Litter decomposition as a function of temperature and land use

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Declaration

I, Lusungu Nkhoma, declare that this work is my own. It is being submitted for the research report requirement of the Degree of Master of Environmental Science at the University of the Witwatersrand, Johannesburg. It has not been previously submitted for any degree or examination at any other University.

Signed on this day: 6 Of: February 2019 at: the University of the Witwatersrand (Braamfontein, Johannesburg).

Signature: Nkhoma Date: 6 February 2019.

Abstract

Soils have to be managed so that carbon stocks are sustained in order to conserve this valuable resource. This study examined litter decomposition in different land use types and different temperatures in South Africa in order to contribute to the development of a global map of litter decomposition rates.

The research project used the Teabag Index developed by Keuscamp *et al* (2013), which used green and Rooibos teabags to assess litter decomposition rate constants through the weight loss of the teabags within a 90 day incubation period. Weighed teabags were planted at a depth of 8cm and recovered after 3 months and reweighed. The study took place during winter and summer. This project also focused on different land use types: savanna, grassland and plantations that were in three Provinces in South Africa and these are Limpopo and Mpumalanga and Gauteng. This study found that there are complex interactions between litter quality, temperature, land use and soil properties, which result in the varying rates of decomposition. Litter quality played an important role in decomposition in this study, green tea with a higher labile fraction decomposed faster than Rooibos tea with a higher recalcitrant fraction.

The different land use types have different soil properties and litter; these contribute to the varying litter decomposition rate constants found in the study. It was found that temperature has an effect on different land use types (temperatures between 15 °C–35 °C increase decomposition rate constants) however this study also found the importance of moisture on the temperature control of litter decomposition. Increased rainfall in summer from below 50mm in winter to above 100mm in summer increased decomposition rate constants. Any changes in rainfall and temperature in the future will impact decomposition rates. This study found decomposition rate constants ranging from 0.00183 to 0.01543 and stabilization values of 0.00327-0.79000. This study shows that changes in climate will have significant effects on soil carbon storage and decomposition rate constants in different biomes.

Key words: Litter decomposition rates, teabag index, soil organic matter, litter quality, temperature, land use types

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“Soils teem with incessant activity of microorganisms, feeding, digging, aerating and transforming. They make the humus, the fertile layer to which all life on land is linked”.

-Home (2009, Film)

Chapter 1: Introduction

Soils connect all ecosystems; they contribute to environmental functions and play an essential role in the carbon cycle (Bardgett *et al*, 2005). Soils have been evolving for millennia and they are a dynamic, complex and interconnected ecosystem of minerals, water, air and microorganisms which support life on earth (Brady, 1984; Brevik *et al*, 2015). Perturbations in the global carbon cycle due to anthropogenic activities, along with increases in other Green House Gases (GHGs) are driving climate change (IPCC, 2014). Pre-industrial levels of carbon dioxide (CO_2) in the atmosphere were around 600Gt but they are currently around 750Gt and this is threatening life on earth (IPCC, 2014). These changes in the magnitude of pools and fluxes of carbon reveal the importance of soils as carbon reservoirs; there are about 3170Gt of carbon in terrestrial ecosystems and 80% of this is stored in soils (Davidson and Janssens, 2006; Todd and Schulte, 2012) (Figure 1).

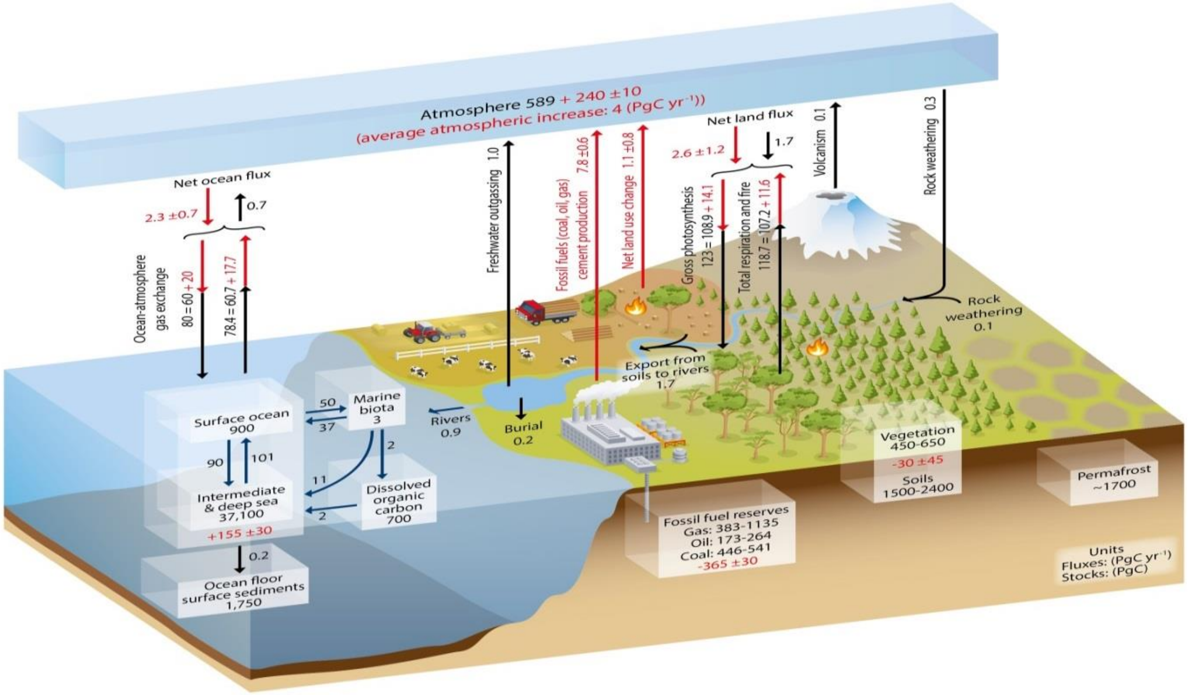


Figure 1: Fluxes and pools of carbon in the global carbon cycle (IPCC, 2013)

Decomposition in soils releases CO_2 into the atmosphere, this process is slower in cold climates and faster in warmer climates. The rise in temperature associated with climate change, will result in more CO_2 being released into the atmosphere and less will be stored in the soil (Melillo *et al,* 2002). Many studies have investigated litter decomposition under varying factors to explore the implications of the rates of litter decomposition on the global carbon cycle but less has been done to develop a global holistic understanding of the rates of litter decomposition and how these will change into the future with climate change. This study aims to contribute to the global map of decay rates by examining litter decomposition using teabags containing standardized litter in 3 different land use types which refers to the vegetation cover found at each site and 2 seasonal variations (summer and winter) within a 90 day incubation period.

1.1. South Africa as the geographical location of the study

South Africa is a country faced with climate change risks. It is predicted that by mid-century the temperature in the South African coastal areas will increase by 5.0 °C-6.0 °C and the interior will warm up by 2.0 °C-3.0 °C, with overall decreases in rainfall but small increases in summer rainfall (Scholes *et al,* 2015). The likelihood of the impact of these shifts in temperature includes adverse human health impacts and poor agricultural outputs, among many others (Scholes *et al,* 2015). Climate change may increase the occurrence and intensity of forest (plantations), grassland and savanna fires, floods and droughts. In addition, these changes may lead to the extinction of some flora and fauna species, thereby threatening South Africa’s biodiversity and ecosystem services (White Paper, 2011). The country’s varied topography and geology provide a template for the diverse soils which are present in the different biomes in the country. South African soils provide a platform for studying litter decomposition across varying climates and land use practices. Soils have a critical role in the global carbon cycle as carbon pools decrease and as decomposition rates increase with temperature; this process acts a positive feedback to climate change (Mellilo *et al*, 2002).

1.2.The purpose of the study

This study explores the dynamics of litter decomposition to gain a greater understanding of carbon pools and sinks which contribute to the global carbon cycle. Three land use types were selected for this research and these sites are savanna, grassland and forest plantation. The rationale for using the research sites is: firstly the savanna biome is the largest biome in South

Africa (occupying over 34% of South Africa, 435 000km) and represents a significant organic carbon pool (Scholes and Walker, 1993). The mixed tree-grass community and regular fires occur on a variety of soils in the biome which generally have low organic matter contents. Secondly, the grassland biome in South Africa is the second largest biome (occupying 28% of South Africa, 360 000km) and has high soil organic matter (SOM) contents (Mucina and Rutherford, 2006; SANBI, 2014). Thirdly, forest plantations occupy the smallest area of South Africa (0.1%, 1062km) and this study will concentrate on Pine plantations which have transformed previous grasslands (Mucina and Rutherford, 2006; Department of Agriculture, Forestry and Fisheries, 2011). This transformation, along with pine litter which makes the soil acidic has implications on decomposition rates.

1.3. Approach to the study

This project is part of an international study which aims to create a global map of decay rates. The “teatime4science” project was developed by researchers from the University of Utrecht, Umeå University, The Netherlands Institute of Ecology and the Austrian Agency for Health and Food Safety Ltd. This study is based on the Tea Bag Index (TBI) method (Keuskamp *et al*, 2013). The TBI method uses green and Rooibos tea as standard plant litter material which makes it easy to compare different study sites and standardises the way of testing climatic warming and land use on decomposition rates. The project is using citizen science to collect data on decay rates from across the globe. The data will develop a global map which will enhance climate models that use maps.

1.4. Research Objectives

Aim:

To study litter decomposition in different land use types and different temperatures in South Africa in order to contribute to the development of a global map of decay rates.

Key questions:

i. How does temperature and moisture affect decomposition rates?

ii. What effects do different land use types have on litter decomposition?

iii. What is the effect of soil properties on decomposition rates?

Chapter 2: Literature Review

This section will include the definition of terms followed by factors controlling decomposition. A review on litter quality, decomposition rate equations and global decomposition rate variations are also included in this section.

The transformation of parent material over time into soil is known as soil formation (Jenny, 1994) and parent material, climate, topography and living organisms form the soil through the process of physical, chemical and biological weathering. The breakdown of rock leads to the formation of the soil mineral components (Brantley, 2010). The biological, chemical and physical decay of organic materials that enter the soil from leaf litter, animal waste, roots or soil biota interacts with the soil mineral component and form soil organic matter (SOM) (Broadbent,1953). Soil organic matter is broken down by soil organisms, both macro and micro-organisms and through the mineralisation process, nutrients such as Nitrogen (N), Phosphorus (P) and Sulphur (S) are released into the soil in forms that can be used by plants (Olson, 1963).

During the decomposition process, carbon structures are also broken down, rebuilt and stored. This is important in the nutrient cycling process. As SOM decomposes, some carbon is mineralized to CO_2 and is lost from the soil (Davidson and Janssens, 2006). Organic matter content increases the capacity of soils to store water and most importantly sequester carbon (Von Lutzow *et al*, 2006).

Fast litter decomposition rates can increase soil fertility and nutrient cycling and thereby increase the rates at which CO_2 is released into the atmosphere and affect the global CO_2 balance (Prescott, 2010). The litter decomposition process is vital in the climate change discourse given the central role of mineralization of organic forms of carbon (C) and its release to the atmosphere (Prescott, 2010; Wang, 2017).

Carbon is a crucial component of SOM which plays a role in biological, chemical and physical properties of soil. It is in view of this that soil carbon is fundamental in the global accounting of carbon (Brady and Weil, 2002). As SOM represents one of the largest pools of C on the global scale (Figure 1), the change in storage of C in response to climatic warming is a key factor for the accounting of terrestrial carbon balance (Von Lützow and Kögel-Knabner, 2009).

2.1. Definition of terms

i. Litter decomposition

Different biomes have various plant parts including leaves, roots, branches and stems, which form litter layers, at different stages of breakdown (Wang, 2017). These stages of breakdown include newly fallen material (litter), fermentation (slightly decomposed material) and advanced decomposed material (humus). These stages provide the platform for the biological transformation of organic matter which is litter decomposition (Bot and Benites, 2005; Wang, 2017). The chemical makeup of litter is mainly grouped into 3 substances: soluble substances, polymer carbohydrates and hemicellulose, and aromatic compounds like lignin and phenolic products (Berg and Mcclaugherty, 2014). The amount and composition of litter varies across soils in different biomes around the globe because of its chemical makeup (Gessner *et al*, 2010).

Pine litter is distinguished by a low concentration of nutrients and proteins and a high level of phenolics which make pine litter slow to decompose (Berg and Staaf, 1980; Klotzbucher *et al*, 2011). On the other hand savanna litter is characterized by a higher quality of litter due to mixed litter (grass leaf litter and tree leaf litter) which is made up of a mixture of sugars, hemicellulose and other longer chained polymers (Furniss *et al*, 1982; Gartner and Cardon, 2004).Nutrient release in labile litter can stimulate decomposition in more recalcitrant litter which makes litter decomposition in savannas very dynamic (Gartner and Cardon, 2004; Bonanomi *et al*, 2010). Conversely in Grasslands, the litter is comprised of cellulose and lignin with varying rates of decomposition: faster rates of decomposition in semiarid and arid grasslands and slower decomposition rates of litter in humid grasslands because of the different ratios of carbon and nitrogen (Moretto *et al*, 2001; Li *et al*, 2011). Litter formed from different plant materials in different biomes affects the constituents of litter and the availability of nutrients or litter quality which in turn affects litter decomposition rate, the higher the C:N ratios, the slower the decomposition (Makkonen *et al*, 2012).

ii. The stabilisation factor S and the decomposition rate k

The stabilization factor S is the extent of the stabilization of the decomposition of organic carbon (Keuskamp *et al*, 2013) and it is a key parameter for measuring changes in decomposition. Stabilization is the binding of SOM to clay minerals which then reduces its degradation or the rate at which the SOM decomposes (Laird *et al*, 2001, Laird, 2001; Marshner *et al*, 2008). Coarse clay (clay with a higher proportion of sand) generally contains more recalcitrant or humified fractions of organic matter than fine clay (clay with a high proportion of silt and clay) which contains more labile and less humified organic matter (Laird *et* al, 2001). Retention of ^{14}C was found to increase in soils with 4-34% clay content (Laird *et* al, 2001). Clay content therefore plays an essential part in the stabilization of soil organic matter (Marshner *et al*, 2008).

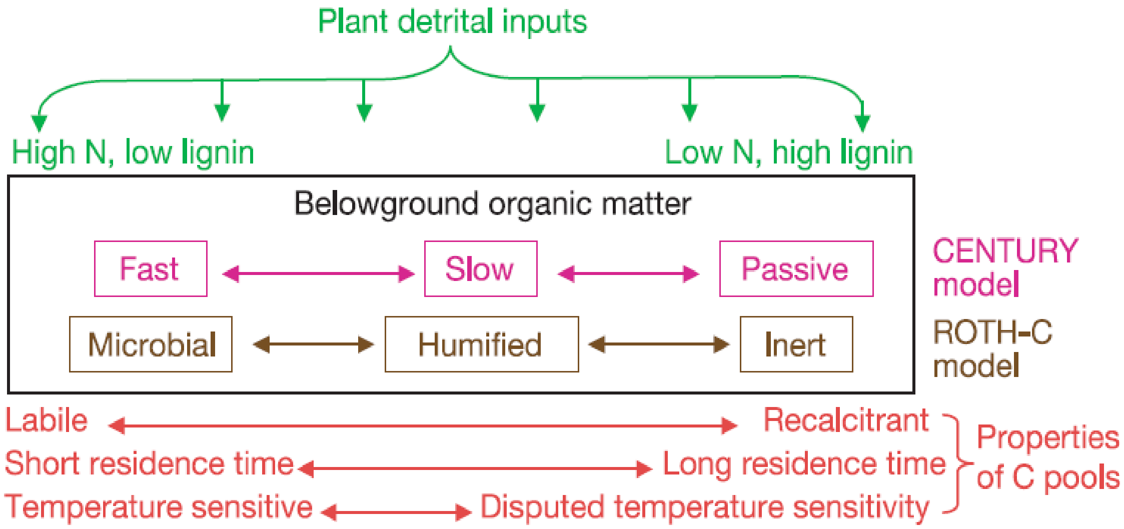
The decomposition rate k is estimated using the weight loss of teabags over time and it defines the slope of the decay in the intermediate stages of the decomposition process. Factors affecting k include climate (temperature, precipitation), litter quality and carbon:nitrogen ratios, among many others (Aerts, 1997). Higher k-values signify a fast rate of decomposition and lower values correspond to a slower rate of decomposition.

iii. Recalcitrant and labile fractions

Soil carbon exists in different forms such as dissolved organic matter, particulate organic matter, humus and resistant organic matter. These forms of carbon take days, 2-50 years, decadal and hundreds to thousands of years for the turnover rate respectively. On the other hand it is argued that the response of soil carbon to climatic warming is based on relatively short periods and this means that fluxes in soil carbon stocks over decadal to centennial time scales remains unclear (Ziegler *et al*, 2017).

Recalcitrant fractions are almost non-reactive organic materials which affect the soil properties. Recalcitrant fractions continue in nature for centuries and resist degradation (Strosser, 2010). Labile fractions on the other hand are readily decomposable organic materials that have temporal fluctuations (Kolář *et al*, 2009; Strosser, 2010) (Figure 2).

Recalcitrant fractions of soil organic matter are regarded as an important factor for soil stabilisation (Marshner *et al*, 2008). Physical protection mechanisms of organic matter slow down decomposition processes of labile fractions and increase the labile pool of organic matter as the organic matter decomposed slowly and therefore have a longer retention time in the soil (Marshner *et al*, 2008). Recalcitrant fractions of organic matter are physically and chemically occluded and as a result decompose slowly thereby increasing the retention time of carbon in soils (Davidsons and Janssens, 2006).



<u>Figure 2: Pools of below ground carbon stocks (Davidson and Janssens, 2006)</u>

2.2. Climate change

Climate change is argued to lead to increased release of carbon from soils and increased effects of further changes in carbon stocks (Schlesinger and Andrews, 1999; Aerts, 2006). Climate change may lead to increased decomposition rates only if there are adequate levels of soil moisture, that is where soil water contents is sufficient so that desiccation stress of roots or microorganisms does not occur (Davidson *et* al, 1998). These two factors, moisture and temperature have strong links to litter decomposition (Aerts, 2006).

Litter decomposition is temperature sensitive and has strong linkages to climatic variables. It is expected that climatic warming will lead to increased litter decomposition and increases in the fluxes of carbon dioxide (Aerts, 2006). Since a Q_{10} of decomposition is 2, every 10 °C rise in temperature will double the rate of decomposition under specific conditions (Davidson *et al*, 1998). So for the predicted 2.0 °C to 3.0 °C in the interior of South Africa, the decomposition rates should be expected to increase by 0.2 to 0.3 (Davidson *et al*, 1998; Scholes *et al*, 2015). The conditions for the rate of decomposition to increase vary because of litter quality, differences in the amount labile and recalcitrant materials which have different sensitivities to temperature and soil moisture availability, among many other factors (Zhang *et al*, 2008).

Climatic warming has generally been said to control decomposition on a regional scale while litter quality controls decomposition on a local scale (Berg, 1999).Climate affects litter decomposition directly through temperature and moisture regimes of regions and indirectly through plant composition and litter quality (Aerts, 2006; Pérez-Harguindeguy *et al*, 2007). The direct effects change the rate of litter mass loss at a short time scale and at longer time scales climate affects litter decomposition indirectly (Aerts, 2006). Indirect effects are manifested through litter quality, in the phenotypic responses of plant species or through changes in plant structure (Aerts, 2006). Moreover, most research show that decomposition rates change as a function of temperature and as a result SOM storage decreases in response to climatic warming (Kirshbaum, 1994; Melillo *et* al, 2002; Von Lützow and Kögel-Knabner, 2009). When carbon emissions from warmed soils exceed vegetation growth, soils become sources of atmospheric CO_2 (Von Lützow and Kögel-Knabner, 2009).

Additionally climate change will have impacts on soil pH, affect electrical conductivity, and reduce soil moisture and SOM (Schmidt *et al*, 2011). A study by Berg *et al* (1993) found that average yearly temperatures only account for 18% of annual mass loss rates of the Pinus litter studied but total annual precipitation accounted for 30% and actual evapo-transpiration (AET) accounted for 50% of the variation in mass loss rates. These are fundamental interactions which need better understanding in order to gain new insights into global climate effects on decomposition and to be able to utilize litter decomposition as a baseline for future carbon stocks and fluxes estimations/calculations.

2.3. Factors controlling decomposition

i. Temperature and moisture

There are environmental constraints that affect decomposition rates such as drought and floods, chemical and physical protection of the soil which influence the substrate concentration at enzymatic reaction sites (Davidson and Janssens, 2006). However, most approaches to modelling decomposition accept that decomposition of soil organic matter is temperature sensitive (Schimel *et al,* 1994; Kirshbaum, 1994; von Lützow and Kögel-Knabner, 2009; Haddix *et al*, 2010; Zhu and Cheng, 2011; Muñoz *et al*, 2016). Carbon dioxide, energy, water, plant nutrients and resynthesized organic carbon compounds are produced in soils from decomposition of organic matter. These processes are temperature dependent (Davidson and Janssens, 2006).

Soil moisture is an essential factor in net primary productivity and it affects the storage and cycling of soil carbon (Moyano *et al*, 2013). Soil carbon stocks at the global scale have a positive correlation with the mean annual precipitation and a negative correlation with the mean annual temperature (Moyano *et al*, 2013). These correlations result in significant carbon storage in moist and cold ecosystems, as well as soils which are continuously saturated (Moyano *et al*, 2013).

Some studies have shown that decomposition rates were found to be greater at sites which were colder and wetter, contradicting most studies which find that decomposition is faster at higher temperatures (Murphy *et al*, 1998; Aerts, 2006, Bothwell *et al*, 2014). This contradiction is due to the fact that some studies have found that decomposition was limited by moisture at sites with warmer temperatures (Murphy *et al*, 1998).

Soil moisture availability affects litter decomposition directly through litter fragmentation and leaching of labile components as well as through affecting biotic activity of litter decomposing microorganisms (Yahdjian *et al*, 2006; Moyano *et al*, 2013). Soil microorganisms reduce their activity with a decreased soil water availability (Manzoni and Schimel, 2012; Moyano *et al*, 2013) and these constraints on microorganisms have impacts on carbon storage and cycling. The indirect effects of soil water availability on decomposition include the change of species abundance and composition of plants and microorganisms (Gonzalez and Seastedt, 2001). High levels of moisture in the soil results in a slow decomposition rate because water fills the airspace in the soil, inhibiting oxygen diffusion and conversely low moisture decreases the decomposition rates as microorganisms in the soil cannot survive without water (Davidson *et* al,1998; Riutta *et al*, 2012). A study by Aerts (2006) found that the changes in summer precipitation have a strong impact on decomposition, as moisture limitation dwarfs the effect of increasing temperatures.

A study on climatic controls of leaf litter decomposition across European forests and grasslands found that decomposition rates were generally higher in sites that were warmer and wetter than colder and dry sites (Portillo-Estrada *et al*, 2016). Contrastingly another study in China found that high quality litter in grasslands is more likely to be limited by soil moisture availability than low quality litter which is more sensitive to nutrient availability (Liu *et al*, 2005). On the other hand savannas have a mixed-species litter from the grass and tree components which has implications for microbial decomposer abundance and activity and this affects decomposition rates (Gartner and Cardon, 2004). Litter from different species have impacts on the total litter surface on which decomposition occurs (Gartner and Cardon, 2004). Additionally, a study in South Africa on Pine forests in Mpumalanga found that decomposition rates were slower in high altitude sites which lead to high accumulation of litter in high altitude site (Dames, 1996). Another study in Mpumalanga also found that litter decomposition of needle litter increased with temperature making temperature a strong factor influencing decomposition over litter quality (Salah and Scholes, 2011). Furthermore, soil temperature impacts the rate at which SOM decompose and areas with higher temperatures decompose SOM faster than colder areas (Aerts, 2006; Yoon *et al*, 2014). Litter decomposition experiments in grasslands and forests across a climatic gradient (5.6 °C-11.4 °C annual temperature and 511mm-578mm of precipitation) found that decomposition rates were higher in wetter and warmer sites than in drier and colder sites (Portillo-Estrada *et al*, 2016). Furthermore, for savannas, moisture has also been found to increase decomposition rates (Wuta *et al*, 2013) which highlights the importance of moisture in litter decomposition.

A meta-analysis in cold biomes, of warming experiments, showed a slight increase in decomposition rates and this slight increase was attributed to moisture constrained decomposition (Aerts, 2006). Many studies have found the importance of temperature and moisture on litter decomposition as they are factors controlling SOM decomposition (Chen *et al,* 2000; Wang *et al,* 2016). Astudy by Chen *et al* (2000) found that too little water constrained litter decomposition due to an oxygen limitation or too much water stopped litter respiration because of an oxygen diffusion limitation. If soil moisture is limiting or in excess, temperature effects on soil decomposition are suppressed (Schaufler *et al*, 2010).

ii. Soil properties

a. Texture

The role of soil texture in the decomposition process has been extensively studied and clay soils have been found to contain higher amounts of SOM than sandy soils (Giller *et al*, 1997). Clay soils are argued to protect organic matter against rapid break down through a high cation exchange capacity through encrustation and entrapment (Giller *et al,* 1997). The higher the clay content, the higher the residual carbon content in the soil (Amato *et al*, 1984). Soil texture is also an essential factor affecting decomposition as soils with higher clay contents retain higher amounts of humus (Mtambanengwe *et al*, 2004).

Clay binds to organic matter and develops soil aggregates that protect the soil from breaking down rapidly. Soil C loss is therefore expected to occur slowly in soils with higher clay fractions than soils with high sand fractions (Giardina *et al*, 2001). Clay aggregates reduce soil oxygen (O_2) levels and increase protection of SOM by reducing the amount of substrate accessible for breakdown by microorganisms and weathering (Fissore *et al*, 2016). However there is a contradiction to this finding as increasing amounts of clay increase the rate of SOM decomposition by augmenting the water holding capacity and nutrient cycling of the soil (Fissore *et al*, 2016). This contradiction is supported by findings that high organic matter is found in fine texture soils than soils with coarse texture (Silver *et al*, 2000).

Soil texture is an important factor affecting litter decomposition as it influences organic matter content, pH levels and cation exchange capacity of soils (Fissore *et al*, 2016).

b. Soil chemical properties

Litter decomposition is also controlled by a wide range of soil chemical properties including nitrogen (N), phosphorus (P) and carbon (C) concentrations (Aerts, 1997). In the tropics N and P are important controllers of litter decomposition as high concentrations during initial litter decomposition lead to high decomposition rates (Aerts, 1997). Nitrogen and phosphorus are essential limiting elements for plants in terrestrial ecosystems and P availability is usually low compared to N because the predominant source of phosphorus is rock weathering (Manzoni *et al*, 2010).

Carbon and nitrogen ratios are also an important factor for decomposition as material with high C:N ratios take longer to decompose than a low C:N ratio material which is more labile (Fog, 1988; Manzoni *et al*, 2008).

c. Exchangeable cations

Exchangeable cations calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) often occur in amounts as listed in that order. Calcium occurs in larger amounts than all the other bases (Thomas, 1982). Magnesium may be higher in soils which have dissolved from clays and sodium is usually present in low amounts, except where the parent material is granitic (Thomas, 1982).These cations affect the pH of soils: low pH soils that are acidic reduce the rate of decomposition as they reduce the microbial population (Mtambanengwe *et al,* 2004) and this has implications for soil nutrient cycling. Soils with a neutral pH will have a higher cation exchange capacity (CEC) than soils with a pH of 5 or lower (Ketterings *et al*, 2007).

Soils with higher (CEC) have been found to reduce SOM decomposition by restricting the substrate or enzymes on the exchange sites or in soil aggregates (Chivenge *et al,* 2011). Sariyildiz *et al* (2005) found conflicting results as their study found that a high concentration of cations corresponded to a high decomposition rate as it reveals rapid nutrient cycling. Organic matter and clay fractions contribute primarily to CEC and fine textured soils have a higher CEC than coarse textured soils because of the low clay content in the latter (Turpault *et al*, 1996; Gruba and Mulder, 2015).

2.4. Litter quality

The relationship between climate, litter quality parameters and decomposition rate are often not linear. There are complex interactions between litter quality and climate parameters which control litter decomposition (Zhang *et al*, 2008). Litter quality is an important factor controlling decomposition rates (Singh *et al*, 1999); decomposition of leaf litter is critical in the C balance and nutrient cycling processes of all terrestrial ecosystems (Scheffer *et al,* 2001). Studies have shown that slower decomposition rates in terrestrial ecosystems create potential temporary C sinks (Jeyanny *et al*, 2014).

Litter quality affects decomposition rates through microclimatic and microbial community composition (Zhao *et al*, 2013). One study by Hobbie (1996), found that differences in rates of litter decomposition were more related to carbon quality than to nitrogen concentration. On the other hand it has been postulated that litter decomposition rates are controlled by environmental conditions, chemical composition and soil organisms and that these factors apply a hierarchical control on rates of decomposition. This hierarchy places climate at the top, litter quality in the middle and soil microbes at the bottom (Lavelle *et al*, 1993). However under warm, wet conditions, climate is less of a limiting factor for decomposition and litter quality is the essential factor (Couteaux *et al*, 1995).

A litter bag experiment which used needle or leaf litter from a range of litter types found that decomposition is limited by carbon substrates rather than nutrient content (Murphy *et al,* 1998). In another study, Wang *et al* (2007) found that leaf litter plays a critical role in decomposition as the mixed stand in their study had faster decomposition rates which accelerated the return of nutrients to the soil than the monoculture in their study. Terrestrial ecosystems which have the highest C content are those that have low litter decomposition rates but C can also accumulate at places with high decomposition rates if primary production is high (Couteaux *et al,* 1995). It is expected that the increase in atmospheric CO_2 will increase net primary production and this will increase litter production which will in turn increase soil organic matter accumulation (Coteaux *et al,* 1995; Morgan *et al,* 2011).

2.5. The approach used in this study to quantify the decomposition rate constant

There are many approaches to estimate the above ground litter decomposition such as the mass balance method which estimates litter decomposition for whole ecosystems (litter fall/detrital litter mass = k) (Karberg *et al,* 2008). This method assumes that the annual above ground litter decomposition (which consists of leaves and twigs above the soil) should equal the annual input of fresh litter while the detrital litter stored in the ecosystem stays constant. Another estimation method of leaf litter is the cohort layered screen which places mesh screens to separate layers of litter on the forest floor. The leaf litter then decomposes on site and is studied for 3 or more years (Hoover, 2008). Other approaches use laboratory incubations or measure the emissions of carbon dioxide in order to estimate the rate of decomposition in ecosystems (Sun *et al,* 2017).

The litter bag method is the most commonly used approach in estimating litter decomposition rates and it involves leaving litter samples, in the field, to decay in mesh bags. The mesh bags are then recovered after a period of time (Didion *et al*, 2016). The calculation for the decomposition rate has evolved from the first order kinetics model first proposed by Jenny *et al* (1949) ($M_t = M_o e^{-kt}$ where M_t = final weight of the litter bag, M_o = initial weight of the litter bag, k = decomposition rate constant and t = time in days or years) which assumed the process of decomposition proceeded at a constant rate regardless of the amount of material left at any given time (Berg, 2014). The newer approach uses a decomposition rate equation ($W(t) = ae^{-kt} + (1-a)$ where W (t) = weight of the substrate after incubation time t in days, a = labile and 1-a =

recalcitrant fraction of the litter) takes into account the labile and recalcitrant compounds and estimates k separately for the two groups (Wieder and Lang, 1982). This is the equation that was used for this study as the decomposition rate "k" can only be estimated from the early stages of decomposition and the decomposable fraction "a", can only be estimated when most of the labile material is consumed (Keuskamp *et al*, 2013).

To calculate k: $k = \{\ln ([a_r/w_t] – (1 – a_r)\} / t$, where a_r is the decomposable fraction of Rooibos tea which can be estimated from the decomposable fraction of green tea (1 – [final $\text{weight}_{\text{green tea}}$/ initial $\text{weight}_{\text{green tea}}$]). Wt is the fraction remaining which is calculated from the Rooibos tea (final $\text{weight}_{\text{Rooibos tea}}$/ initial $\text{weight}_{\text{Rooibos tea}}$) and t is the time period in days (number of days between date of burial and date of recovery) (Keuskamp *et al*, 2013).

Keuskamp *et al* (2013) assumed that the decomposition rate is constant and can be fitted to an exponential decay function. However, easily degradable compounds in plant litter decompose much faster than recalcitrant compounds which decompose at a much slower rate (Keuskamp *et al*, 2013). Green and Rooibos Lipton tea were used because of their commercial availability and also because they have different decomposing rates (Keuskamp *et al,* 2013). Green tea and Rooibos tea were decomposed in a laboratory and found that green tea decomposes much faster than Rooibos tea. The decomposition of green tea had started to level off at the beginning of the 40-60 day period, while Rooibos tea only started to level off at the end of the period. The study uses two types of tea to address this assumption; a 90 day period is long enough to measure the weight loss of green tea to determine the stabilization factor (S) and short enough to determine the initial decomposition rate (k) of Rooibos tea (Keuskamp *et al*, 2013).

The limitations of this approach include the exclusion of certain macroinvertebrates from the litterbags which may play a role in the decomposition of the litter (Karberg *et al*, 2008). Additionally the burying of teabags is subject to the alteration of the microclimate and decomposition conditions at the study sites (Wider and Lang, 1982; Karberg *et al*, 2008).

2.6. Global decomposition rate variations

A comprehensive global database of litter decomposition rates was developed by Zhang *et al* (2008) and k was found to correlate positively with latitude because of indirect effects of mean annual temperature (MAT), mean annual precipitation (MAP) and associated vegetation composition on decomposition. Decomposition rates increased linearly with MAT and MAP. In addition, decomposition rates at the equator were the highest and decreased with latitude towards the north and south poles (Zhang *et al,* 2008). This study found that at the global scale MAT was more important than MAP in controlling litter decomposition but at the local scale, MAP becomes more important in regulating litter decomposition. The decomposition rate was ranked according to land use and was found to be in decreasing order: Rainforest> swamp> broad leaved forest> mixed forest > grassland> shrubland> coniferous forest> tundra. It was also observed that k varied with litter types in decreasing order: grass leaf> moss> broad leaved litter> roots> conifer needles> bark> branch> woody litter. The variance was due to litter quality, microclimates, soil properties and community composition (Zhang *et al*, 2008).

Contrastingly a study on Hawaiian montane wet forest found k to vary between across a MAT gradient (*Bothwell et al,* 2014). Even though there was an increase in decomposition with an increase in temperature, MAP was found to be an insignificant factor regulating decomposition. Subsequently another study on pinewood litter found that pine litter decomposed more slowly than broad leaf litter owing to the strong regulation of substrate on decomposition (Gholz *et al,* 2000). In the wet tropics temperature and moisture are less limiting variables and decomposition rates depend largely on soil properties and litter quality (Couteaux *et al*, 1995). On the other hand Mediterranean regions are mostly moisture constrained in areas close to the southern parts of the Mediterranean zone and additionally tropical regions have an average k-value of leaf litter which are significantly higher than Mediterranean regions (Couteaux *et al*, 1995).

The global pool of carbon has a mean residence time of 32 years and by looking at the mean residence time of soil organic matter in different vegetation types, the soil C turnover can be used to estimate the decomposition rate. Grasslands have a higher soil C turnover than woodlands and forest and as a result grasslands should be expected to have higher decomposition rates (Table 1) (Raich and Schlesinger, 1992).

Table 1: Soil carbon turnover in different vegetation types

Vegetation type	Soil C (kg/m^2)	Turnover (years)
Temperate grassland	18.9	61
Temperate forests	13.4	29
Tropical grasslands	4.2	10
Tropical and lowland forests	28.7	38
Woodlands	6.9	14

(Adapted from Raich and Schlesinger, 1992)

The lowest soil respiration is expected from the coldest and driest biomes and tropical moist rainforests are expected to have the highest soil respiration rates (Raich and Schlesinger, 1992). Soil respiration can be used as a proxy for soil decomposition rates as it has a strong link to productivity. Consequently, productivity provides the organic material for soil litter which then gives insight into how land use type influences decomposition rates.

Chapter 3: Methodology

3.1. Study site locations

The study was conducted in 3 South African provinces: Gauteng, Limpopo and Mpumalanga (Figure 3). In each province 2 study sites where chosen based on access and suitability of the site. Three land use types used namely: grassland, Pine forest plantation and savanna were chosen for this study. Furthermore, two sites were identified for each land use type were chosen based on temperature variations, with one site being cooler or warmer than the other

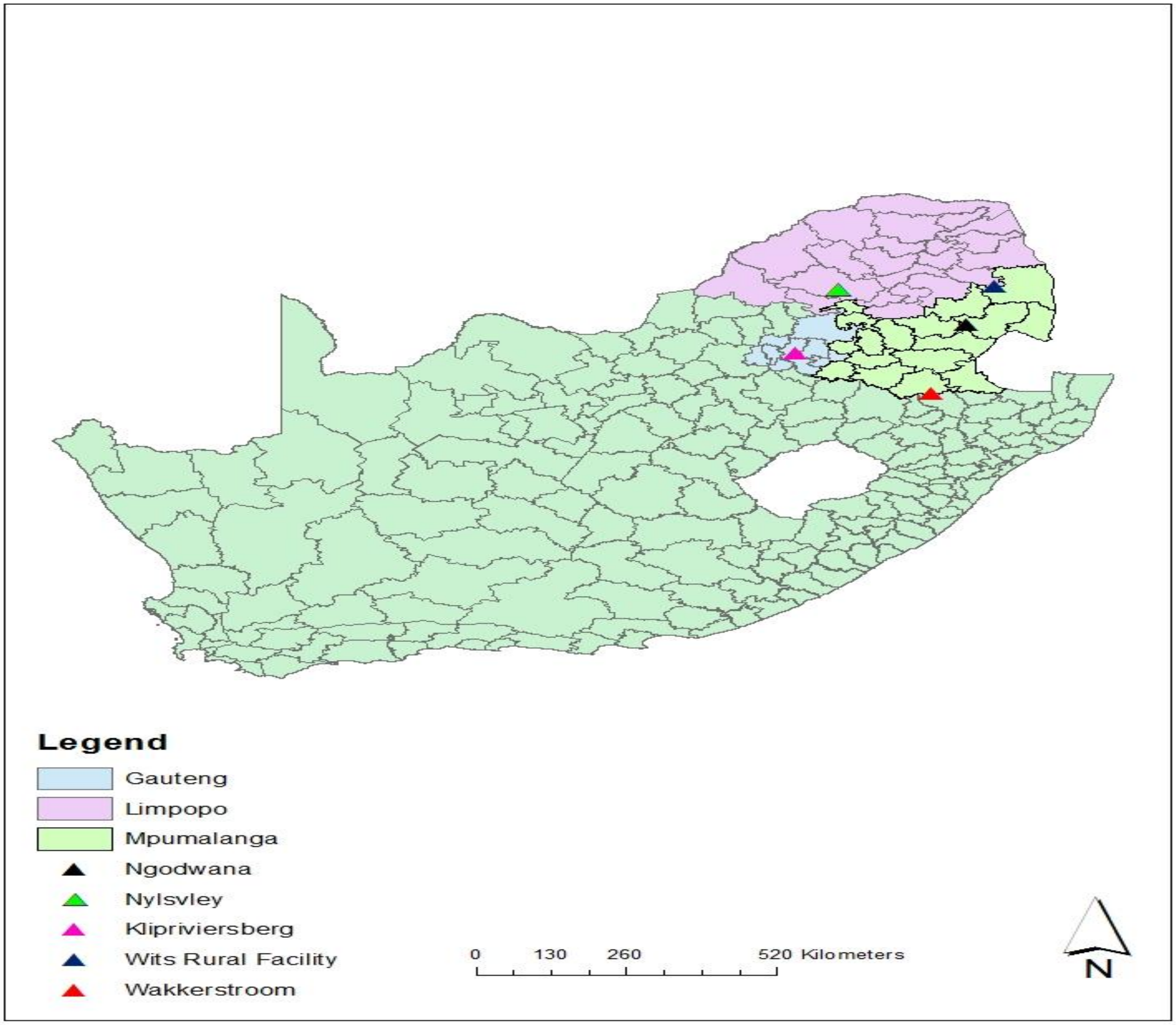


Figure 3: Study site map (Created in ArcMap, 10.3)

3.2. Grassland

Grasslands are dominated by a layer of grasses and forbs. The amount of cover depends on the rainfall, grazing and fire regimes that occur in the area. Grasslands in South Africa occur mostly in summer rainfall areas and are adapted to survive fires. Grasslands are characterized by acidic soils where they occur in high rainfall regions and C-4 grasses dominate the grasslands except in high altitudes (Low and Rebelo, 1996). The litter found in grasslands is composed predominantly of the grass litter as the forbs do not make up a significant portion of the biomass (Carbutt *et al*, 2011).

3.2.1. Wakkerstroom

Wakkerstroom is a small town in Mpumalanga, South Africa (-27° 35’ 34.7”, 30° 14’ 31.4”). The rainfall varies between 800mm to 1250mm per year (Mucina and Rutherford, 2006). The average maximum temperatures range between 27.2 °C-32.0 °C and the average minimum temperatures range between 15.6 °C-23.0 °C (South African Weather Service, 2017). Wakkerstroom is a warmer grassland site compared to the Klipriviersberg site (Figure 4). The dominant grass species in Wakkerstroom are *Eragrostis curvula* (Schrad.), *Heteropogon contortus* (L.) and *Hyperthelia dissoluta* (Nees ex Steud.).

Figure 4: Wakkerstroom study site

3.2.2. Klipriviersberg

Klipriviersberg is about 11 km south of Johannesburg (26° 18' 13.00”, 28° 00' 39.00”) and has a mean annual rainfall of 604mm per year. The warm season has average daily temperatures of 26.0 °C-32.1 °C and the cold season has average daily temperatures of 19.0 °C-22.6 °C (South African Weather Service, 2017) (Figure 5). This site is dominated by *Cymbopogon plurinodis* (Stapf) and *Hyperthelia dissoluta* (Nees ex Steud.).

Figure 5: Klipriviersberg study site

3.3. Pine Plantations

South Africa has a plantation area of about 1.5 million hectares which only represents 1.2% of the land area. Pine plantations have transformed previous grasslands because of the conversion of natural grasslands to commercial pine plantation forests (Department of Agriculture, Forestry and Fisheries, 2011). Pine needles form the litter found in pine forest plantations which are predominantly characterized by acidic soils. Two pine plantation sites were chosen for this study in the same area and the two sites were differentiated by their altitude. One site is at an altitude of 1270m while the other is at an altitude of 932m: the altitude variation provided the temperature variation between the two sites with the top site (1270m) being cooler than the bottom site (932m).

3.3.1. Ngodwana

The Ngodwana sites are located west of the Kruger National Park in Mpumalanga (25° 44’ 93.2”, 28° 16’ 15.1”). The mean annual rainfall over most of the area is 600 mm (Mills and Gorman, 2004). The cold, dry season has annual average temperatures of 18.8 °C-25.7 °C and the warm, wet season has annual average temperatures of 25.8 °C-30.0 °C (South African Weather Service, 2017). The tree species at both sites selected in Ngodwana is *Pinus elliottii x caribaea* (Engelm.) The top site (Figure 6) site has trees aged 8.1 years whilst the bottom site (Figure 7) has trees aged 9.4 years. The geology is shale at the high altitude site with a soil depth of 0-300mm and dolomite/ quartzite at the low altitude site with a soil depth of 300-600mm.

Figure 6: Ngodwana Top site

Figure 7: Ngodwana Bottom site

3.4. Savanna

Both sites, in Nylsvley and the Wits Rural Facility, are broad leaf savannas which occur in moist areas and receive between 235mm-1000mm of rainfall a year and are also characterized by nutrient poor soils. Savannas have a grassy layer and an upper layer of woody plants. Semi-arid savannas are characterized by nutrient poor soils where the grass layer is dominated by C-4 grasses and the tree layer are C-3 trees (Mucina and Rutherford, 2006). The litter found in savanna is a mixed, tree-grass litter.

3.4.1. Nylsvley

Nylsvley Nature Reserve (NNR) is situated in the Limpopo Province (24° 39’ 50.00”, 28° 39’ 54.40”). It has a mean annual rainfall of 623 mm; the NNR falls on the border between a moist and dry savanna (Scholes and Walker, 1993). The reserve has a rotational burning regime of 2-3 year intervals for each plant community which is applied in the reserve. Soils in Nylsvley are characteristically sandy, infertile and 1-2m deep (Scholes and Walker, 1993). The daily maximum temperatures in the warm season range from 29.5 °C-36.5 °C whereas the daily minimum temperatures in the cold season range from 25.1 °C-28.7 °C (South African Weather

Service, 2017). The Nylsvley site is much cooler than the Wits Rural Facility site (Figure 8) and it is predominantly covered by *Eragrostic pallens* (Hack.) grasses and *Burkea africana* (Hook) trees.

Figure 8: Nyslsvley study site

3.4.2. Wits Rural Facility

The Wits Rural Facility (WRF) is also located in the Limpopo Province of South Africa (24° 33’ 07.80”, 31° 05’ 50.18”). It is situated close to the Limpopo and Mpumalanga border. The mean annual rainfall over most of the area is 600 mm (Mills and Gorman, 2004). The maximum average temperatures range between 32.0 °C-37.2 °C whereas the minimum average temperatures range between 24.4 °C-28.7 °C (South African Weather Service, 2017). *Eragrostis curvula* (Schrad.) and *Digitaria eriantha* (Steud.) predominantly cover the site whereas *Burkea africana* (Hook) and *Acacia tortilis* **(**Forssk.) form the tree vegetation cover (Figure 9).

Figure 9: Wits Rural Facility study site

3.5. The Tea Bag Index method

The method used in this study was the Tea Bag Index (TBI) (Keuskamp *et al*, 2013). The TBI approach uses two types of teabags (green and Rooibos) (Figure 10) as standard plant material and the tea is used as standard litter (Keuskamp *et al*, 2013). Lipton used to make the Rooibos and green tea in fine mesh, woven, nylon teabags (old teabags) which had 0.25mm pores but they changed the material of the teabags to non-woven, polypropylene teabags (new teabags).

The TBI study started across the world with the use of the nylon teabags but once Lipton started using the new material, the old teabags were in limited supply and studies that started after the change used more of the new teabags and a limited number of old teabags that were still available. This study was one of the studies that started after the teabag material was changed but a comparison was conducted between the decomposition rates of the old teabags and the new teabags.

Figure 10: Nylon, old teabags (left) and non-woven, new teabags (right)

The initial period of study was for 3 of the winter months of 2017 (June–August); 48 Lipton green and 48 Rooibos teabags of the new teabags as well as 24 Lipton green and 24 Rooibos teabags of the old teabags were weighed and buried at the different study sites. Two Rooibos and 2 old green tea teabags as well as 4 Rooibos and 4 new green tea teabags were buried at each site; teabags were buried in separate holes. Litter covering the soil was moved aside and then stainless steel corers were used to remove soil cores to a depth of 8cm. The teabags were then buried in the holes, the soil was replaced to cover the teabags and the litter was moved back to cover the soil again. The teabags were buried 15cm apart, this was not randomised and tea bags were buried in a straight row, with their labels firmly kept visible above the soil using metal nails. Burial depth of 8 cm made sure that the tea bags could still be found after 3 months by preventing their displacement or loss and there were nails used too that made sure the tea bags would not get lost. The burial sites were marked with dowels and red tape to mark the study sites. Soil temperatures were recorded using a soil temperature sensor for each planted teabag at the time of burial to a depth of 15cm.

3.5.1. *Soil analyses*

Soil samples were taken at the sites (0-10cm), 3 soil samples were taken from each study site and were analysed at Bemlab (a South African National Accreditation System (SANAS), an accredited testing laboratory in accordance with ISO 17025:2005).The soils were tested for their soil cation exchange capacity, pH, carbon, nitrogen and phosphorus contents, as well as their texture by assessing the different soil fractions. The exchangeable cations were calculated as centimoles of charge per kilogram of dry soil (cmol(+)/kg) and then expressed as a percentage of the total exchangeable cations .The pH was measured using potassium chloride (KCl at 4M), Phosphorus was tested using the Bray II test and the carbon and nitrogen soil content were calculated with a volumetric analysis using titrations.The teabags were then recovered after 90 days, removed of all ingrown fine roots by hand, dried in the oven for 48hrs at 70.0 °C without being washed and then the experiment was repeated in 3 of the warmer months of 2017 (October-December).

3.5.2. *Weather data*

Long-term and short term weather data were obtained from the South African Weather Service for each of the study sites in order to explore the changes in temperature and rainfall. The data obtained were averaged daily maximum and minimum temperatures from 1990 to 2014. The total cumulative rainfall and average daily minimum and maximum temperatures for the duration of this study were also obtained from the South African Weather Service.

3.5.3. *Equations used for the study*

The following equations were then used to calculate the stabilisation factor S and the decomposition rate k (Keuskamp *et al*, 2013):

1. $W (t) = ae-kt + (1-a)$

2. $S = 1- ag / Hg$

$W (t)$ = weight of teabags after incubation time (t)

(a = labile fraction of the litter, k = decomposition rate constant, 1– a = recalcitrant fraction of the litter, ag = decomposable fraction of the tea, Hg = hydrolysable fraction of the tea)

The k constant characterizes mass loss and can be easily compared with other data sets. The assumption that the decomposition rate decreases linearly as the amount of substrate decreases is consistent with the understanding that as decomposition proceeds, the labile fraction (sugars, starches and proteins) are rapidly degraded while recalcitrant fractions (fats, tannins, lignin, waxes and cellulose) are decomposed at a significantly slower rate (Wider and Lang, 1982). The equation used has the two components: labile and recalcitrant fractions which demonstrate the robustness of the equation.

3.6. Data analyses

The litter quality of the two different types of tea were tested for normality and it was observed that they were not normally distributed and were then analysed using a Kruskal-Wallis test to test the difference in mass loss between the two types of tea at the different study sites and between seasons.

The soil texture was analysed using the particle size distribution. The mean data were tested for normality using the Shapiro-Wilk test then analyzed using a non-parametric Kruskal-Wallis test and were not normally distributed. The Kruskal-Wallis tested the difference between clay, sand and silt content across all the study sites. The soil texture was then correlated with the decomposition rate constant to illustrate the effect of the soil texture on litter decomposition. The correlation was done in Excel using the Analysis Toolpak add-in to calculate the correlation coefficient between the two variables. A value of +1 represents a perfect positive correlation whereby one variable increases, the other variable also increases. A value of -1 shows a negative correlation where as one variable increases the other decreases.

The soil pH and exchangeable cations, soil temperature, soil phosphorus, short term and long term weather data were tested for normality using the Shapiro-Wilk test. The aforementioned parameters were not distributed normally and hence were analyzed using a non-parametric Kruskal-Wallis test. The means and standard deviations of the exchangeable cations were calculated to compare their occurrence in the soil. All of these parameters were then correlated with the decomposition rate in Excel to illustrate their effect on litter decomposition. The soil temperature was analyzed by comparing the soil temperature between the two different seasons of summer and winter. Soil temperatures were then compared with soil temperatures within each season across the different sites. Furthermore, a principle component analysis was carried out on all the soil quality variables using Stata/IC version 13.

The standard deviations on the figures represent the deviation in the replicate samples collected. To test if there were significant differences between variables, an alpha value of 0.05 or 0.001 was used as the cut-off for significance and p-values greater than the alpha values were not significant. The symbol x^2 is used to represent the value of significance of the Kruskal-Wallis test.

The teabag decomposition rate was analyzed using the amount of weight lost by the teabags over time and this weight loss was then used to calculate the decomposition rate constant. The data were tested for normality and were found to be normal and then analyzed using a one way Anova.

Chapter 4: Results

The results section will discuss litter quality, soil properties and long term ambient temperatures for the areas in which the study took place and then the teabag litter decomposition data.

4.1. Litter quality

There were two types of teabags used in the study: Rooibos and green tea, because the two have different decomposition rates and litter quality (Table 2). There were significant differences in the mass loss of the green tea between the two seasons ($x^2 = 11.56$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$) and there were also significant differences between the mass loss of the Rooibos tea between the two seasons ($x^2 = 8.79$, d.f. = 1, $p < 0.01$, $\alpha = 0.05$). Green tea and Rooibos tea have significantly different mass losses with the green tea having a higher mass loss than the Rooibos tea across all sites and the two seasons of winter and summer ($x^2 = 35.97$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$) (Figure11).

Rooibos tea decomposes slower than green tea and using two teas allowed for the estimate of the amount of labile material left in one tea after the labile material had been consumed in the other tea. Green tea had a greater component of labile carbon than Rooibos tea and a smaller fraction of recalcitrant carbon than Rooibos tea. This allows for the estimation of labile fraction of the green tea and recalcitrant fraction of the Rooibos tea from the litter material that was left and both were then used to calculate the decomposition rate constant. The decomposition rate constant calculated from the green and Rooibos teas is what has been used to analyze litter decomposition as a function of land use and temperature.

Table 2: Litter quality of the teas used in the study

	Green tea	Rooibos tea
	Mean ± SD	Mean ± SD
Water soluble fraction (g g^{-1})	0.493 ± 0.003	0.215 ± 0.009
Acid soluble fraction (g g^{-1})	0.283 ± 0.017	0.289 ± 0.040
Acid insoluble fraction (g g^{-1})	0.156 ± 0.009	0.444 ± 0.040
Mineral fraction (g g^{-1})	0.002 ± 0.0009	0.004 ± 0.0006
Hydrolysable fraction (H)(g g^{-1})	0.842 ± 0.023	0.552 ± 0.050
Total carbon (%)	49.055 ± 0.109	50.511 ± 0.286
Total nitrogen (%)	4.019 ± 0.049	1.185 ± 0.048
C:N ratio	12.229 ±0.129	42.870 ± 1.841

(Adapted from Keuskamp *et al*, 2013)

Keuskamp (*et al* 2013) analyzed green tea and Rooibos teas using a sequential extraction technique. The green tea had a higher water soluble fraction that Rooibos tea and lower acid soluble and insoluble fractions than Rooibos tea. The hydrolysable fraction was found to decompose faster than the acid insoluble fraction (Keuskamp *et al, 2013*) and green tea had a higher fraction of the hydrolysable fraction than Rooibos tea. Additionally, green tea had a higher N content and lower C content than Rooibos tea but Rooibos tea had a higher C:N ratio than green tea.

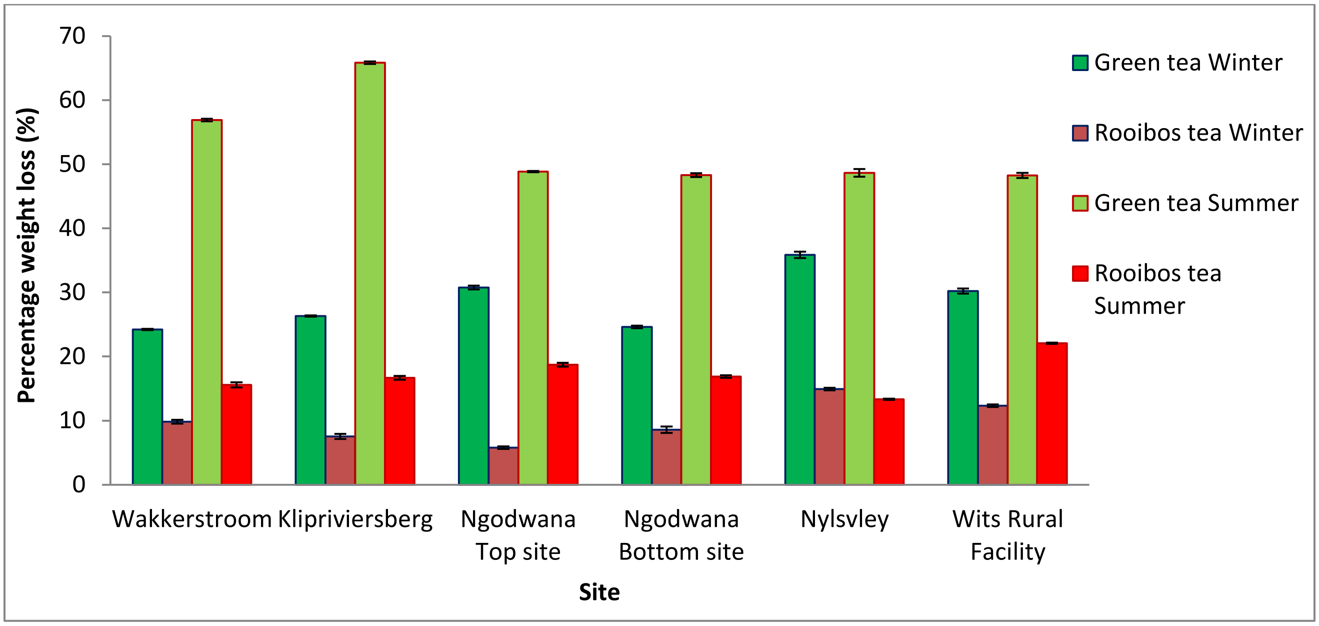


Figure 11: Mean percentage weight loss for Rooibos tea and green tea, in winter and summer as influenced by land use ($x^2 = 35.97$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$)

4.2. Soil properties

4.2.1. *Soil texture*

From the classifications of the soil using the Northcote classification (Hazelton and Murphy, 2007) the soils were classified as sandy clay loam for the Wakkerstroom site (20-30% clay), clay loam for Klipriviersberg (30-35% clay), clay for the Ngodwana Top site (>50% clay), sandy loam for the Ngodwana Bottom site (15-20% clay), loamy sand for the WRF and Nylsvley sites (5-10% clay) (Figure 12).

The results show that there were significant differences between the clay content across all study sites ($x^2 = 16.50$, d.f. = 5, $p < 0.01$, $\alpha = 0.05$). The Ngodwana Top site had the highest clay content whilst the site at the Wits Rural Facility had the lowest clay content. Clay content and the decomposition rate constant have a negative, weak correlation (R= -0.312) (Figure 13). As the clay content increases, the decomposition rate constant decreases.

The results also show that there were significant differences between the sand content across all study sites ($x^2 = 16.33$, d.f. = 5, $p < 0.01$, $\alpha = 0.05$). The Ngodwana Bottom site, Nylsvley and Wits Rural Facility sites had sand contents of above 60% whereas the other sites had sand contents of below 50%. The sand content and decomposition rate constant have a positive, weak correlation (R= 0.311) (Figure 14). As the sand content increases, the decomposition rate constant also increases.

The silt content shows no significant differences across all study sites ($x^2 = 15.08$, d.f. = 5, $p > 0.05$, $\alpha = 0.05$). The Nyslsvley (1.3%) and WRF (6%) sites had the lowest mean percentages of silt particles and silt particles were commonly the lowest represented particles across all sites. As the silt content increases, the decomposition rate constant decreases as the two variables have a negative, weak correlation (R= -0.249) (Figure 15). The different soil classifications were a key factor in determining the role soil texture plays in decomposition with an essential connection to moisture as the texture determines the pore size that can be filled with either water or air.

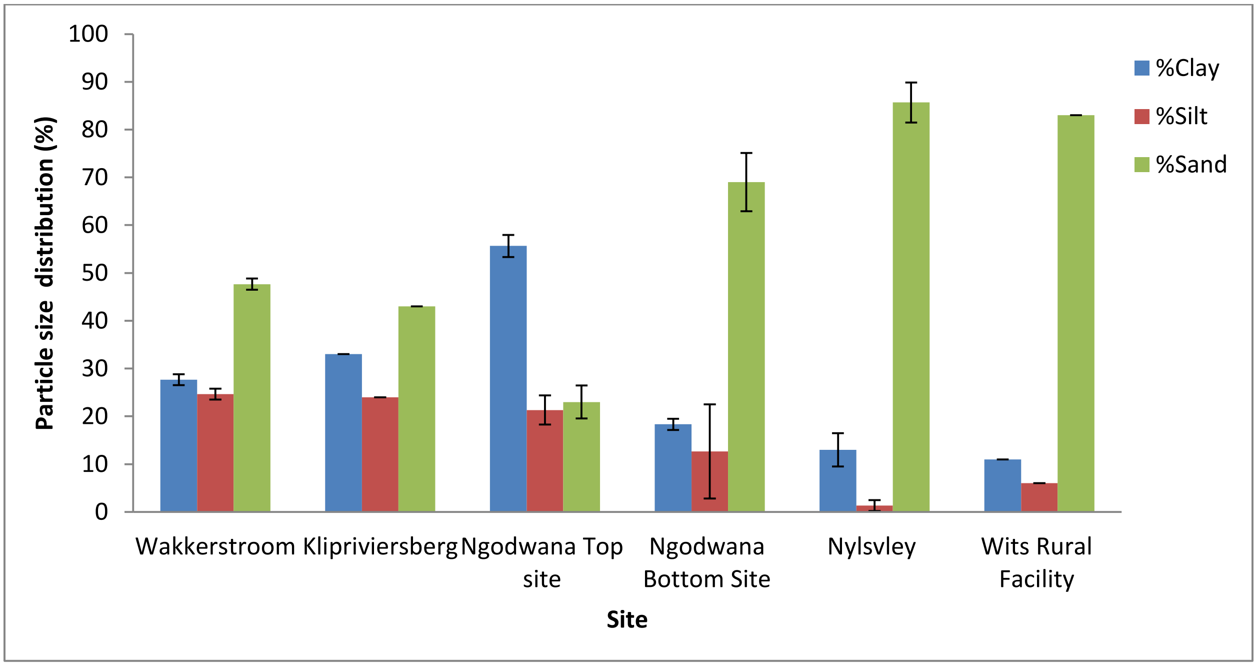


Figure 12: Mean particle size distribution of soils from the study sites

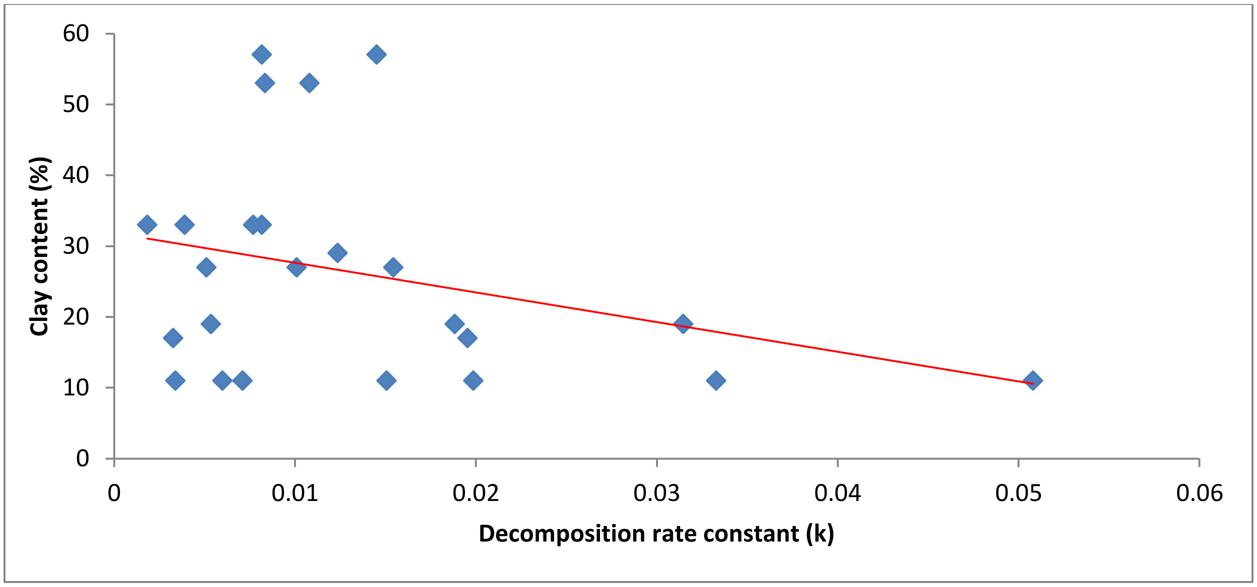


Figure 13: Correlation between clay content and decomposition rate constant (R= -0.312)

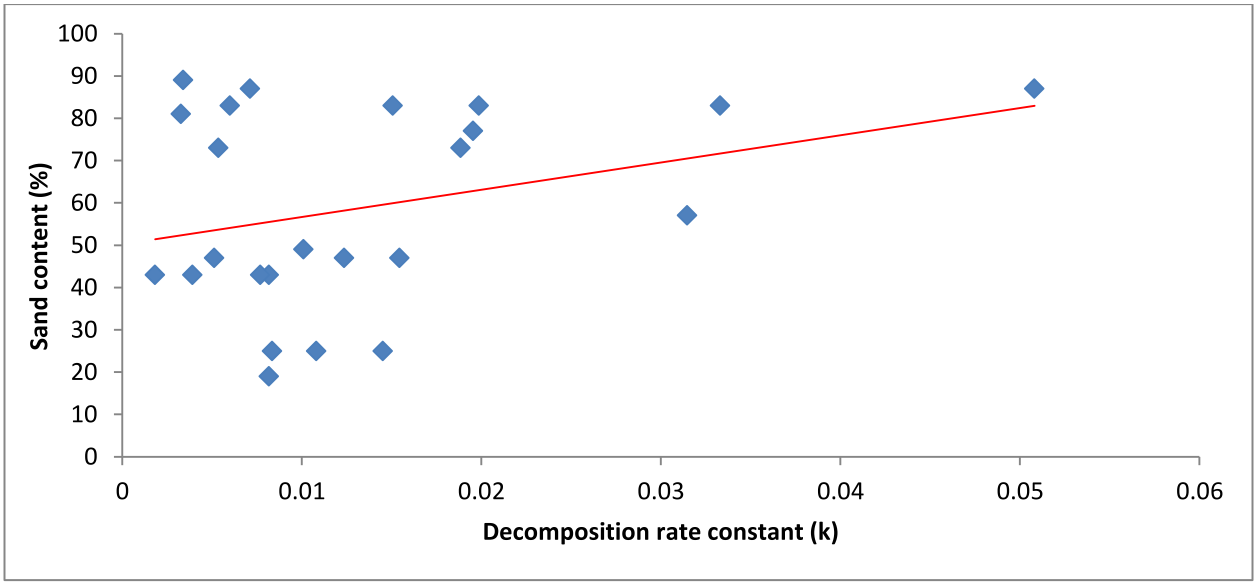


Figure 14: Correlation between sand content and decomposition rate constant (R= 0.311)

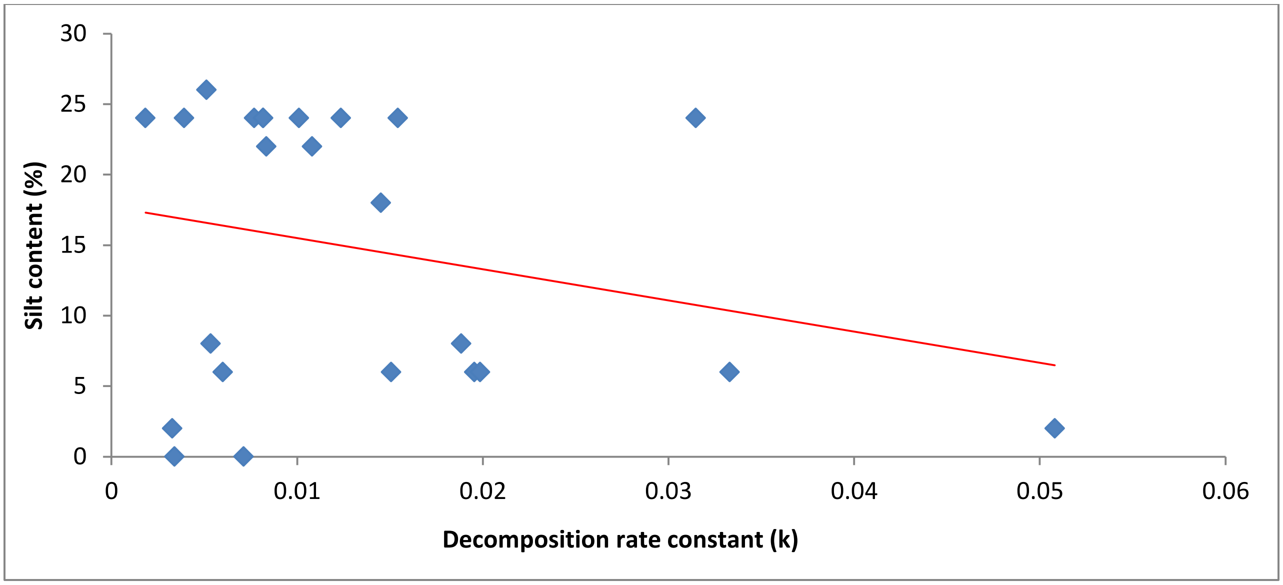


Figure 15: Correlation between silt content and decomposition rate constant (R= -0.249)

4.2.2. *Soil pH and exchangeable cations*

Significant differences in soil pH were not evident across all study sites ($x^2 = 0.234$, d.f. = 2, $p > 0.05$, $\alpha = 0.05$). All soils collected were acidic with the Ngodwana Bottom site being the only soil that was close to neutral with a pH average of 6.7 (Figure 16). The most acidic soils are those of the Ngodwana top site with a pH of 3.2. Soil pH affects the availability of other nutrients and the results showed that soil pH had a weak effect on decomposition as the two variables have a weak, positive correlation (R= 0.071) (Figure 17). The general trend shows that most soils across all study sites are acidic (with a pH below 5) and that acidic soils have slow decomposition rates.

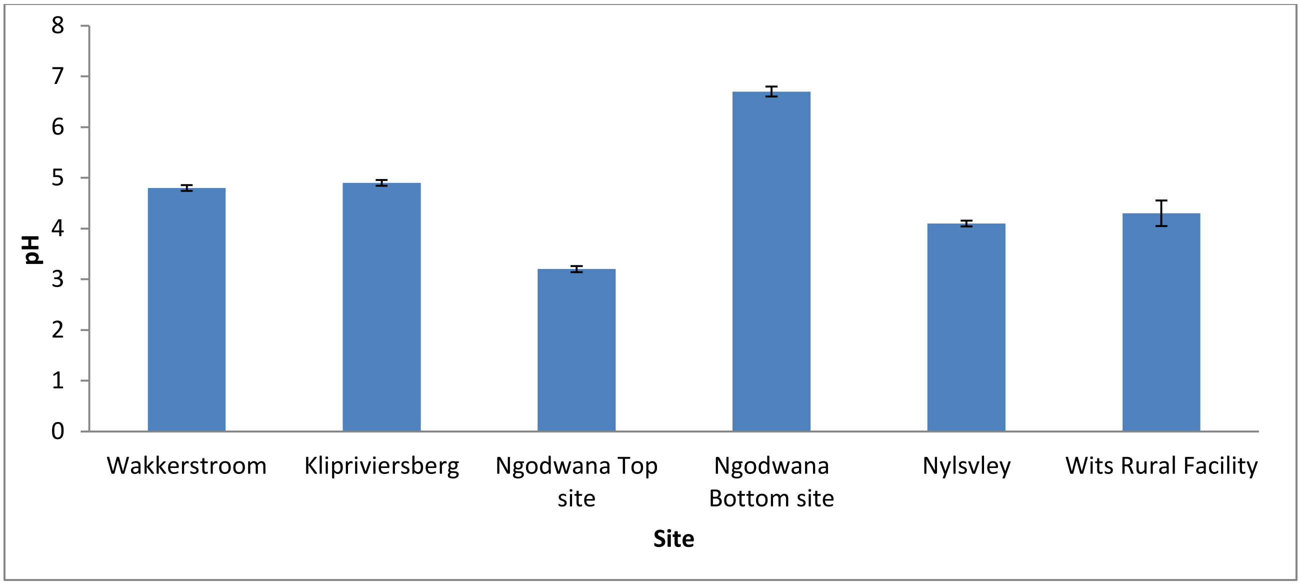


Figure 16: Soil pH across all sites ($x^2 = 0.234$, d.f. = 2, $p > 0.05$, $\alpha = 0.05$)

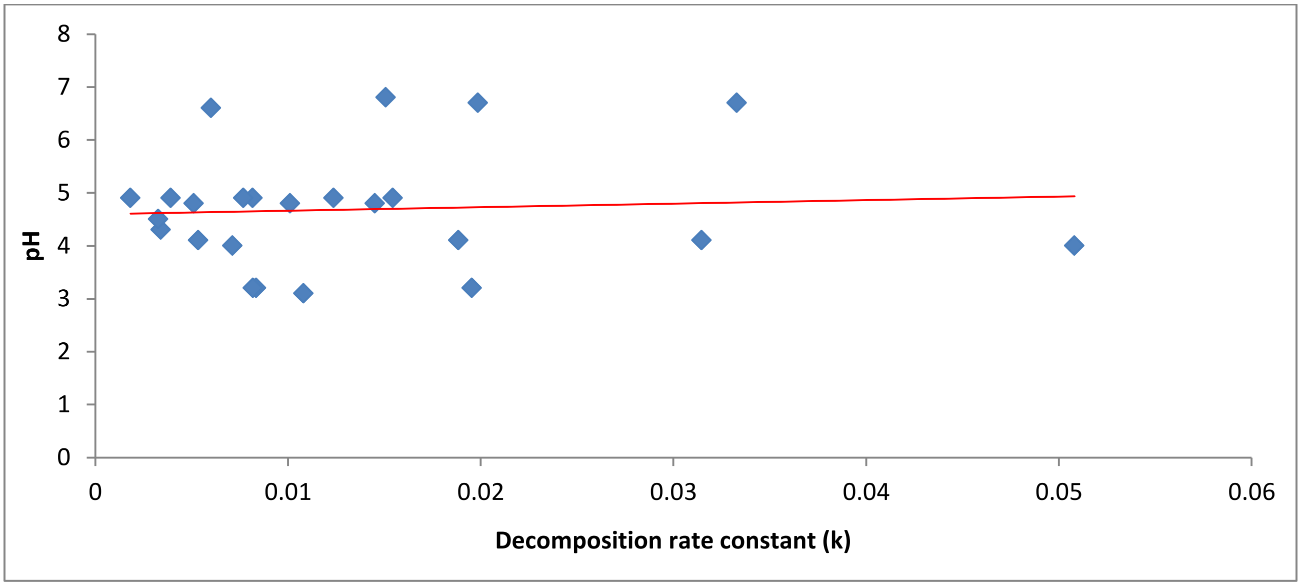


Figure 17: Correlation between pH and decomposition rate constant (R= 0.071)

From the exchangeable cations assessed, calcium (Ca) occurred in the highest concentrations followed by magnesium (Mg), potassium (K) and sodium (Na) (Figure 18), (Ca: $\overline{x}$ = 54.63%, s.d. = 24.926, Mg: $\overline{x}$ = 17.52%, s.d. = 8.781, K: $\overline{x}$ = 1.862%, s.d. = 1.221, Na: $\overline{x}$ = 1.51%, s.d. = 1.0397). The standard deviation for magnesium, sodium and potassium are relatively low compared to the calcium standard deviation which shows that the exchangeable calcium cation values are more spread out and have more variation than the other cations which are all close to the average value. There were statistical differences between the exchangeable cations across all the sites ($x^2 = 18.59$, d.f. = 3, $p < 0.001$, $\alpha = 0.05$). Calcium and magnesium occurred in amounts of greater than 20 cmol (+)/kg and greater than 10 cmol (+)/kg respectively whereas sodium and potassium occur in amounts less than 4 cmol (+)/kg. Calcium, magnesium and potassium have a negative, weak correlation with the decomposition rate constant (R= -0.18, -0.341 and -0.257 respectively) (Figures 18-21). The decomposition rate constant increases as the amount of these exchangeable cations decreases. In addition the decomposition rate constant increases as the exchangeable sodium cations increase (R= 0.0959). Exchangeable sodium and the decomposition rate constant have a weak, positive relationship.

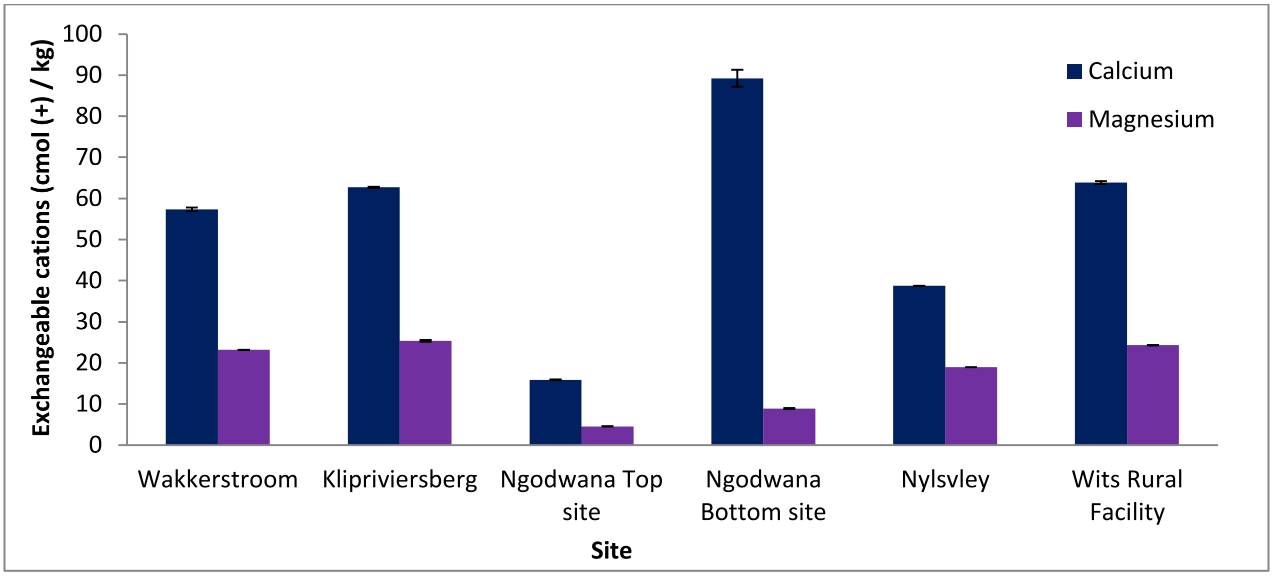


Figure 18: Calcium and magnesium exchangeable cations for the study sites ($x^2 = 18.59$, d.f. = 3, $p < 0.001$, $\alpha = 0.05$)

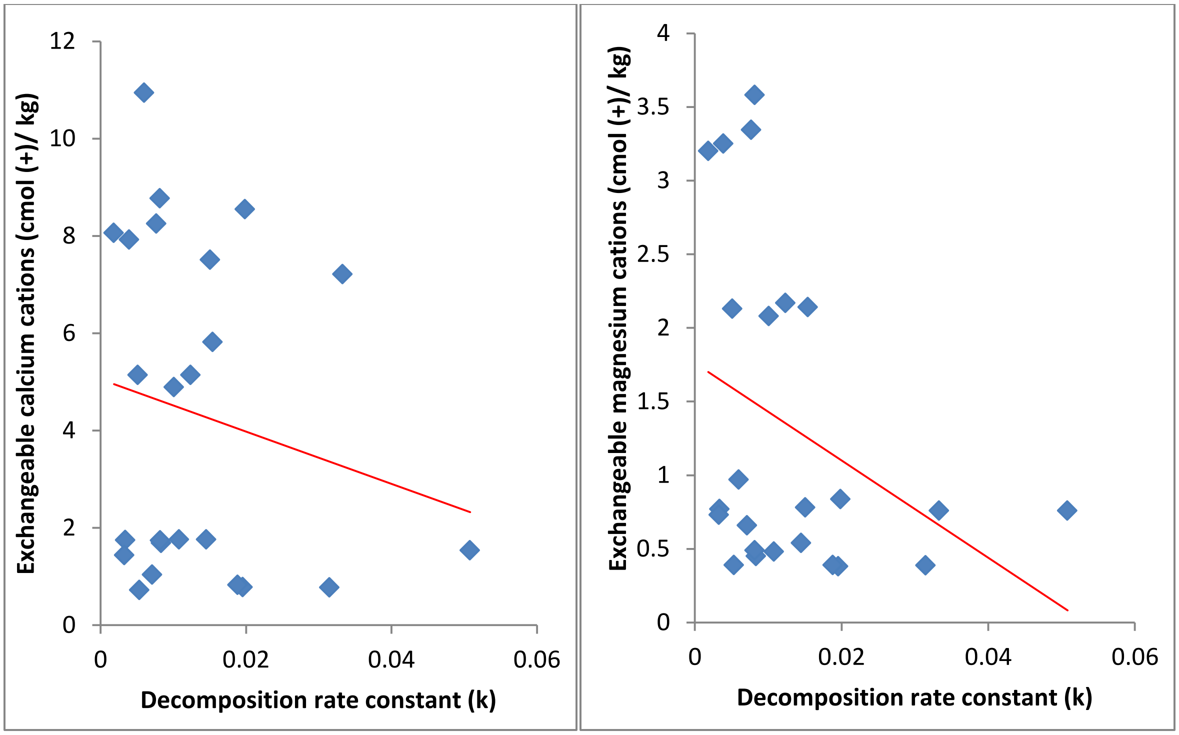


Figure 19: Correlation between exchangeable calcium and magnesium cations and decomposition rate constant (R= -0.18 for calcium and -0.341 for magnesium)

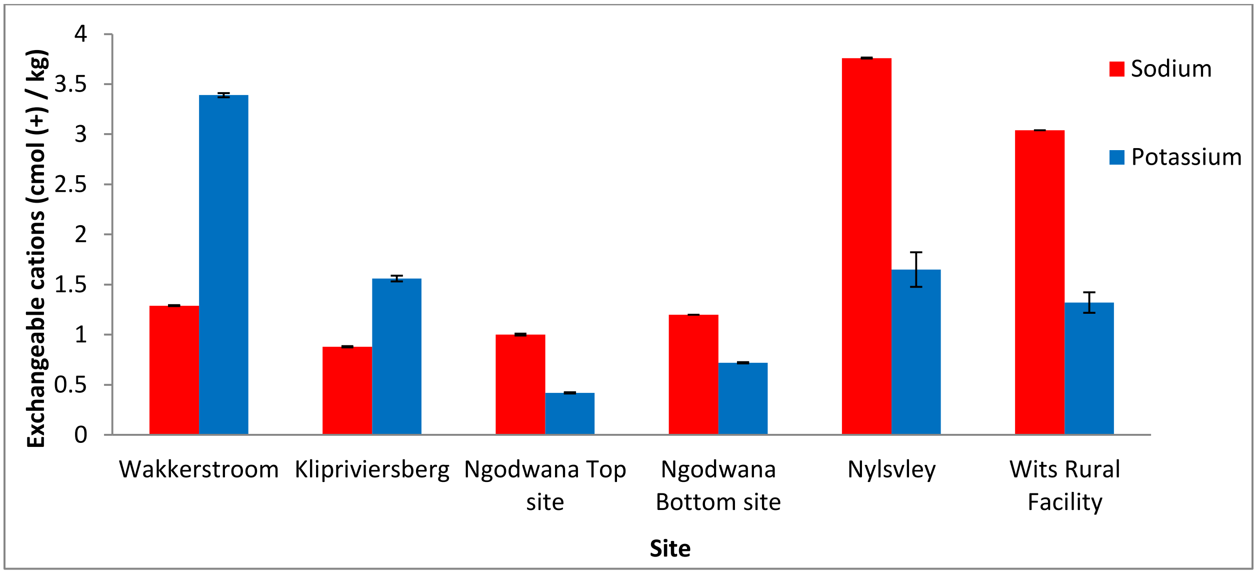


Figure 20: Sodium and potassium exchangeable cations for the study sites

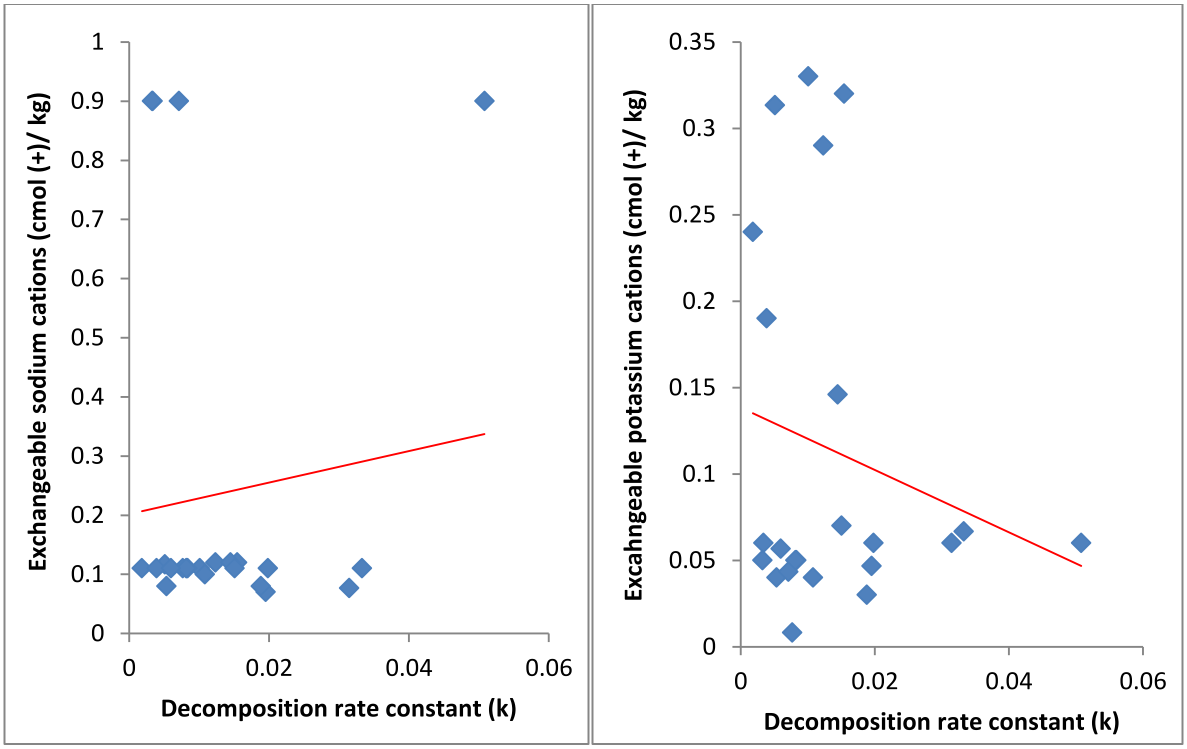


Figure 21: Correlation between exchangeable sodium and potassium cations and decomposition rate constant (R=0.0959 for sodium and -0.257 for potassium)

4.2.3. Soil temperature

Soil temperature was another parameter measured when the teabags were buried at 8cm depth at each site. Two reading were taken for each buried teabag, both in summer and winter (Figure 22). The soil temperatures from the 6 sites were significantly different between the two seasons ($x^2 = 6.564$, d.f. = 1, $p < 0.05$, $\alpha = 0.05$) with summer soil temperatures being much higher than winter temperatures across all the study sites. The winter soil temperatures across all the sites and summer soil temperatures across all the sites were also significantly different ($x^2 = 57.289$, d.f. = 5, $p < 0.001$, $\alpha = 0.05$ and $x^2 = 59.67$, d.f. = 5, $p < 0.001$, $\alpha = 0.05$ respectively). Nylsvley and the Wits Rural Facility sites had the highest soil temperatures in summer whilst the high altitude site in Ngodwana and Wakkerstroom sites had the lowest soil temperatures during the same season. The lowest winter soil temperatures were at the Klipriviersberg and Wakkerstroom sites and the highest winter soil temperatures were at the Wits Rural Facility and the Nylsvley site. Soil temperature affects the rate of litter decomposition and the results showed that the soil temperature in winter and summer have weak, negative correlations (R= -0.214 and -0.324 respectively) (Figure 23). As temperatures in both seasons increased the decomposition rate constant decreased showing that very high temperatures do not increase the decomposition rate constant but there is an optimal range of temperature within which the decomposition rate constant increases (10 °C-15 °C for winter and 15 °C-20 °C for summer).

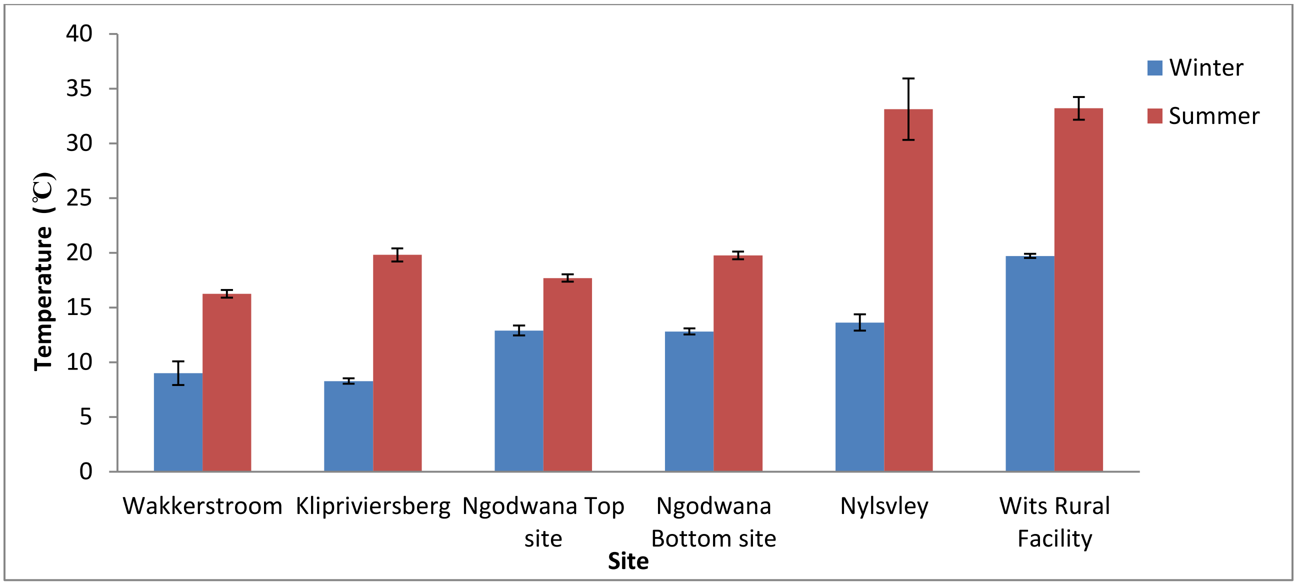


Figure 22: Soil temperatures for the study sites ($x^2 = 6.564$, d.f. = 1, $p < 0.05$, $\alpha = 0.05$)

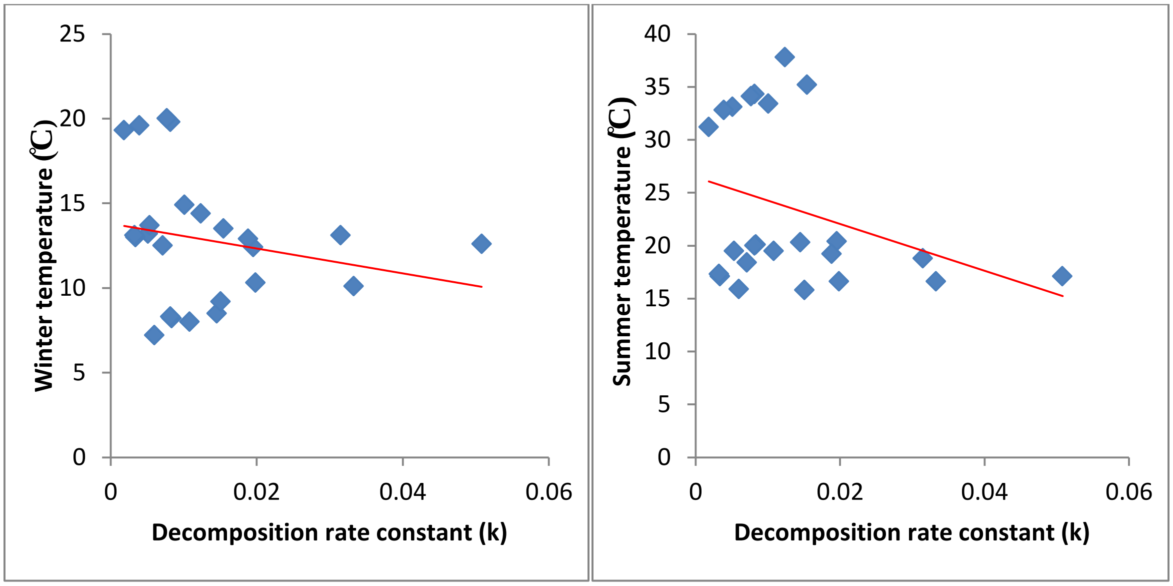
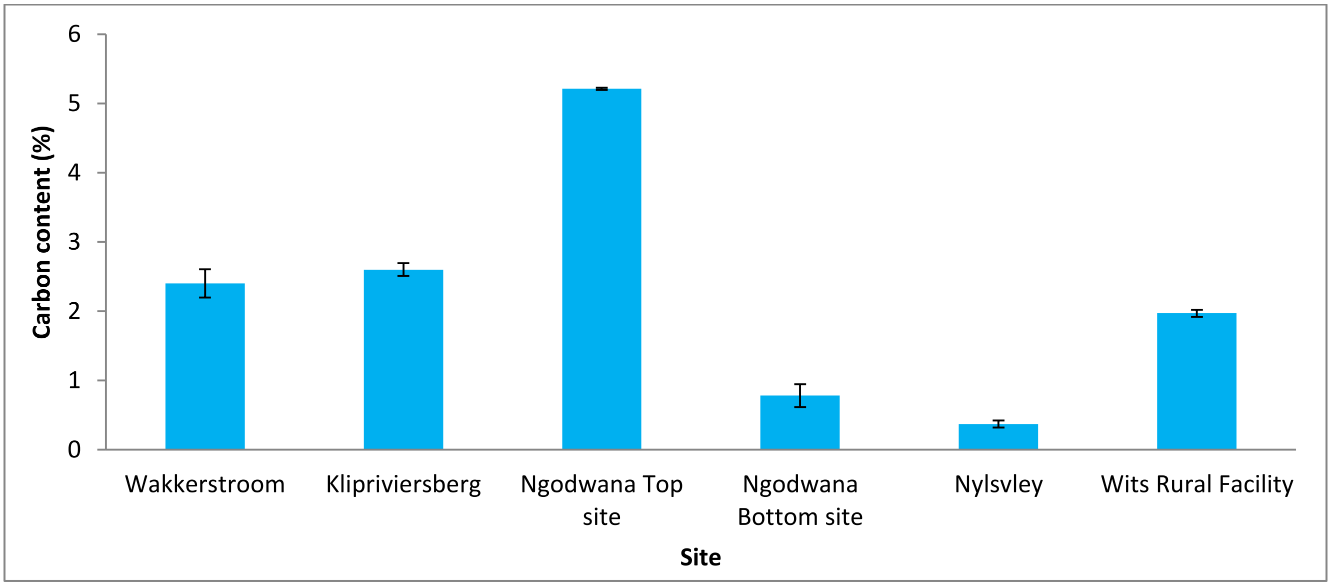


Figure 23: Correlation between the winter and summer soil temperatures and decomposition rate constant (R= -0.214 for winter and -0.324 for summer)

4.2.4. Soil carbon and nitrogen levels

There was a significant difference across all the sites for the soil carbon and nitrogen levels ($x^2 = 29.339$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$). All the study sites had higher levels of C compared to N (Figures 24 and 25). The C:N ratio for Wakkerstroom is 14:1, 11:1 for Klipriviersberg, 16:1 for the Ngodwana Top site, 12:1 for the Ngodwana Bottom site, 10:1 for Nylsvley and 35:1 for the Wits Rural Facility and these were also significantly different ($x^2 = 9.466$, d.f. = 6, $p < 0.001$, $\alpha = 0.05$). The lower the C:N ratio, the more easily degradable the litter is and that means that sites with low C:N ratios should have higher decomposition rate constants than sites with high C:N ratios. Both C and N have negative correlations with the decomposition rate constant (R= -0.232 and R= -0.209, respectively): as C and N increase, the decomposition rate constant decreases (Figure 26).



<u>Figure 24: Carbon levels across all sites ($x^2 = 29.339$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$)</u>

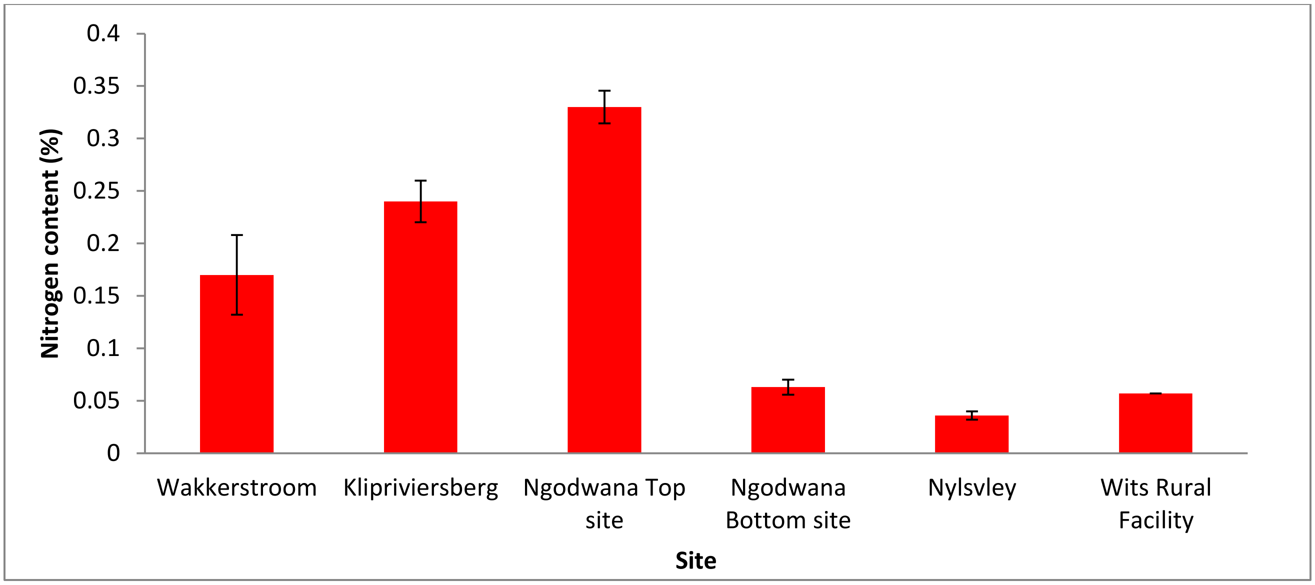


Figure 25: Nitrogen levels across all sites ($x^2 = 29.339$, d.f. = 1, $p < 0.001$, $\alpha = 0.05$)

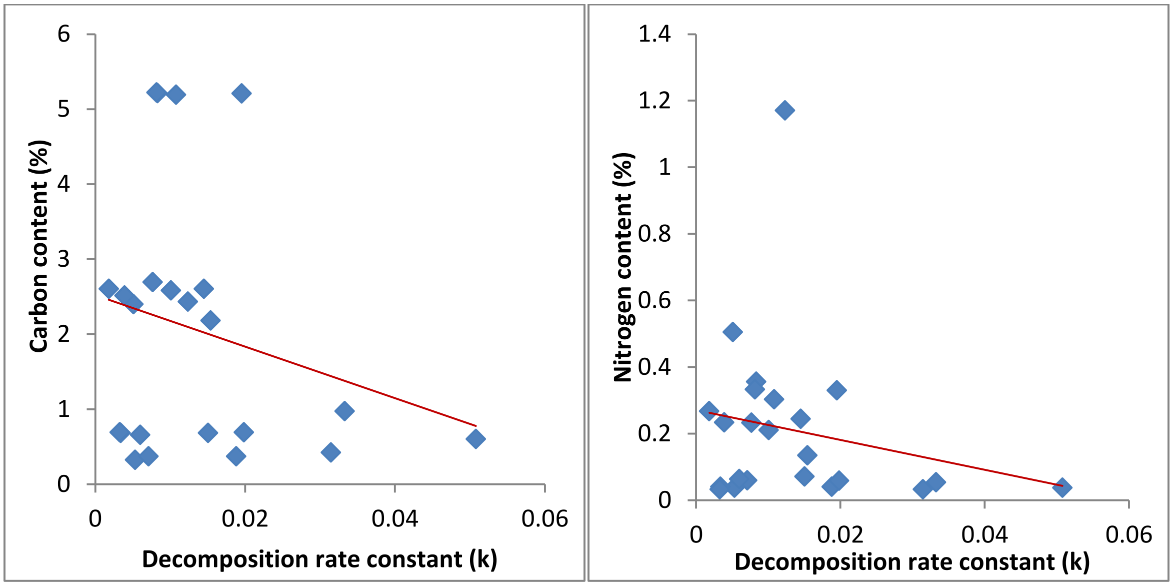


Figure 26: Correlation between the carbon and nitrogen levels in the soil and decomposition rate constant (R= -0.232 for carbon and R= -0.209 for nitrogen)

4.2.5. Soil phosphorus levels

The Ngodwana Bottom site had the highest amounts of Phosphorus (20 mg/kg) with the Wakkerstroom site having the second highest amount of 12.3mg/kg (Figure 27). The rest of the other sites had Phosphorus values between 6.3mg/kg and 2.7mg/kg. There were significant differences between the phosphorus levels across all sites ($x^2 = 15.210$, d.f. = 5, $p < 0.01$, $\alpha = 0.05$). Phosphorus also contributes to how nutrients are cycled in the soil and has implications for decomposition rates. The results showed that as the decomposition rate constant increase, the amount of phosphorus increases. The decomposition rate constant and the amount of phosphorus have a weak, positive correlation (R= 0.234) (Figure 28).

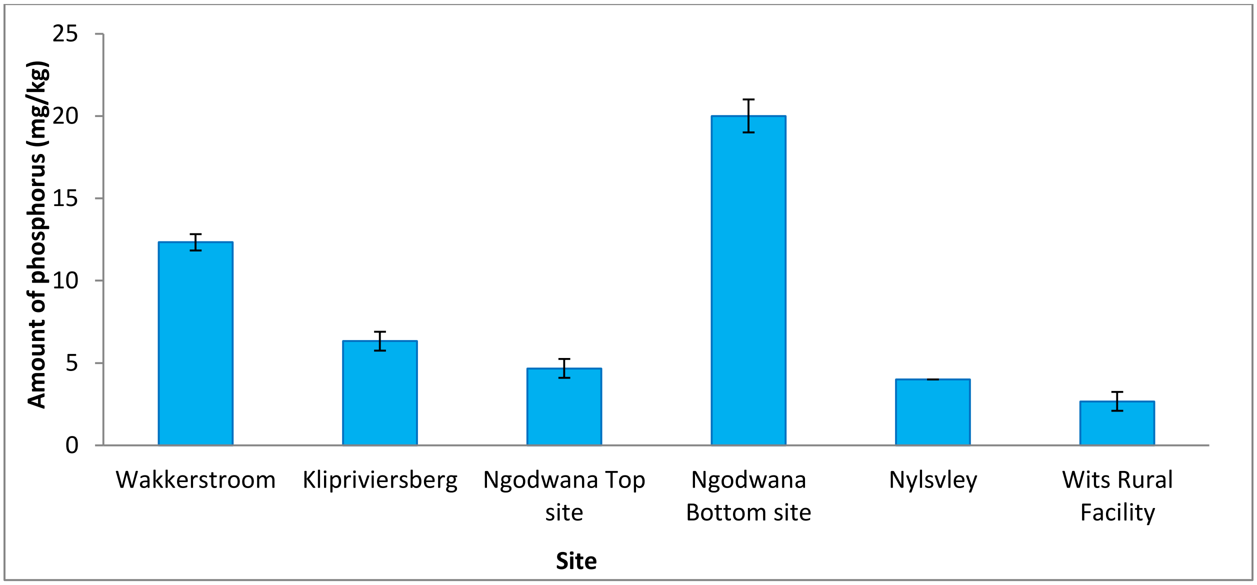


Figure 27: Amount of soil phosphorus across all sites ($x^2 = 15.210$, d.f. = 5, $p < 0.01$, $\alpha = 0.05$)

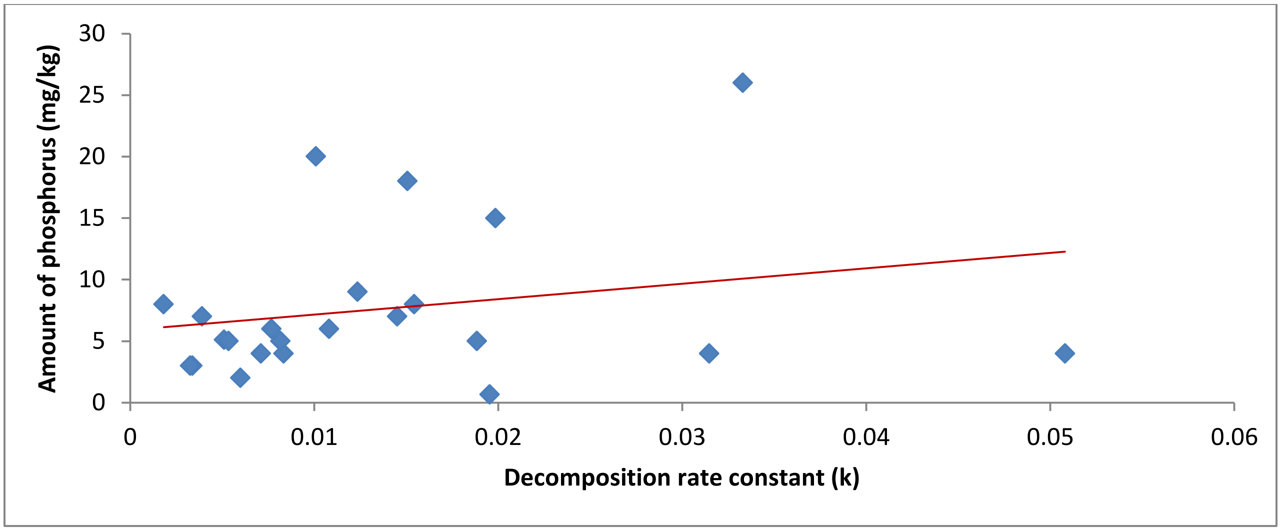


Figure 28: Correlation between the amount of phosphorus in the soil and decomposition rate constant (R= 0.234)

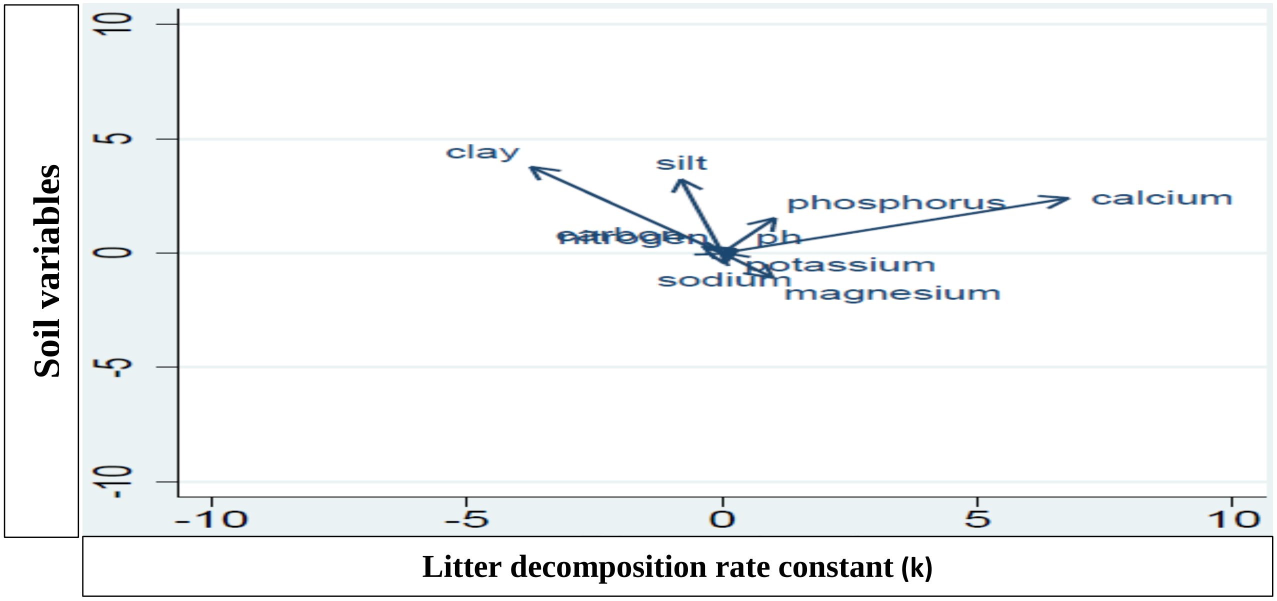


Figure 29: Principle component analysis of soil variables collected at the study sites

The principle component analysis (PCA) (Figure 29) shows that all soil variables are important for litter decomposition. However calcium, pH and clay are the strongest variables contributing to litter decomposition across all study sites as they have the biggest Eigen values (0.499, 0.491 and 0.3875 respectively).

4.3. Long term and short term weather data

Ambient temperature data were obtained from the South African Weather Service, from weather stations closest to the study sites. Average daily long term (1990–2014) and short term maximum and minimum temperatures from Skukuza are used for Wits Rural Facility, Warmbad for Nylsvley, Volkrust for Wakkerstroom, Zuurbekom for Klipriviersberg and Nelspruit for Ngodwana (Figures 30-33). Short term rainfall data were also obtained from the same weather stations for the study sites (Figure 34).

There were significant differences between average daily maximum and minimum temperatures from each site ($x^2 = 225.619$, d.f. = 9, $p < 0.001$, $\alpha = 0.05$).Furthermore, the maximum temperatures across all sites and the minimum temperatures across all the study sites were significantly different ($x^2 = 101.003$, d.f. = 4, $p < 0.001$ and $x^2 = 85.808$, d.f. = 4, $p < 0.001$, $\alpha = 0.05$, respectively).

Temperatures for Wits Rural Facility reach as high as 37.2 °C and lowest temperature reached as low as 24.4 °C which is much warmer than the other savanna site at Nylsvley. Nylsvley's highest and lowest temperatures recorded were 34.7 °C and 20 °C respectively. The Pine plantations reach high temperatures of 30˚C and the lowest temperature recorded was 18.8 °C. The savanna and Pine plantation sites' temperatures were generally much warmer than those of the grassland sites where the highest and lowest for Wakkerstroom were 27.7 °C and 18.5 °C respectively. On the other hand Klipriviersberg temperatures reach temperatures of 32.1 °C and have low temperatures of 11.9 °C. It is assumed that the Pine plantations differ in temperatures because of their difference in altitude in that the 1270m site should be much cooler than the 932m site. This is supported with the soil temperature data (Figure 22) which show that the low altitude site was much warmer in summer and slightly less cool in winter than the high altitude site. The general trend is that the maximum temperatures are in the ranges of: Wakkerstroom: 24.3 °C–27.7 °C; Klipriviersberg: 26 °C–32.1 °C; Ngodwana: 25.8 °C–30°C; Nylsvley: 29.5 °C–34.7 °C and Wits Rural Facility: 32 °C–37.2 °C. The minimum temperatures, on the other hand have been more variable.

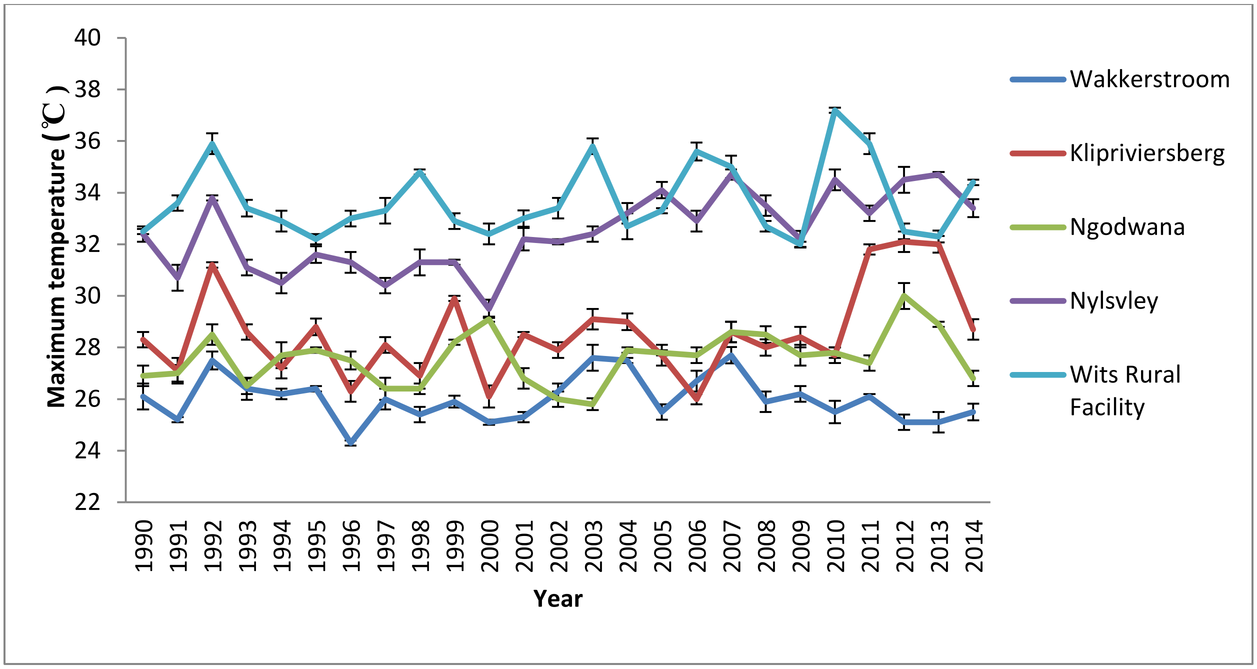


Figure 30: Average maximum temperatures by year for all study sites from 1990- 2014 ($x^2 = 101.003$, d.f. = 4, $p < 0.001$, $\alpha = 0.05$)

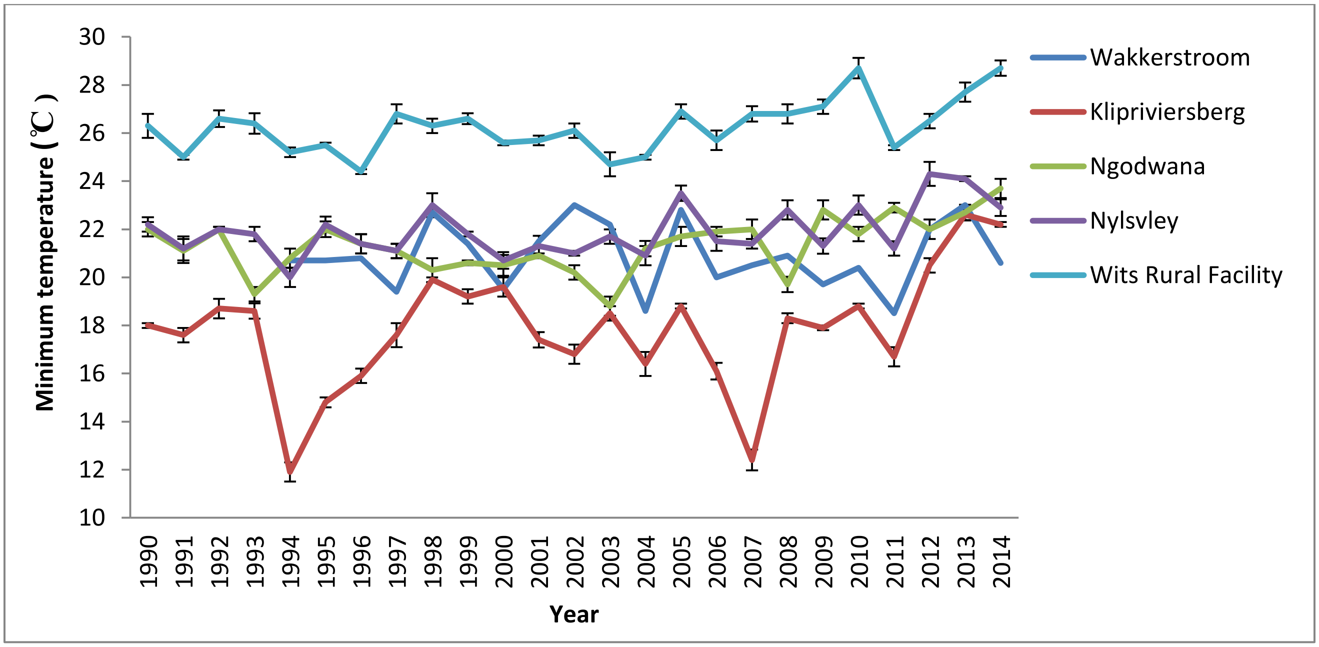


Figure 31: Average minimum temperatures by year for all study sites from 1990- 2014 ($x^2 = 85.808$, d.f. = 4, $p < 0.001$, $\alpha = 0.05$)

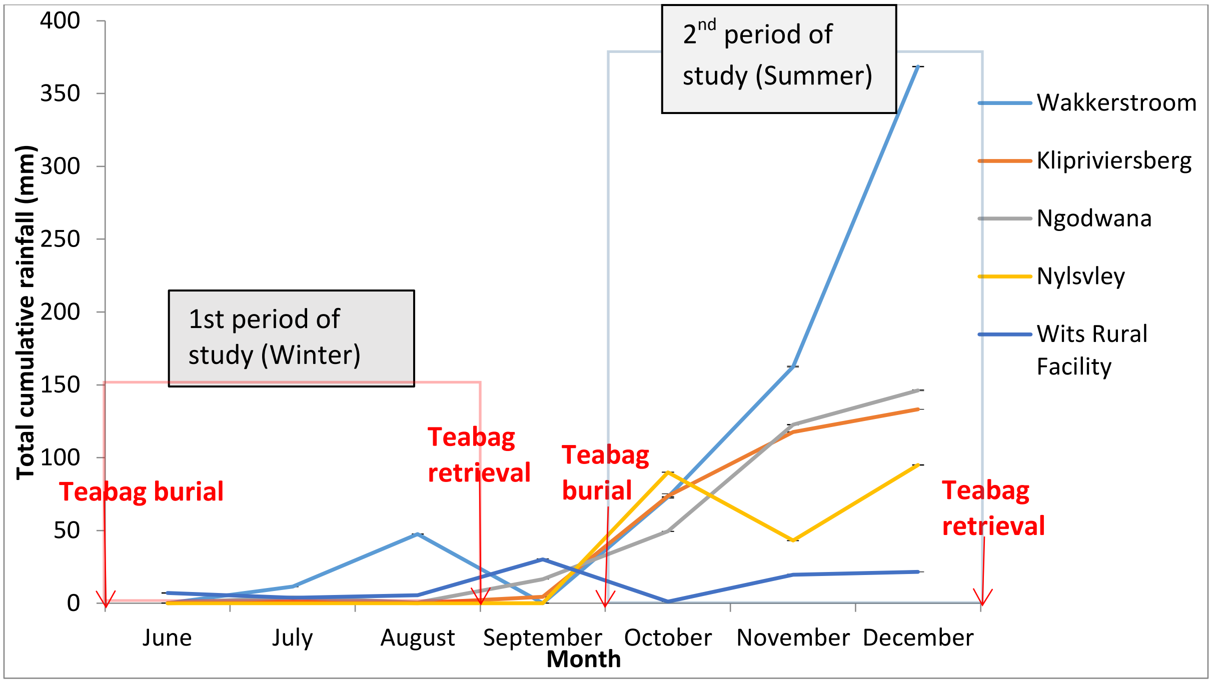


Figure 32: Total cumulative rainfall for the months the study took place

The total daily rainfall for the 1st study period (June to August) and the 2nd study period (October to December) were significantly different across all study sites ($x^2 = 9.898$, d.f. = 4, $p < 0.05$, $\alpha = 0.05$) and ($x^2 = 10.678$, d.f. = 4, $p < 0.05$, $\alpha = 0.05$) respectively. From June to August South Africa experiences a dry winter and the levels of moisture were significantly lower than the summer values. On the other hand September to December the season is a wet summer and the levels of moisture increased across all sites. The levels of moisture were significantly lower at the time of teabag placement during the 1st study period in June compared to the time of teabag placement during the 2nd study period in October. The amount of rainfall was significantly higher at the time of teabag collection in December during the 2nd study period compared to the 1st teabag collection during the 1st study period.

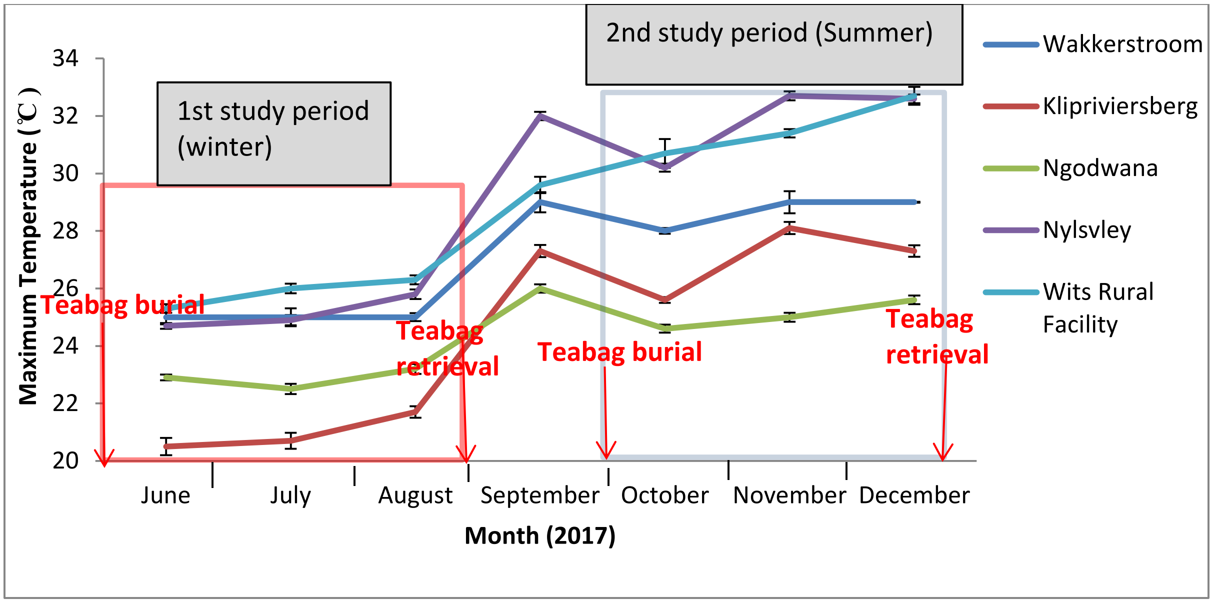


Figure 33: Average maximum temperatures for the duration of this study

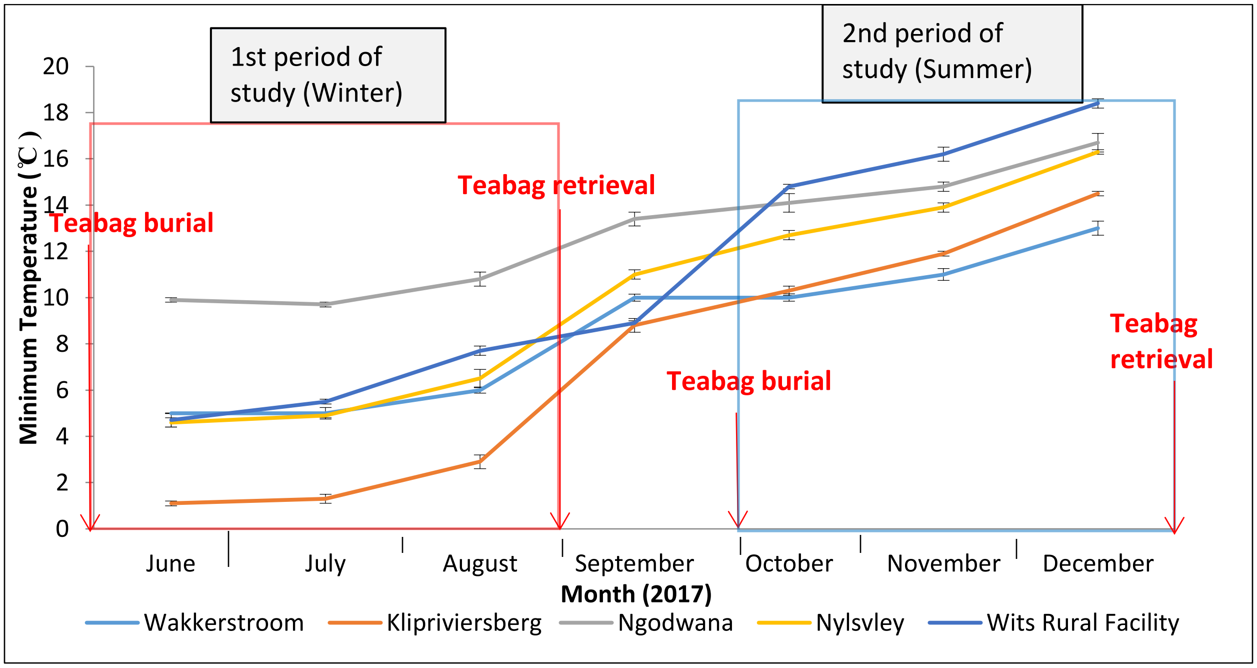


Figure 34: Average minimum temperatures for the study period

The minimum and maximum temperatures for the duration of this study were significantly different across all study sites ($x^2 = 56.0772$, d.f. = 9, $p < 0.001$, $\alpha = 0.05$) (Figures 33 and 34).

Nylsvley and the Wits Rural Facility study sites had the highest maximum temperatures while the Ngodwana and Kliprivierberg sites had the lowest maximum temperatures for the duration of the study periods. On the other hand the Ngodwana area (both sites) had the highest minimum temperature until October; thereafter the Wits Rural Facility's minimum temperature is the highest till December. The lowest minimum temperatures for the period of the study were recorded at Klipriviersberg and Wakkerstroom.

Both the rainfall and temperatures during the months of this study have a positive correlation with the decomposition rate constant (R= 0.283 and R=0.327 respectively) (Figures 35 and 36). The correlations are weak but they show that as the temperature and amount of rainfall increase, the decomposition rate constant also increases.

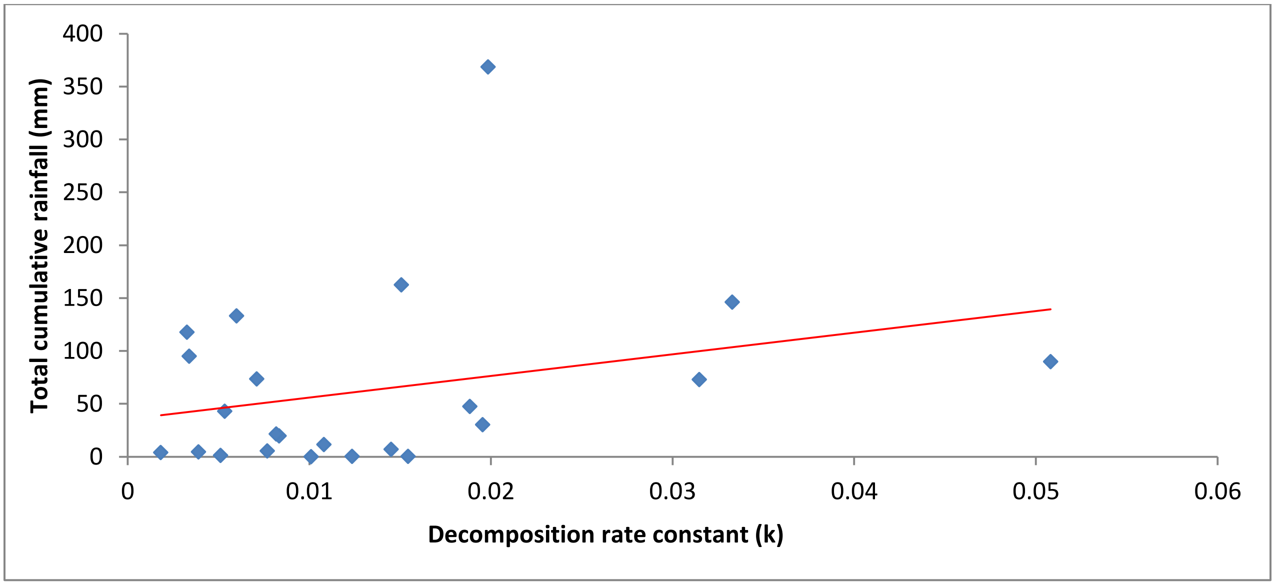


Figure 35: Correlation between total cumulative rainfall for the duration of this study and the decomposition rate constant (R= 0.283)

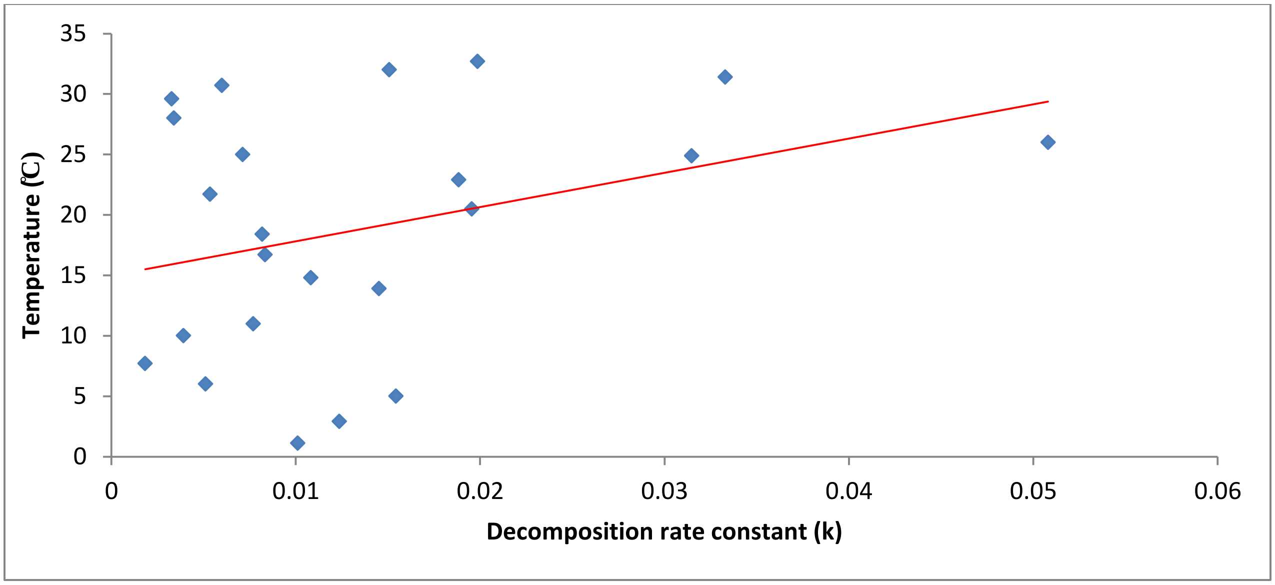


Figure 36: Correlation between temperatures for the duration of this study and the decomposition rate constant (R=0.327)

4.4. The rate of litter decomposition using teabag mass loss

4.4.1. Non-woven and woven tea bags weight loss

Lipton used to make the Rooibos and green tea in fine mesh, woven, nylon teabags (old teabags) which had 0.25mm pores but they changed the material of the teabags to non-woven, polypropylene teabags (new teabags). This study compares the decomposition rate constants of the old teabags and the new teabags. A large weight loss should translate into a fast decomposition rate and a high decomposition rate constant (Figures 37 and 38). The tea bag data for the non-woven tea bags showed that there was a significant difference between the percentage weight loss across the different sites, in winter and in summer (F= (3, 20) = 31.38, $p < 0.001$, F (0.05)). In general the summer percentage weight loss was higher than the winter weight loss. A higher percentage weight loss for green tea than Rooibos tea was recorded in both summer (green tea loses were on average 41% more mass than Rooibos tea) and winter (green tea loses were on average 23.06% more mass than Rooibos tea).

The woven bags tell the same story as the non-woven bags. There was a higher percentage weight loss for green tea than Rooibos tea in both summer and winter. The tea bag data for the woven tea bags show that there was a significant difference between the percentage weight loss among the different sites, in winter and in summer (F= (3, 20) = 13.635, p < 0.001, F (0.05)). The general trend seen here is also that the percentage weight loss in summer was much higher (green tea mass loses were on average 29.41% more than Rooibos tea) than the winter weight loss percentage (green tea mass loses were on average 14.62% more than Rooibos tea). The highest average percentage weight loss for the green tea in winter was recorded at the Ngodwana Top site while the highest average percentage weight loss for the Rooibos tea was recorded at the Ngodwana Bottom site. On average the new non-woven tea bags lose more weight than the old woven tea bags. This shows that the teabag material is not an absolute measure but a relative measure. The values of the teabag weight loss of the two different materials are not expected to ever be the same but their general trend is expected to be the same as is shown by the data (Figures 37 and 38).

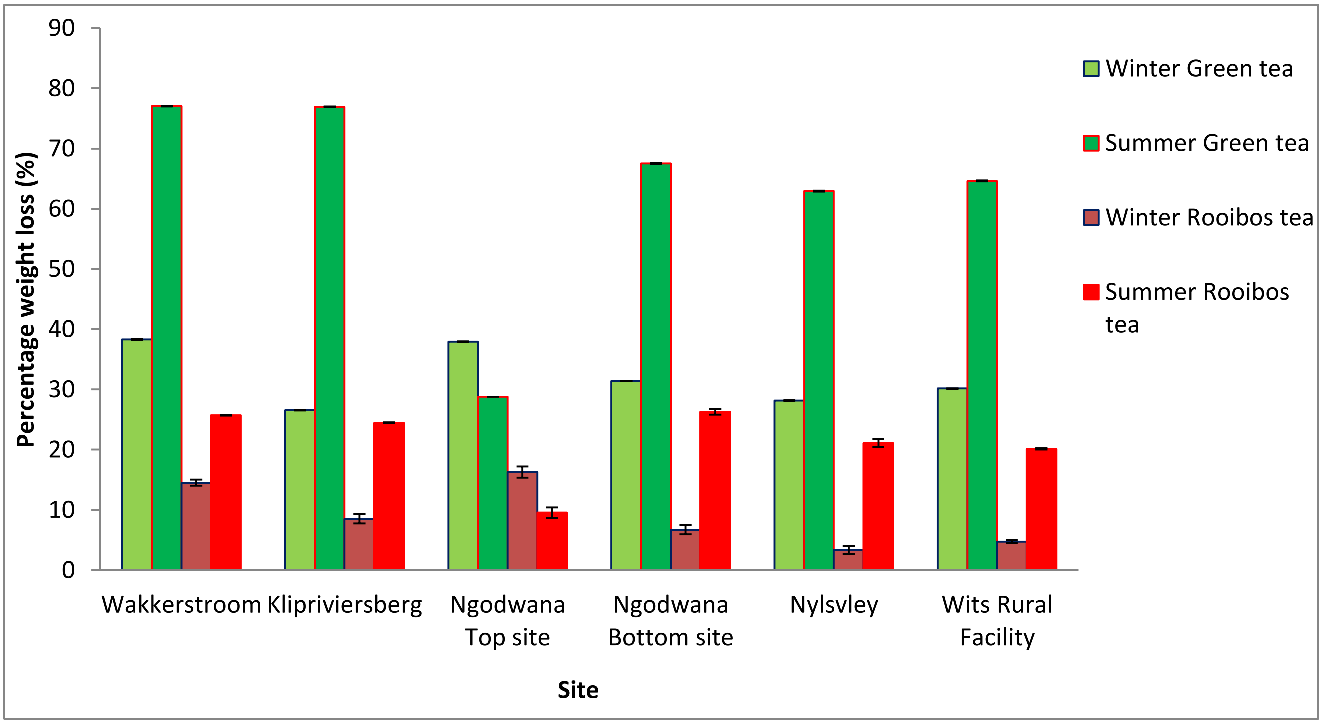


Figure 37: Mean percentage non-woven teabag weight loss for Rooibos tea and green tea, in winter and summer (F= (3, 20) = 13.635, p < 0.001, F (0.05))

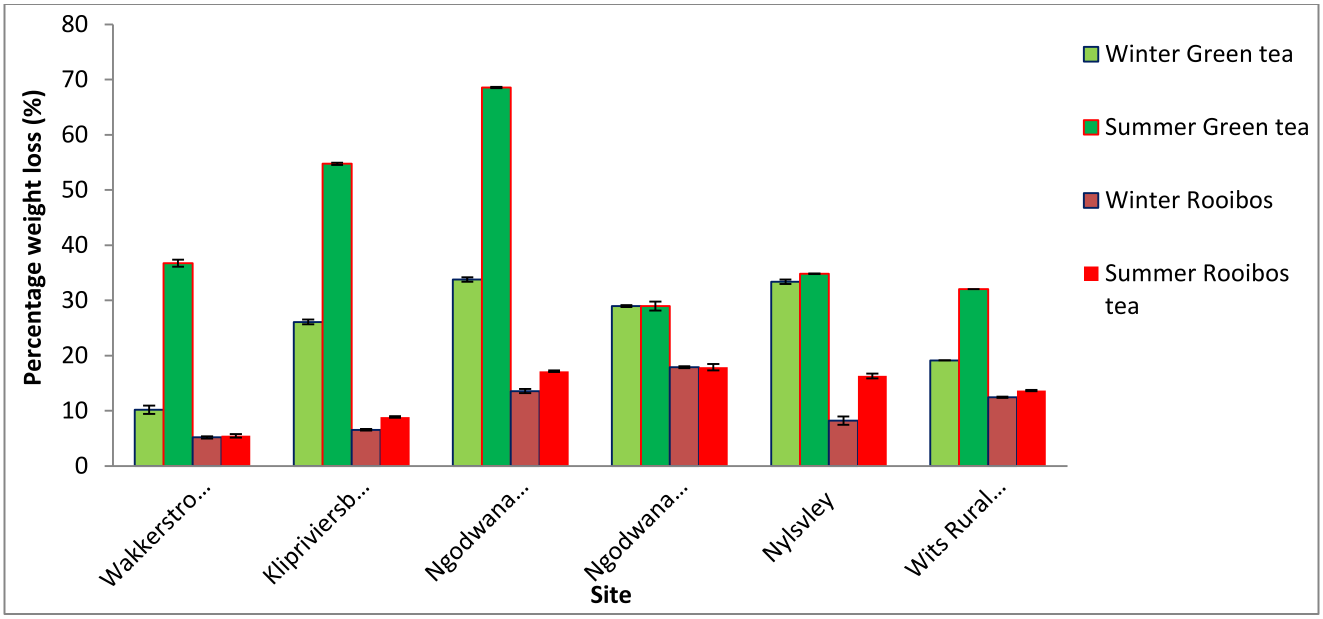


Figure 38: Mean percentage woven teabag weight loss for Rooibos tea and green tea, in winter and summer (F= (3, 20) = 13.635, p < 0.001, F (0.05))

4.4.2. Non-woven and woven teabags s and k values

There is a significant difference between the k values of the woven and non-woven teabags across all sites and between the two different seasons (F= (1, 22) = 5.475, p < 0.05, F (0.05)) (Tables 3 and 4). A larger s and k value show a bigger stabilization factor and larger decomposition rate constant.

In winter, for the non-woven teabags, the fastest decomposition rate constant was recorded at the Wits Rural facility followed by the Ngodwana Bottom site whereas for the woven teabags it was recorded at the Ngodwana Top site followed by the Klipriviersberg site. In summer the non-woven teabags were recorded as Ngodwana Bottom site followed by the Wits Rural Facility with fastest decomposition rate constants and the woven teabags were recorded as the Ngodwana Top site followed by the Ngodwana Bottom site with the fastest decomposition rate constants. There were significant differences between the decomposition rate constants of the non-woven and woven teabags in winter (F= (1, 10) = 5.998, p < 0.05, F (0.05)). There were also significant differences between the decomposition rate constants of the non-woven and woven teabags in summer (F= (1, 10) = 0.609, p <0.05, F (0.05)).

Furthermore, there were significant differences between the s values of the woven and non-woven teabags between the two different seasons ($x^2 = 1.921$, d.f. = 1, $p < 0.05$, $\alpha = 0.05$). The s values were larger in winter than they were in summer for both the different types of teabag materials.

Table 3: Mean stabilization factors (S) and decomposition rate constant (k values) for non-woven, polypropylene tea bags and woven, nylon tea bags across sites and seasons

Location	Treatment	S (non-woven)	k (non-woven)	S (woven)	k (woven)
Wakkerstroom	Winter	0.0195	0.0101	0.8790	0.0101
Klipriviersberg	Winter	0.0054	0.0124	0.6900	0.0123
Ngodwana Top site	Winter	0.0188	0.0154	0.5985	0.0154
Ngodwana Bottom Site	Winter	0.0330	0.0051	0.6560	0.0051
Nylsvley	Winter	0.0711	0.0018	0.6035	0.0018
Wits Rural Facility	Winter	0.0508	0.0039	0.7730	0.0039
Wakkerstroom	Summer	0.0034	0.00817	0.5635	0.00812
Klipriviersberg	Summer	0.0033	0.0077	0.3500	0.0077
Ngodwana Top site	Summer	0.0059	0.0145	0.1860	0.0145
Ngodwana Bottom Site	Summer	0.0330	0.0108	0.6560	0.0108
Nylsvley	Summer	0.0151	0.0083	0.5870	0.0083
Wits Rural Facility	Summer	0.0199	0.0082	0.6195	0.0082

Table 4: Comparison of k values between the two different types of teabags

Rank	Site	k (Non-woven teabags)	Site	k (Woven tea bags)
Winter				
1	Wakkerstroom	0.0101	Ngodwana Top site	0.0154
2	Nylsvley	0.0018	Klipriviersberg	0.0123
3	Wits Rural Facility	0.0039	Wakkerstroom	0.0101
4	Ngodwana Bottom site	0.0051	Ngodwana Bottom site	0.0051
5	Klipriviersberg	0.0124	Wits Rural Facility	0.0039
6	Ngodwana Top site	0.0154	Nylsvley	0.0018
Summer				
1	Klipriviersberg	0.0077	Ngodwana Top site	0.0145
2	Wakkerstroom	0.0082	Ngodwana Bottom site	0.0108
3	Wits Rural Facility	0.0082	Nylsvley	0.0083
4	Nylsvley	0.0083	Wits Rural Facility	0.0082
5	Ngodwana Bottom site	0.0108	Wakkerstroom	0.0082
6	Ngodwana Top site	0.0145	Klipriviersberg	0.00767

(Rank 1= Fastest, 6= slowest)

4.5. S and K correlation

There is no significant difference between the s values of the woven and the non-woven teabags across all sites and between the two different seasons ($x^2 = 1.921$, d.f. = 1, $p > 0.05$, $\alpha = 0.05$. In addition, a correlation (Figure 39) between the decomposition rate constant k and stabilization factor S was also analyzed and it shows a very weak negative correlation (R = -0.002432483) for the non-woven teabags and a very weak positive correlation (R= 0.4640998) for the woven teabags. This shows that the material of the teabags is not a significant factor affecting the stabilization factor or decomposition rate constant.

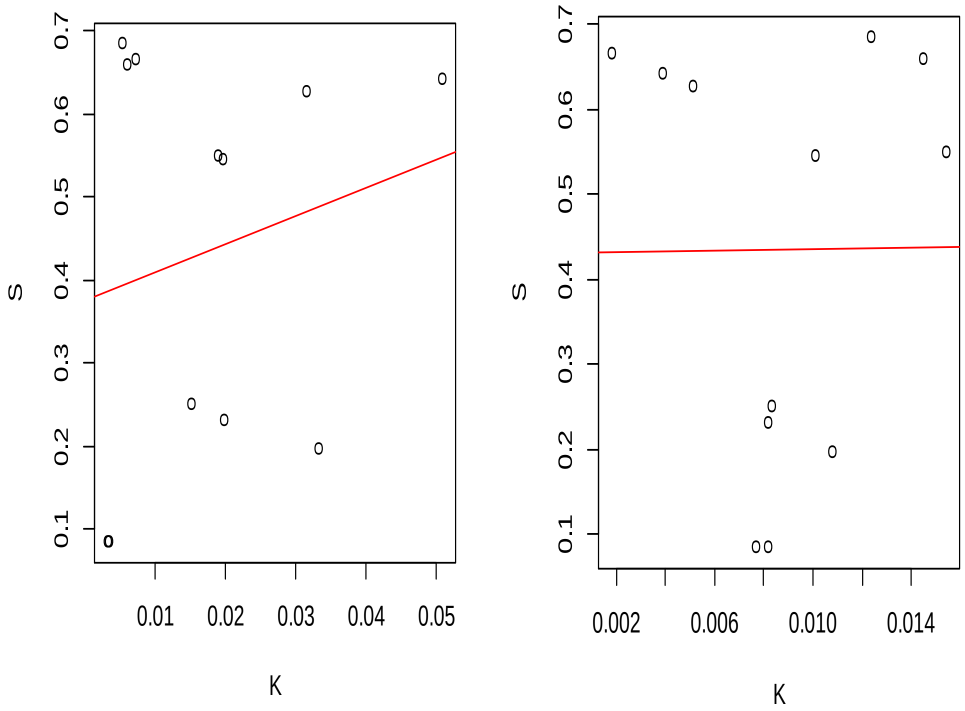


Figure 39: S and k correlation for woven teabags (left) and non-woven teabags (right) (R = -0.002432483 for the non-woven teabags and R = 0.4640998 for the woven teabags)

Chapter 5: Discussion

This section will look at the links between the soil properties at the study sites and litter decomposition. The effects of temperature, rainfall and land use types on litter decomposition rate constants will also be discussed.

5.1. Litter quality and decomposition

Keuscamp *et al* (2013) conducted lab experiments that showed that green tea decomposes faster than Rooibos tea and the results of this study also showed the same trend. The green tea decomposes at significantly faster rate than the Rooibos tea showing that the litter quality of green tea has more readily decomposable fractions (Kolář *et al,* 2009; Strosser, 2010). However, recalcitrant fractions are important for soil stabilisation as they increase the retention time of carbon in the soil (Marshner *et al,* 2008). Carbon fractions in the litter can then be used to determine carbon fractions in the soil and it is expected that the increase in atmospheric CO_2 will increase net primary production and this will increase litter production and in turn increase soil organic matter accumulation (Morgan *et al,* 2011).

Green tea has a lower C:N ratio than Rooibos tea and material with high C:N ratios take longer to decompose than a low C:N ratio material which is more labile (Fog, 1988; Manzoni *et al,* 2008). The green tea decomposes faster than Rooibos tea and this is also because the hydrolysable fraction of green tea is higher than that of Rooibos tea. Terrestrial ecosystems which have the highest C content are those that have low litter decomposition rates (Couteaux *et al,* 1995) and this also corresponds with the litter quality of the material decomposing. As the decomposition rate constant was calculated using both teas, the rest of the data analysis was carried out looking at the woven and non-woven teabags of the green and Rooibos tea.

5.2. Soil properties and litter decomposition

When it comes to texture, a high clay content has been found to protect soil organic matter from rapid break down (Giller *et al,* 1997) however the results show that the sites with the highest clay content (from highest to lowest: Ngodwana Top site (>50%), Klipriviersberg (30-35%), Wakkerstroom (20-30%) and Ngodwana Bottom site (15-20%)) had the fastest decomposition rates in winter, in that order. The WRF and Nylsvley sites had the lowest clay content (5-10%) had the slowest decomposition rate constants in winter which contradicts the Giller *et al* (1997) findings. The summer decomposition rate constants did not have a clear trend as the highest clay content sites also had the fastest decomposition rate constants and Wakkerstroom and Kliprivierberg had the slowest decomposition rate constants. These data imply that temperature maybe a more important driver of litter decomposition than soil texture.

A low C:N ratio is expected to have a faster turning over pool of soluble and labile carbon than a soil with higher C:N ratio (Fog, 1988; Manzoni *et al*, 2008). However the results did not have a clear trend as Nylsvley has the lowest C:N ratio and yet had the slowest decomposition rate constant and the Ngodwana Top site had a higher C:N ratio than Nylsvley and yet had the fastest decomposition rate constant. According to Couteux *et al* (1996), as C and N increase, the decomposition rate constant decreases. It has also been found that another variable controlling decomposition is the exchangeable cations and litter decomposition is expected to decrease as the amount of exchangeable cations increase (Chivenge *et al,* 2011). The results of this study showed that, except for sodium, as all the other exchangeable cations' increase, litter decomposition rate constant decreases and these interlink with the pH and soil texture. The pH has a strong effect on decomposition as the results showed that acidic soils have slow decomposition rate constants. This is supported by evidence from other studies which show that the pH decreased the microbial population which played an essential role in decomposition (Mtambanengwe *et al*, 2004). Nutrient cycling in soils has also been found to be affected by pH and this study shows that there might be a threshold effect on all the soil properties such that even though sand fractions and phosphorus increased the decomposition rate constant, these effects are dwarfed by acidic soils which decrease the decomposition rate constant. (Ketterings *et al*, 2007). Additionally, the clay content, C:N content and soil temperature all had a negative correlation with the decomposition rate constant and these effects might mask the effects that increase the decomposition rate constant.

5.3. Effect of temperature and moisture on decomposition rate constants

One of the aims of this study was to examine whether temperature affects litter decomposition across different land uses. Temperature has been found to regulate litter decomposition and the implications of climate change make temperature a crucial variable to be examined with regards to litter decomposition because an increase in temperature has been found to increase the decomposition rate (von Lützow and Kögel-Knabner, 2009; Haddix *et al*, 2010; Zhu and Cheng, 2011; White Paper, 2011, ; Muñoz *et al*, 2016). Temperatures between 15 °C–35 °C increase decomposition rate constants however this study also found the importance of moisture on the temperature control of litter decomposition. The summer rainfall altered soil moisture conditions as precipitation increased from below 50mm in winter to above 100mm in summer. This is in tandem with Riutta *et al* (2012) findings which suggest that changes in climate will have a significant effect on soil turn over and decomposition rates in different biomes.

The long term ambient temperature data show that the Wits Rural Facility (WRF), Nylsvley, Klipriviersberg, Ngodwana, Wakkerstroom, in that order is the warmest to coolest sites. The decomposition rate constant in winter shows that, the rates of decomposition from fastest to slowest is Ngodwana Top Site, Klipriviersberg, Wakkerstroom, Ngodwana Bottom site, WRF and then Nylsvley. Studies have found that temperature and decomposition have a strong correlation (Kirschbaum, 1994; Liski *et* al, 2003; David and Janssens, 2006) and it is expected that warmer sites should have the fastest decomposition rate constants. However, Ngodwana is one of the cool sites and yet it has the fastest decomposition rate constants and this could be due to heat retention by the litter layers at the site. Consequently, the summer decomposition rate constants show that, the rates of decomposition constant from fastest to slowest is Ngodwana Top site, Ngodwana bottom site, Nylsvley, WRF, Klipriviersberg and then Wakkerstroom. Wakkerstroom is the coolest site and as a result its slow decomposition rate constant corresponds well with surveyed literature (Zhu and Cheng, 2011; Muñoz *et al*, 2016). Therefore it was expected that the summer decomposition rate constants would be significantly faster than the winter decomposition rates as the ambient and soil temperatures in summer are much higher than the winter temperatures.

The results showed that temperature has a positive correlation with the decomposition rate constant and this corresponds well with the general trend that the teabags lost more weight in summer than in winter (green tea: $\bar{x}$ = 32.08% in winter, $\bar{x}$ = 62.97% in summer, Rooibos tea: $\bar{x}$ = 0.016% in winter, $\bar{x}$ = 21.200% in Summer).

Lavelle *et al* (1993) postulated that climate is at the top of the hierarchy for factors affecting decomposition but on the other hand it is argued that this only happens at the global scale (Aerts, 1997). The emerging pattern from the results about temperature and decomposition rate constants display that temperature may have indirect effects on decomposition at the local scale. Climate, litter quality and chemistry are considered to be in a triangular relationship (Pérez-Harguindeguy *et al*, 2007) and these are factors to be considered when analyzing the effect of temperature on the decomposition rate constant.

The Ngodwana Top site had at least 5cms worth of pine litter covering the soil and this acts as insulation which retains heat and could explain why the site had the fastest decomposition rate constant in summer and winter. The Ngodwana site had the second lowest maximum temperatures (22.0 °C–25.6 °C), the site also had the highest minimum temperature until October and the second highest minimum temperatures until the end of the study period (9.9 °C–16.7 °C). Furthermore, under warm, wet conditions, climate is regarded as less of a limiting factor for decomposition and litter quality is the essential factor (Couteaux *et al*, 1995). South Africa experiences a wet summer and this could explain why the teabags weight losses in winter were much less than the summer teabags weight losses. Moisture is an important factor affecting decomposition however high levels of moisture in the soil results in a slow decomposition rate constant as water fills up all the airspaces in the soil and hence the summer teabags very moist at the time of their recovery.

Aerts (2006) proposed that climate affects litter decomposition through changes in soil temperature and soil moisture as these have a direct impact on the rate of litter mass loss and these factors played essential roles in litter decomposition rates across all study sites. The decomposition rate constant for this study was markedly higher at higher temperatures. This implies that seasonal variations play an essential role in mass loss of litter and litter decomposition rates. The seasonal variation will affect nutrient cycling and suggests that there is a positive feedback loop of these study sites becoming carbon sources with future climate change implications (Zhang *et al*, 2008, Salah and Scholes, 2011). The litter decomposition constant increased when the temperature and rainfall increased and this shows that there is potential for increased release of carbon dioxide from carbon sinks. Therefore instead of soils being carbon storage sites, there is an increased potential for more carbon to be released into the atmosphere thereby creating more perturbations in the biogeochemical cycle (Figure 40). The seasonal variation where moisture increases plays an essential role in litter decomposition for land uses in South Africa. It was found that temperature has an effect on different land use types (temperatures between 15 °C–35 °C increase decomposition rate constants). However this study also found the importance of moisture on the temperature control of litter decomposition. The summer rainfall suggests that moisture conditions were altered (precipitation increased from below 50mm in winter to above 100mm in summer). It therefore follows that changes in climate will have a significant effect on soil turn over and decomposition rates in different biomes (Riutta *et al*, 2012).

As temperature increases the rate of the decomposition rate constant, it also decreases the stabilization fraction S because temperature, along with moisture increases the amount of readily decomposable material by decreasing the physical and chemical protection of the soil (Davidsons and Janssens, 2006). As found by Marshner *et al* (2008), this study found that a high decomposition rate constant has a low stabilisation factor and a low decomposition rate constant has a high stabilisation factor. This is because the physical protection mechanisms of organic matter slows down decomposition processes but when the decomposition process is fast, the labile fractions increase as the organic matter decomposed faster and therefore soil carbon will have a shorter retention time in the soil (Marshner *et al*, 2008).

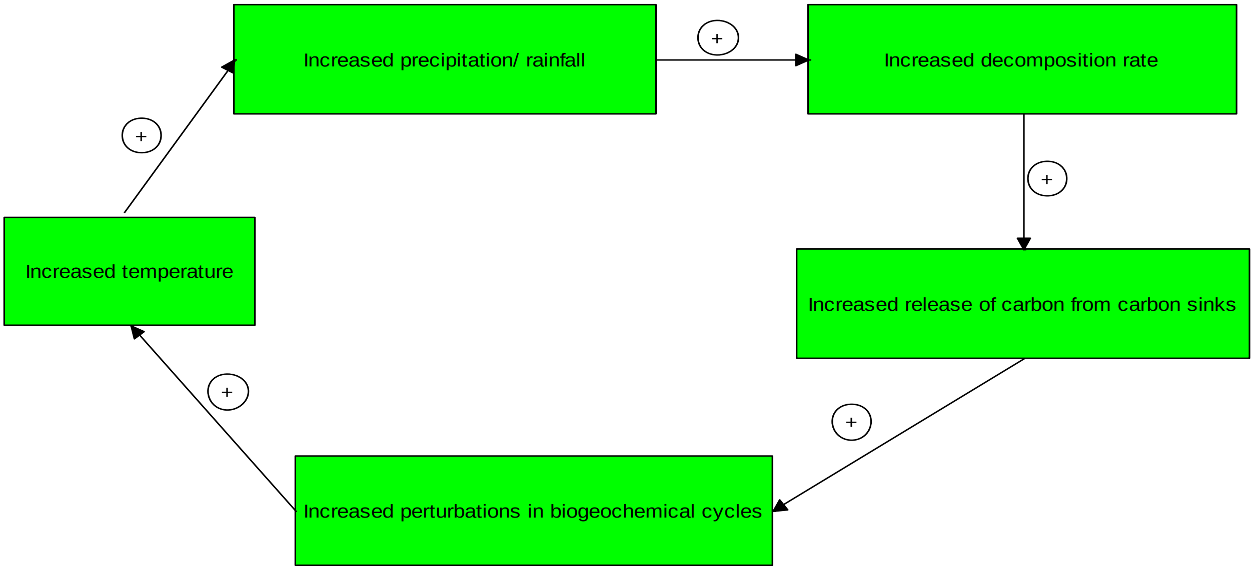


Figure 40: Causal loop diagram of potential feedback

5.4. Effects of different land use types on litter decomposition

Land uses for this study were chosen to allow for a temperature gradient, different vegetation types and hence the different litter quality found at the different sites. From the land use perspective, temperature seems to have a direct effect on decomposition rate constants because the warmer sites had faster decomposition rate constants than the cooler sites. Globally it has been found that moist forests have the fastest decomposition rates and dry and cold land use types have slow decomposition rates (Raich and Schlesinger, 1992). The results from this study show that in winter the decomposition rate constants from fastest to slowest are: Pine forest top site, the grasslands, the cooler Pine forest bottom site and then the savanna sites. Accordingly in summer the decomposition rate constants from fastest to slowest are: Pine forest plantation, savanna sites followed by grassland sites (in all instances, the warmer sites had a faster decomposition rate constant compared to the cooler sites).

The forest plantation had the fastest decomposition rate constant whereas in winter the grasslands had a faster decomposition rate constant compared to savanna sites. The opposite is, however, true in summer signifying that moisture plays an essential role in the decomposition process. The different land use types have different soil properties and the litter of the different land use contributes to the varying soil properties and litter found at each site. The soil property variables show that there are more complex interactions between all the variables that result in the varying rates of decomposition as was found by a study by Prescott (2010). This reflects the limitations of predicting mass loss of teabag litter from initial resource quality variables as they only show some general trends. Changes in soil property variables as decomposition proceeds should be measured throughout the incubation period. Additionally, the project would have benefitted from the sequential harvesting of the teabags throughout the seasons in order to gain more insight to the progress of decomposition. Lastly, temperature and moisture should have been measured at the sites throughout the two seasons in order to better understand the effect of soil moisture and temperature on decomposition.

Chapter 6: Conclusion

In conclusion, this study contributed to the global map of litter decomposition and a manuscript is currently being compiled which includes the South African data points from this study. This study has shown that litter quality has a significant effect on decomposition, with faster rates of decomposition constants being recorded with teabags that had higher labile and lower hydrolysable fractions. There were also significant variations found in the decomposition rate constants of different land use types at different temperatures (Pine forest> grassland> savanna in winter and Pine forest> savanna> grassland in summer). The soil moisture within and between the different land uses largely explained litter mass losses as has been found by Prescott (2010). Differences in the decomposition rate constants between the land use types demonstrate that litter decomposition is significantly influenced by the biotic and abiotic conditions. Soil moisture seems to have the most direct influence on different land uses while the different soil variables have interlinking effects which influence decomposition.

There's clearly a need for long-term studies on temperature and soil moisture as controls on litter decomposition of various land use types. It was found that temperature has an effect on different land use types (temperatures between 15 °C–35 °C increase decomposition rate constants). However this study also found that moisture and temperature are critical variables that influence litter decomposition. Summer rainfall evidently altered soil moisture content as precipitation increase from below 50mm in winter to above 100mm in summer. It can therefore be concluded that climate change will have a significant effect on soil turn over and decomposition rates in different biomes as were found by Riutta *et al* (2012).

Litter decomposition is affected by interlinked factors of land use, temperature, moisture and soil properties and more studies are needed to assess litter decomposition whilst examining the interlinkage of these variables. This study found that litter decomposition is a strongly influenced by both moisture and temperature across all the different land uses that were selected for this study. It is particularly worth noting that an increase in temperature leads to corresponding increases in the decomposition rate constant although this tended to be limited by soil moisture content.

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