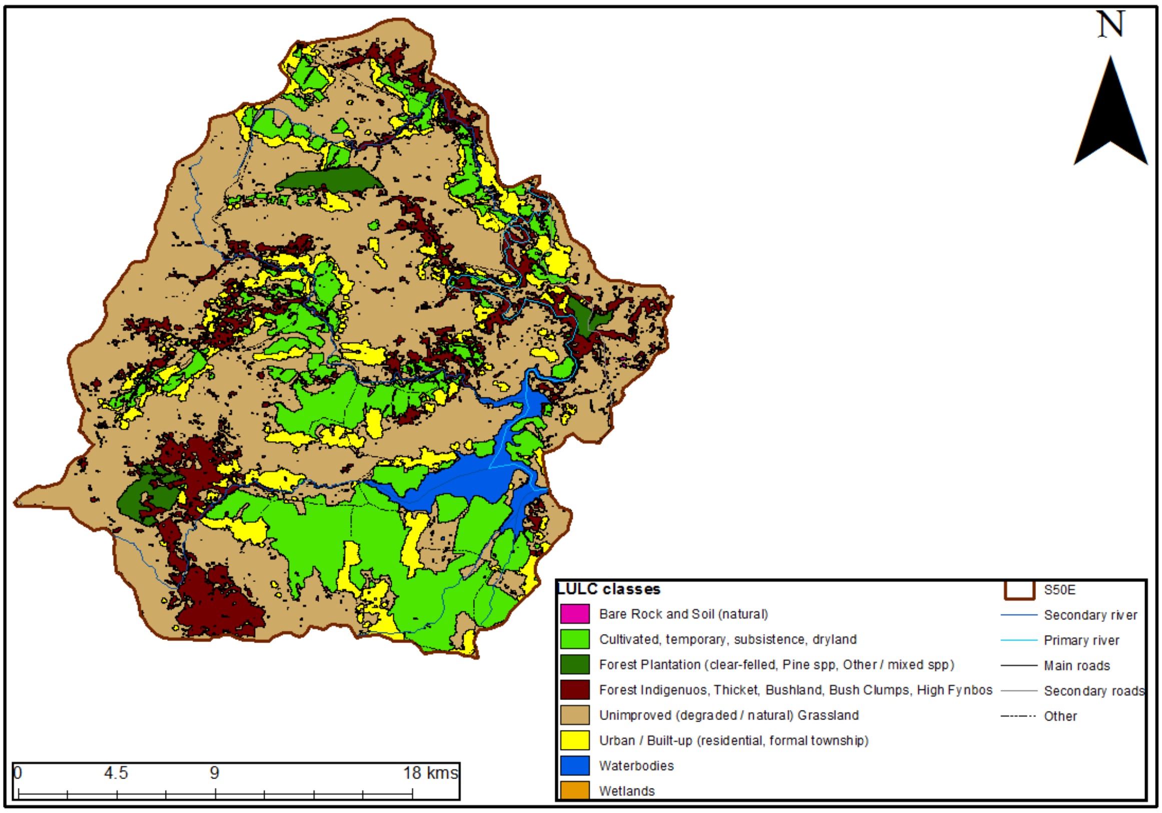


Figure M 3 Derived land cover (DLC) 2014 for the QC S50E

APPENDIX N

Indicator based approach for land cover conversion for the three QCs using NLC 2000.

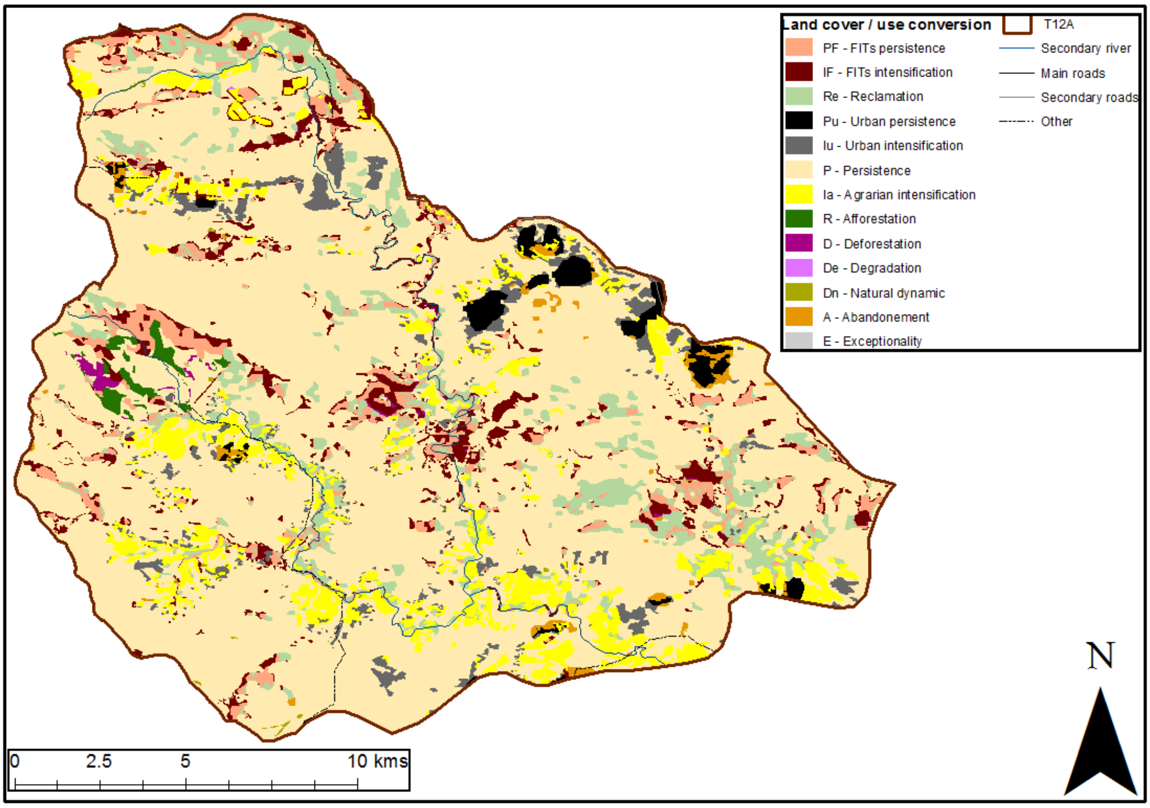


Figure N 1 Indicator based approach for land cover conversion using NLC 2000 for T12A

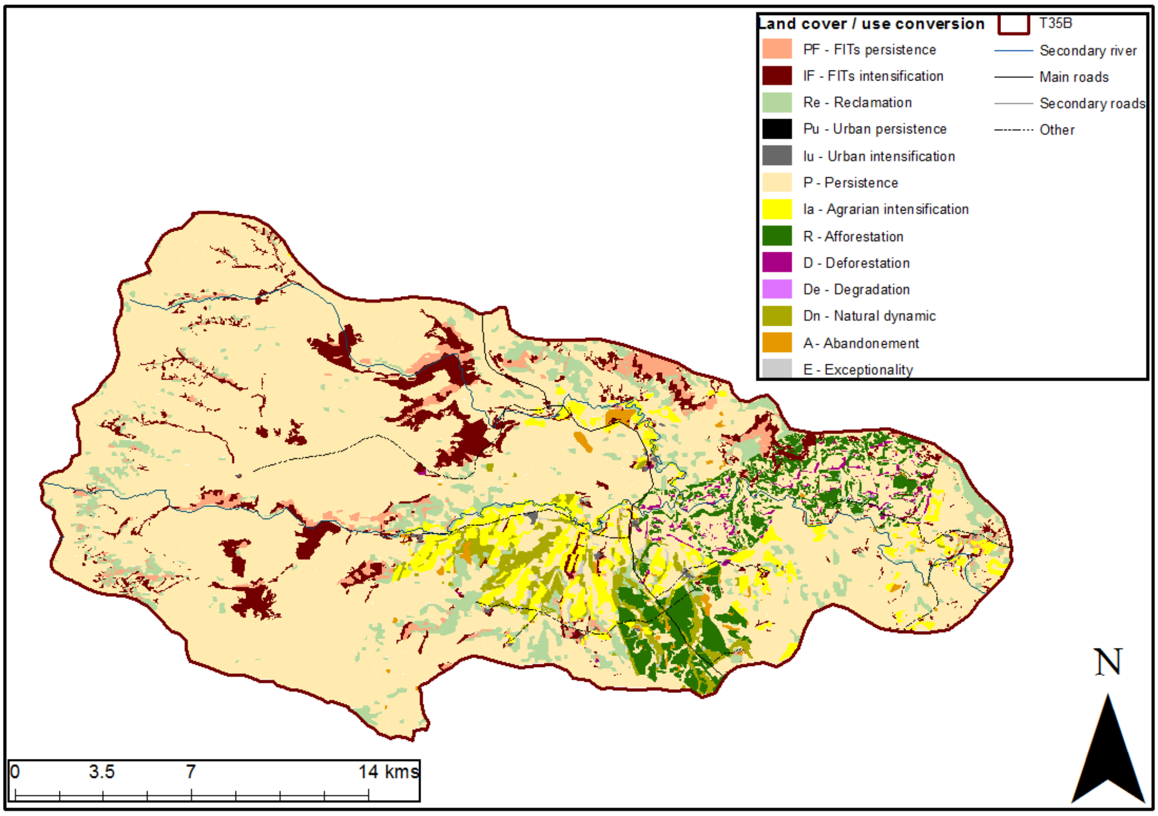


Figure N 2 Indicator based approach for land cover conversion using NLC 2000 for T35B.

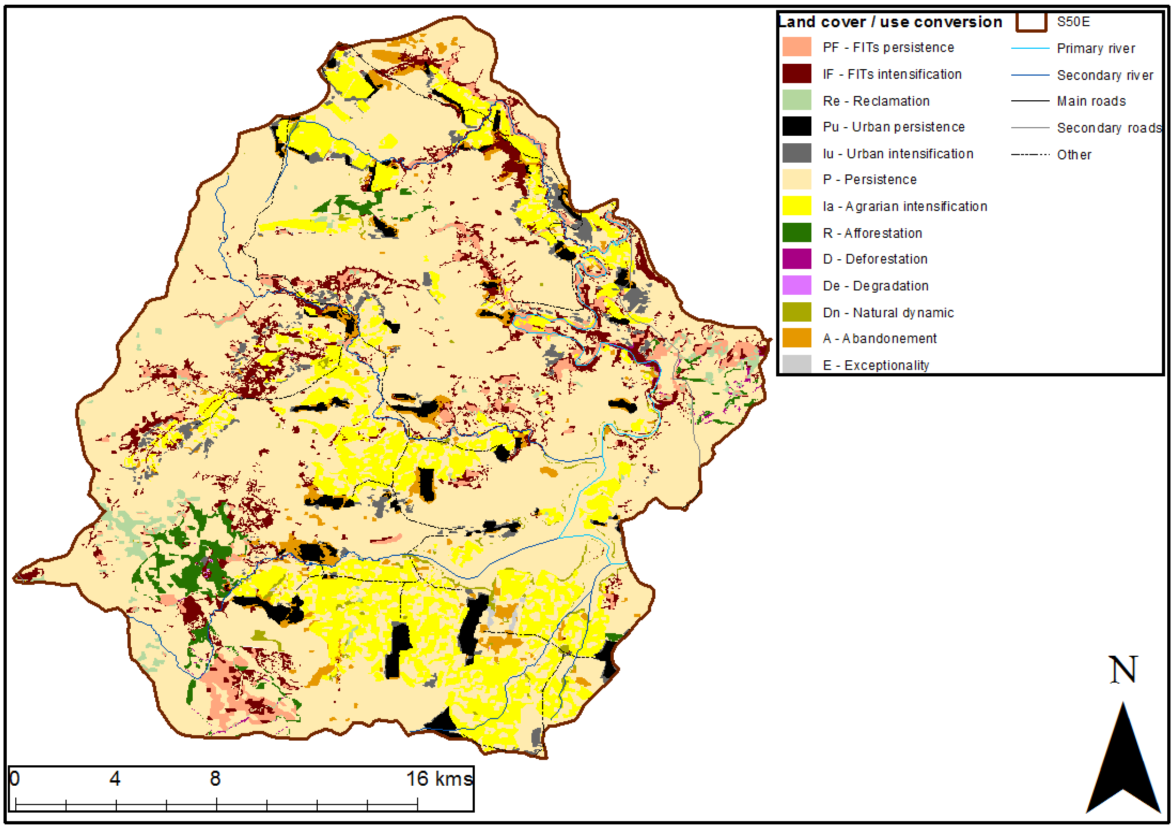


Figure N 3 Indicator based approach for land cover conversion using NLC 2000 for S50E.

APPENDIX O

Indicator based approach for land cover conversion for the three QCs using ENLC 2000.

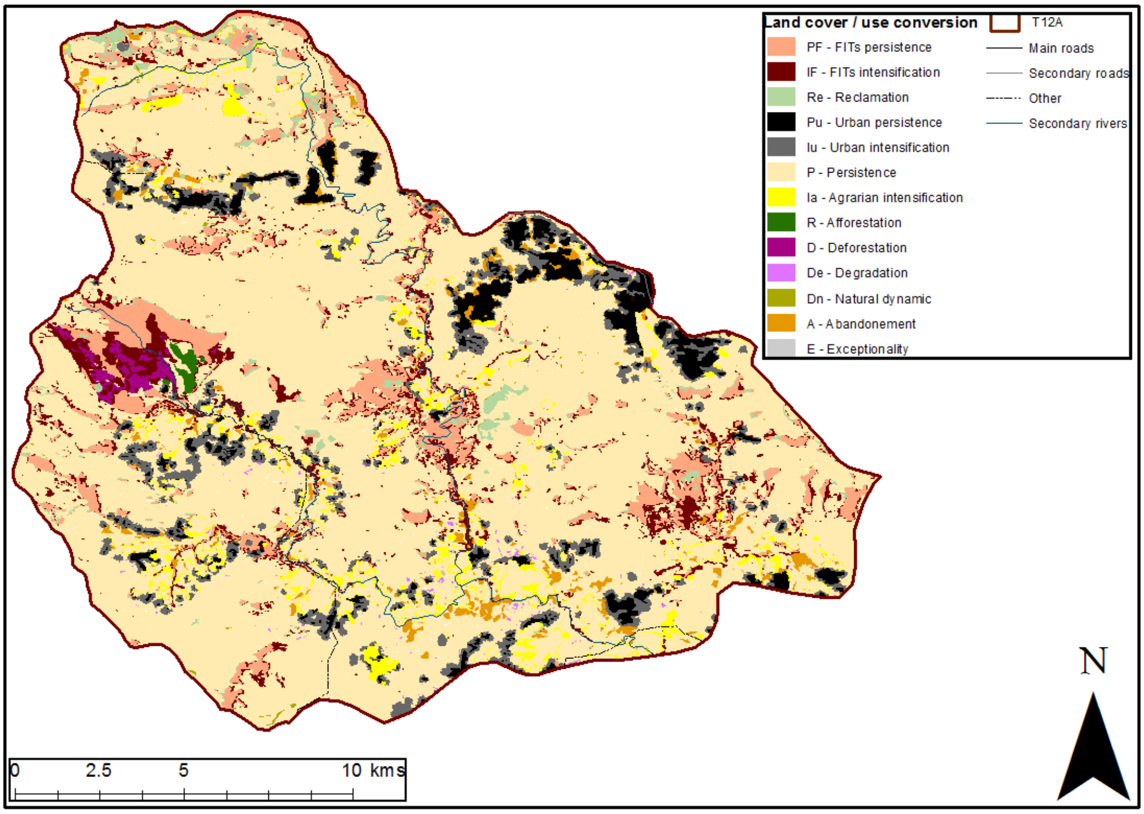


Figure O 1 Indicator based approach for land cover conversion using ENLC 2000 for T12A

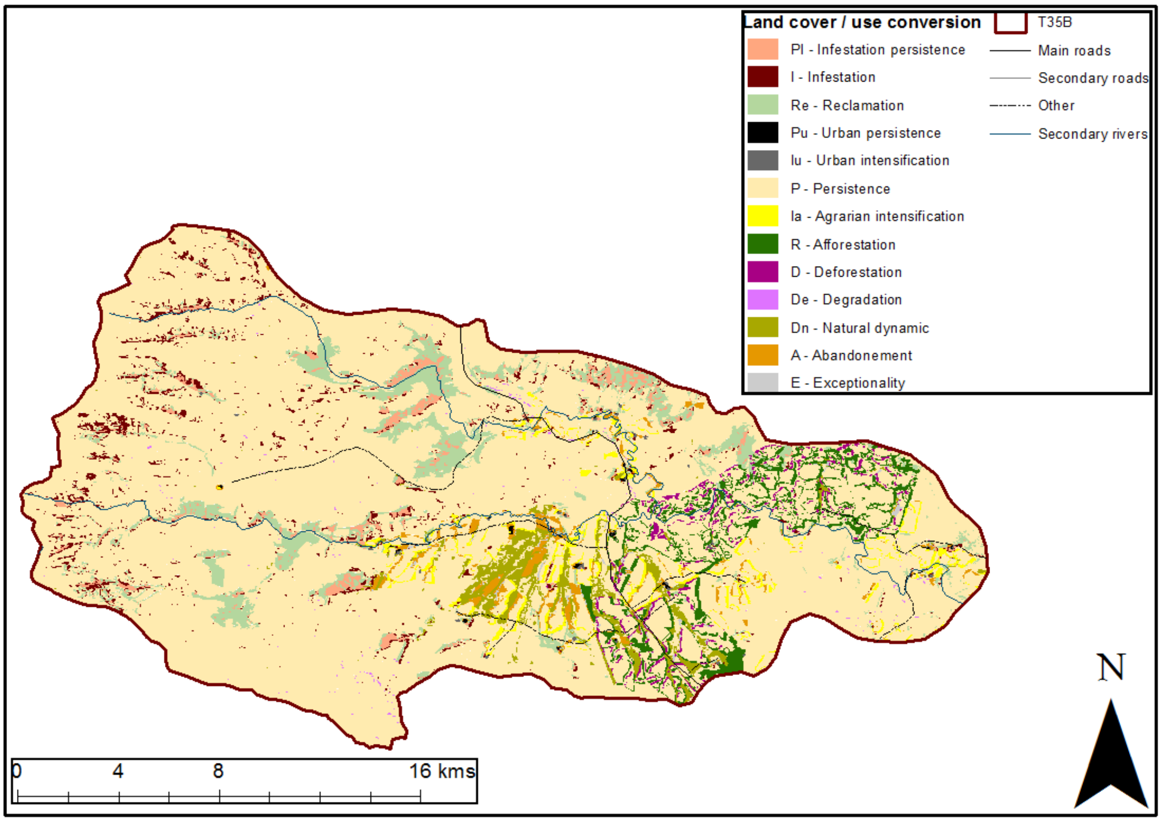


Figure O 2 Indicator based approach for land cover conversion using ENLC 2000 for T35B

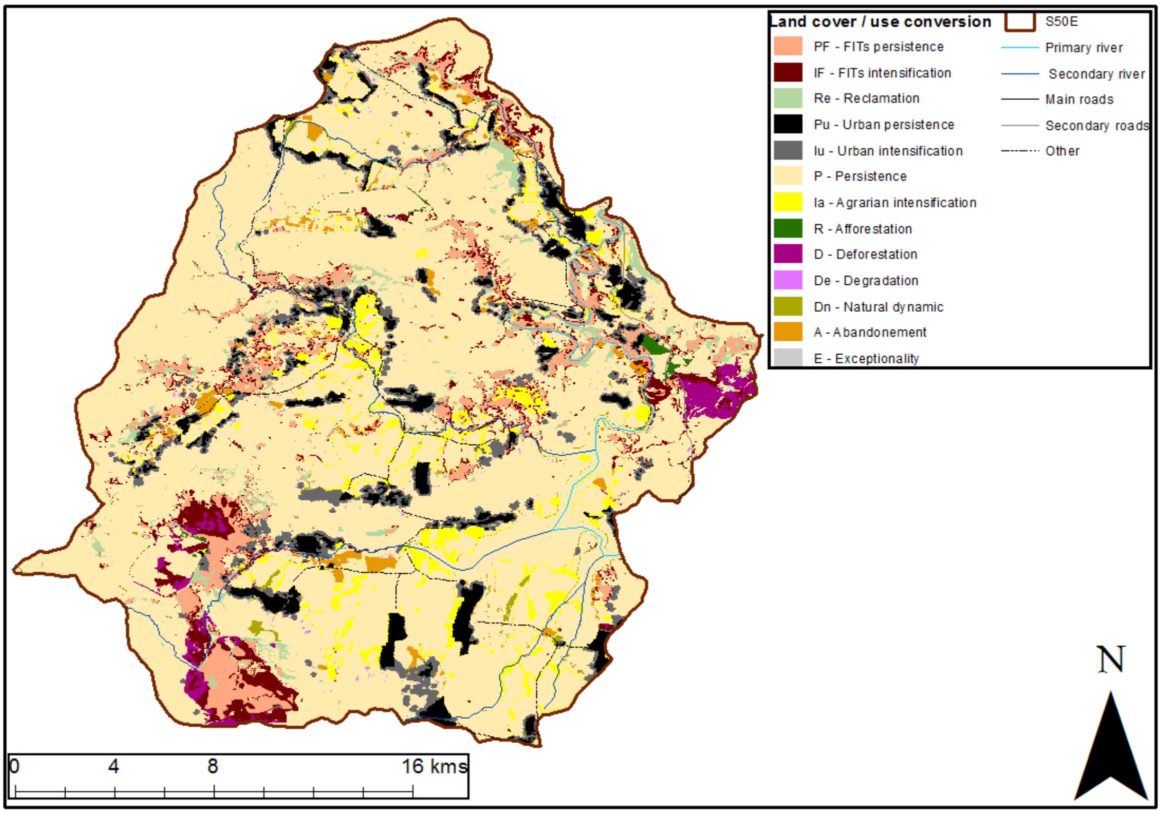


Figure O 3 Indicator based approach for land cover conversion using ENLC 2000 for S50E

APPENDIX P

Raw data on land cover areas (ha) filtered from the Reference State (NLC 2000) and Edited version (ENLC 2000) for 2014 DLC.

Table P 1 Raw data on land cover areas (ha) filtered from the Reference State (NLC 2000) for 2014 DLC

QC T35B													
		Bare rock	**Cultivated**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**FI**	**FP**	**Unknown**	**Total: 2000**	**Total loss**	**% loss**
1	**Bare rock**	0.03	6.59	1.95							**8.56**	**8.53**	**99.65**
2	**Cultivated**	1.31	717.16	215.73	25.65	0.65	18.70	4.82	174.15		**1158.16**	**441.01**	**38.08**
3	**Grassland**	69.87	1113.33	27511.80	28.78	1.58	107.64	936.40	1715.18	0.13	**31484.70**	**3972.77**	**12.62**
4	**Urban**	1.30	5.72	73.26	1.38			0.47			**82.13**	**79.45**	**96.73**
5	**Waterbodies**		0.47	2.02	0.00	6.52	4.33		0.49		**13.83**	**7.31**	**52.87**
6	**Wetland**	0.08	121.15	446.68		5.79	170.39	0.83	28.33		**773.26**	**602.78**	**77.95**
7	**Forest Indigenous**	1.39	452.22	3258.84	19.41	2.42	164.12	674.16	310.01		**4882.56**	**4208.41**	**86.19**
9	**Forest Plantation**	2.25	24.66	53.77	2.08	0.10	5.98	12.06	1044.35		**1145.24**	**100.89**	**8.81**
10	**Unknown**									0.00	**0.00**		
	Total: 2014	**76.23**	**2441.28**	**31564.04**	**77.29**	**17.06**	**471.16**	**1628.73**	**3272.51**	**0.13**	**39548.44**		
	Sum of class gain	**76.23**	**1724.13**	**4052.25**	**75.91**	**10.54**	**300.76**	**954.58**	**2228.16**				
	% class gain	**100.00**	**70.62**	**12.84**	**98.21**	**61.80**	**63.83**	**58.61**	**68.09**				

QC T12A													
		Bare rock	**Cultivated**	**FP**	**FI**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**Unknown**	**Total 2000**	**Total loss**	**% loss**
1	**Bare rock**	0.46	28.53		0.60	7.05	1.39				**38.02**	**37.56**	**98.78**
2	**Cultivated**	1.16	102.84		11.57	88.46	24.05		0.00		**228.08**	**125.24**	**54.91**
3	**FP**		1.43	44.87	552.60	141.63	2.42		0.11		**743.07**	**698.19**	**93.96**
4	**FI**	0.11	382.77	1.52	1447.28	1806.03	77.82		1.58		**3717.11**	**2269.83**	**61.06**
5	**Grassland**	44.17	2000.71	48.20	1451.86	16845.73	207 and 2.62	0.23	16.36		**22479.88**	**5634.15**	**25.06**
6	**Urban**	3.57	18.50		3.83	87.92	540.76		0.09		**654.67**	**113.91**	**17.40**
7	**Waterbodies**					0.24		0.51	0.98		**1.73**	**1.22**	**70.65**
8	**Wetland**		1.49		0.29	2.03					**3.81**	**3.81**	**100.00**
9	**Unknown**												
	Total: 2014	**49.48**	**2536.26**	**94.59**	**3468.03**	**18979.10**	**2719.06**	**0.74**	**19.12**		**27866.37**		
	Sum of class gain	**49.01**	**2433.42**	**49.72**	**2020.75**	**2133.37**	**2178.30**	**0.23**	**19.12**				

	% class gain	**99.06**	**95.95**	**52.56**	**58.27**	**11.24**	**80.11**	**31.54**	**100.00**				
						QC S50E							
		Bare rock	**Cultivated**	**FP**	**FI**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**Unknown**	**Total: 2000**	**Total loss**	**% loss**
1	**Bare rock**		98.66		5.57	34.22	1.85				**140.30**	**140.30**	**100.00**
2	**Cultivated**	2.17	1517.98	0.04	42.57	437.83	80.29	0.29	12.31		**2093.49**	**575.51**	**27.49**
3	**FP**	12.13	1.52	467.21	727.69	505.90	6.47	0.74	1.00		**1722.66**	**1255.45**	**72.88**
4	**FI**	1.79	150.51	159.73	1374.21	668.62	28.03	0.05	1.66		**2384.60**	**1010.39**	**42.37**
5	**Grassland**	70.53	5810.04	177.03	2591.41	23096.86	2566.80	7.54	41.39	0.24	**34361.83**	**11264.74**	**32.78**
6	**Urban**	10.15	351.38	0.12	54.09	418.96	1541.35	0.92	0.38		**2377.35**	**836.00**	**35.17**
7	**Waterbodies**	0.13	133.79		19.54	113.20	5.63	1293.33		2.62	**1568.23**	**272.28**	**17.36**
8	**Wetland**	0.48	40.22	2.78	2.54	60.44	1.24		3.85		**111.55**	**107.70**	**96.55**
9	**Unknown**									0.00	**0.00**		
	Total: 2014	**97.38**	**8104.09**	**806.91**	**4817.62**	**25336.03**	**4231.67**	**1302.88**	**60.60**	**2.86**	**44760.03**		
	Sum of class gain	**97.38**	**6586.11**	**339.70**	**3443.41**	**2239.17**	**2690.32**	**9.54**	**56.75**				
	% class gain	**100.00**	**81.27**	**42.10**	**71.48**	**8.84**	**63.58**	**0.73**	**93.65**				

Table P 2 Raw data on land cover areas (ha) filtered from the Reference State (ENLC 2000) for 2014 DLC.

						QC T35B							
		Bare rock	**Cultivated**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**FI**	**FP**	**Unknown**	**Total: 2000**	**Total loss**	**% loss**
1	**Bare rock**		0.22	0.58	0.07				1.66		**2.53**	**0.80**	**31.63**
2	**Cultivated**	2.54	1772.42	497.72	5.38	1.23	63.57	21.08	52.69		**2416.63**	**644.21**	**26.66**
3	**Grassland**	64.02	409.75	27515.12	23.91	3.43	156.56	906.44	831.07		**29910.30**	**2395.18**	**8.01**
4	**Urban**	0.03	20.20	35.29	27.91	0.16	1.41	4.32	1.81		**91.13**	**59.81**	**65.63**
5	**Waterbodies**	0.10	3.16	15.09	0.04	6.20	7.38	0.15	1.78		**33.89**	**27.44**	**80.98**
6	**Wetland**	3.66	129.48	754.22	1.41	5.55	181.49	6.10	137.98		**1219.89**	**1034.74**	**84.82**
7	**Forest Indigenous**	2.01	95.43	2390.42	17.61	0.44	20.77	687.24	93.65		**3307.57**	**2620.33**	**79.22**
9	**Forest Plantation**	3.98	11.11	355.83	0.93	0.06	39.20	2.99	2151.44		**2565.54**	**374.89**	**14.61**
10	**Unknown**									0.00	**0.00**		
	Total: 2014	**76.33**	**2441.77**	**31564.26**	**77.26**	**17.06**	**470.38**	**1628.32**	**3272.08**	**0.00**	**39547.47**		

	Sum of class gain	**76.33**	**669.35**	**4049.15**	**49.28**	**10.70**	**248.29**	**940.93**	**1118.98**				
	% class gain	**100.00**	**27.41**	**12.83**	**63.78**	**62.71**	**52.78**	**57.79**	**34.20**				
	QC T12A												
		Bare rock	**Cultivated**	**FP**	**FI**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**Unknown**	**Total 2000**	**Total loss**	**% loss**
1	**Bare rock**	0.22	0.01		0.35	1.35	1.59				**3.52**	**3.30**	**100.00**
2	**Cultivated**	2.35	1670.97		74.76	436.47	217.35		0.45		**2402.34**	**731.38**	**30.44**
3	**FP**			41.15	218.92	135.74	1.18		0.25		**397.24**	**356.09**	**89.64**
4	**FI**	0.11	47.27	9.93	1984.50	652.90	37.03		2.45		**2734.19**	**749.69**	**27.42**
5	**Grassland**	43.59	714.84	43.47	1165.95	17640.43	1323.85	0.55	14.76		**20947.44**	**3307.01**	**15.79**
6	**Urban**	1.86	100.64	0.03	11.16	118.69	1132.97		0.20		**1365.55**	**232.59**	**17.03**
7	**Waterbodies**				0.10	1.09	0.01	0.17	0.04		**1.41**	**1.24**	**87.77**
8	**Wetland**		0.24		0.34	12.14		0.02	1.30		**14.04**	**12.74**	**90.77**
9	**Unknown**										**0.00**		
	Total: 2014	**48.14**	**2533.97**	**94.59**	**3456.10**	**18998.80**	**2713.97**	**0.74**	**19.43**	**0.00**	**27865.74**		
	Sum of class gain	**47.80**	**863.00**	**53.41**	**1471.60**	**1358.37**	**1581.00**	**0.55**	**17.20**				
	% class gain	**99.30**	**34.06**	**56.46**	**42.58**	**7.15**	**58.25**	**73.66**	**88.54**				
	QC S50E												
		Bare rock	**Cultivated**	**FP**	**FI**	**Grassland**	**Urban**	**Waterbodies**	**Wetland**	**Unknown**	**Total: 2000**	**Total loss**	**% loss**
1	**Bare rock**	0.64	0.11	0.35	0.57	5.15	6.39				**13.21**	**13.21**	**100.00**
2	**Cultivated**	4.03	6235.73	0.05	189.61	677.77	153.70	4.56	2.32		**7267.76**	**1032.03**	**14.20**
3	**FP**	13.90	1.58	714.15	719.15	571.77	5.46	0.31	1.12		**2027.46**	**1313.31**	**64.78**
4	**FI**	3.44	63.47	63.43	2742.85	1280.03	168.38	6.15	1.96		**4329.71**	**1586.86**	**36.65**
5	**Grassland**	73.00	1571.78	25.14	1147.86	22612.01	2004.55	25.71	49.52		**27509.56**	**4897.55**	**17.80**
6	**Urban**	1.52	106.71	1.34	6.24	42.48	1891.37				**2049.66**	**158.29**	**7.72**
7	**Waterbodies**	0.05	39.73		7.04	56.30	1.27	1264.12	0.10		**1368.61**	**104.49**	**7.63**
8	**Wetland**		81.93		1.58	101.50	3.20		4.86		**193.08**	**188.21**	**97.48**
9	**Unknown**									0.00	**0.00**		
	Total: 2014	**96.57**	**8101.05**	**804.46**	**4814.90**	**25347.01**	**4234.33**	**1300.85**	**59.89**	**0.00**	**44759.05**		
	Sum of class gain	**95.88**	**1865.31**	**89.97**	**2072.05**	**2735.00**	**2342.96**	**30.58**	**52.71**				
	% class gain	**99.29**	**23.03**	**1.87**	**43.03**	**10.79**	**55.33**	**2.35**	**88.01**				