The effect of atmospheric nitrogen deposition on fynbos soils and plants in the Cape Town Metropolitan Area

Michelle Malan (MLNMC009)
Supervisor: Ed February
Honours 2009
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Abstract

Does anthropogenic nitrogen deposition influence the plants and soils of the fynbos biome? To determine the potential effect of nitrogen (N) deposition on the nutrient-poor fynbos ecosystem which occurs in and around the Cape Metropolitan Area (CMA), atmospheric nitrogen deposition was measured and tracked through the system, from the atmosphere to the soil and the plants which grow there. Ion exchange resin collectors were placed in 'urban' and 'outlying' sites in Cape Town, measuring the N deposition for four months in the rainy season of 2009. Contrary to expectations, the average monthly deposition of total N was not significantly different between urban and outlying areas but variation in the pattern of deposition over time showed that at different times in the rainy season each area received different amounts of deposition. Total soil N was determined and showed that there was no significant difference in total N between the urban and outlying areas. Total N, nitrate and ammonium content of the soils were seen to decrease over the four month collection period, following a spike in April, the beginning of the rainy season. A radish phytometer experiment found that radish plants grown in the unburnt soil of the urban site had the highest percentage nitrogen. Analysis of fynbos leaf samples found that there was no significant difference in nitrogen content of plants from the shallow-rooted Restionaceae between sites, however, plants from the deeper-rooted Proteaceae and Erica genus had a higher N content in the urban site. It is concluded that N deposition has not significantly affected the plants and soils of the fynbos reserves around the CMA.

Introduction

Cape Town is an unusual city in that it is surrounded by several large nature reserves. The evergreen, sclerophyllous vegetation of the Western Cape Province of South Africa is known as fynbos (Moll et al. 1984), and is characterised by the presence of species from the Restionaceae, Proteaceae and Ericaceae families. The reserves around Cape Town have been specifically legislated to protect the incredible diversity of species in the fynbos biome, a region which boasts an estimated 9030 species of vascular plants (Goldblatt and Manning 2002) with 2250 species occurring on the Cape Peninsula alone and 7.5% of those species endemic (Goldblatt and Manning 2000). A number of researchers have suggested that much of the regional richness may be attributed to the nutrient-poor soils of
the region (Goldblatt and Manning 2002). If this is so then an increase in nitrogen (N) in the soil will affect species richness. Studies of the pollution levels in and around Cape Town have found that there is a background atmospheric deposition of <2kg N ha⁻¹.a⁻¹ measured in the outlying area of Malmesbury (Stock and Lewis 1986a) but since 1950 the N deposition has increased to an estimated rate of 6-13kg N ha⁻¹.a⁻¹ (Wilson et al. 2009). N deposition levels in urban areas such as Kenilworth Racecourse have been found to be much greater than outlying areas such as Silvermine Nature Reserve (Wilson et al. 2009 and Wilson 2005 unpub.).

Pollutants from vehicle emissions include solid particles, carbon dioxide, sulphur dioxide, oxides of nitrogen which may be harmful to vegetation or act as a fertiliser as well as gases, and heavy metals such as lead. Secondary pollutants such as ozone may injure plants and affect plant species composition (Angold 1997). Studies on the effect of traffic on the roadside vegetation in a British heathland found changes in the species composition and an increase in grasses (Angold 1997). The brown haze visible over Cape Town early in the morning in winter is largely composed of gases from car exhaust emissions and industrial sources. These emissions include NOₓ, O₃, SO₂, aerosols and volatile organic carbons. During summer this pollution is blown out to sea by the strong south easterly wind known as the ‘Cape doctor’. In winter, however, with fewer south easterlies the brown haze is trapped over the city and washed out by the winter rains. Nitrogen deposition may be taken up by the soils and plants, introducing more N to a traditionally low N system (Stock and Lewis 1986b). This increase in N deposition could lead to the success of invasive species which grow fast on high nutrient soils with high N, outcompeting the slow growing fynbos plants (Witkowski 1988).

Are our urban reserves being significantly affected by the air around them? The primary objective of this study is to ascertain if there is a difference in amount of N deposited in the centre of the city and an outlying area and if this affects the amount of N in the soil and whether or not this is reflected in the plants.

**Methods**

**Study area**

Within the Cape Metropolitan area two sites were chosen for this study: the first, Kenilworth Racecourse Conservation Area, represents urban areas and is therefore most
likely to be affected by anthropogenic nitrogen deposition, and the other, Silvermine Nature Reserve, is in the middle of the Table Mountain National Park and less influenced by anthropogenic pollution. Each of these sites contained a recently burnt area (both were burnt in 2005) and an unburnt area. At each study site N deposition was determined using ion exchange resin collectors. Soil, leaf and moss samples were also collected from two locations, burnt and unburnt, within each site. The soil samples were analysed for ammonium and nitrate while the leaf and moss samples were analysed for total N. In addition, radish seeds (Raphanus sativus) were grown in the soil collected from the burnt and unburnt areas of both sites in the beginning of May as a control for the leaf sample N values.

Urban site: Kenilworth Racecourse Conservation Area (KRC)

The Kenilworth Racecourse Conservation Area (situated at 33°59'49.00"S 18°29'04.98"E at 26 metres above sea level) is a 52 hectare reserve in the centre of the Kenilworth Racetrack. The vegetation type is Cape Flats Sand Fynbos and apart from infestations of alien and domestic plants in a few areas it has been undisturbed for over 100 years. The soil consists of acidic tertiary sands (Mucina and Rutherford 2006) with very low organic matter. The water table is close to the surface with much of the area prone to flooding in winter. Part of the reserve was burnt in March 2005. The unburnt areas of this site are dominated by Rhinus shrubs and various members of the Iridaceae such as Aristeia and Watsonia. The majority of the recently burnt area is covered by plants from the Restionaceae family and both areas contain the recently reintroduced Erica verticillata.

Outlying Site: Silvermine Nature Reserve

Silvermine Nature Reserve forms part of the larger Table Mountain National Park which runs all the way along the Cape Peninsula. The area used for this study was situated between the Lower Steenberg Peak and Kalk Bay mountains. The unburnt plot for this site was situated at 34°06'27.69"S 18°26'29.92"E at 383 metres above sea level, while the burnt plot (burnt in 2005) was a little further away at 34°05'58.34"S 18°26'58.90"E at 414 metres above sea level.
Data collection methods

Atmospheric nitrogen deposition

Nitrogen deposition was measured using ion-exchange resin collector columns (after Fenn and Poth 2004, assembly instructions supplied by David Huber, University of Arizona). The columns are plastic irrigation pipes containing 60 ml of amberlite MB150 mixed bed ion exchange resin (Sigma-Aldrich, USA), with a funnel on one end to collect the rain, drainage holes in the bottom to let the water out, and several layers of filtering material in between to keep organic matter out and the resin in. Mixed bed resin was used in order to capture both cations and anions from the rain water which filters through the column.

Four deposition collector columns were placed in each site (urban and outlying), two in the burnt area and two in the unburnt area. The columns were attached to a pole at the same height as the vegetation (approximately one meter above ground level). Columns were left in the field and collected at the end of each month from April to July. After collection, columns were refrigerated (4°C) for not more than 48 hours before KCl extraction of the resin (David Huber, Arizona State University, pers. comm.). Resin extracts were frozen until needed for analysis. As well as the field samples, a resin blank was extracted with each month’s worth of samples to control for background nitrogen values in the resin as well as any contamination during the extraction process. The resin extracts were analysed for nitrite, nitrate and ammonia in the Oceanography department of the University of Cape Town (UCT) using a cadmium column to separate nitrate from nitrite and spectrophotometry methods to determine nitrogen concentrations in the processed samples (Wilson et al. 2009).

Soil nitrogen

Four soil samples were collected from each site at the end of each month, two in the burnt area and two in the unburnt area. Soil samples were collected from the top 5 cm of the soil surface using a metal soil corer with a diameter of 12 mm and refrigerated (4°C) for no more than 48 hours until the nitrogen was extracted. To extract NO₃-N and NH₄-N, the soil was thoroughly mixed and a 10 g subsample was shaken with 45 ml of 1 M KCl, made up with de-ionized water, for 1 hour following methods from Coetsee et al. 2008). The extracts were then centrifuged in an Eppendorf centrifuge 5810R at 2000 rpm for 5 minutes and filtered through Whatman No. 42 filter paper and frozen until needed for analysis for NO₃-N and NH₄-N in the Oceanography department at UCT.
Radish phytometer
In order to determine the plant available nitrogen in each site radish seeds (*Raphanus sativus*, Starke Ayres, variety ‘Cherry Belle’) were planted in seed trays filled with soil taken from each site in April. The plants were grown in a greenhouse for 28 days and then harvested. Each plant was labelled and dried individually in a drying oven at 60°C. Once completely dry, each plant was separated into roots and shoots and these were weighed in order to determine biomass and root:shoot ratios. The shoots were then weighed out in order to determine percentage nitrogen using a Thermo Finnigan Delta plus xp mass spectrometer coupled with a conflo iii device to a Thermo Finnigan Flash EA112 elemental analyser with automatic sampler (Thermo Electron Corporation, Milan, Italy) in the Archaeology department of UCT.

Plant nitrogen
Species representative of the three main fynbos families (Restionaceae, Ericaceae and Proteaceae) were identified in each site. At the end of each month leaf samples of the three main fynbos families were collected in both burnt and unburnt areas of each site (Table 1). The moss sample collected from each site was a *Campylopus* species, an acrocarpal, mixohydric (Wilson *et al.* 2009) moss common to unburnt areas of both sites. Prior to mass spectrometry, the moss and leaves were oven dried to constant weight, crushed and ground to a fine powder using a Retsch MM200 ball bearing mill (Retsch, Haan, Germany).

<table>
<thead>
<tr>
<th>Family</th>
<th>Kenilworth Racecourse Reserve (KRC)</th>
<th>Silvermine Nature Reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restionaceae</td>
<td><em>Restio</em> spp. (unburnt) and <em>Stauroheda</em> spp. (burnt)</td>
<td><em>Hypodiscus</em> spp.</td>
</tr>
<tr>
<td>Ericaceae</td>
<td><em>Erica verticillata</em></td>
<td><em>Erica erucoides</em></td>
</tr>
<tr>
<td>Proteaceae</td>
<td><em>Serruria glomerata</em></td>
<td><em>Leucadendron laevigatum</em></td>
</tr>
<tr>
<td>Moss</td>
<td><em>Campylopus</em> spp.</td>
<td><em>Campylopus</em> spp.</td>
</tr>
</tbody>
</table>
Results

Nitrogen deposition

On average, Kenilworth Racecourse Conservation Area (KRC) received 0.58 kg atmospheric N deposition per ha\(^{-1}\) month\(^{-1}\) while Silvermine Nature Reserve received 0.66 kg N. ha\(^{-1}\) month\(^{-1}\). These amounts were however highly variable over the four month sampling period. At the beginning of winter KRC received more deposition while Silvermine Nature Reserve received more at the end of the sampling period (Fig. 2). There was more nitrate in the deposition than ammonium (there were no significant differences in amount of deposition between sites). There was also no correlation between rainfall and deposition (Fig. 1) for either KRC or Silvermine.

\[ r = \text{?} \quad \text{Sample size} = \text{?} \]

**Figure 1:** Shows the relationship between rainfall and deposition for each site (excluding Silvermine rainfall for July). There was no correlation between rainfall and deposition for either site (☐ = KRC, ▲ = Silvermine)
Figure 2: Nitrogen deposition at Kenilworth (clear bars) and Silvermine (hatched bars) from April to July. (a) shows nitrate deposition, (b) shows ammonium deposition and (c) shows total nitrogen, which is the sum of nitrite, nitrate and ammonium. Were there significant differences?
Figure 3: Nitrate (a) ammonium (b) and total N (c) of soil samples from burnt and unburnt areas of Kenilworth Racecourse Conservation Area (KRC) and Silvermine Nature Reserve (Silv).
Soil

Soil samples from both KRC and Silvermine Nature Reserve show a general trend of high nitrate, ammonium and the total N in the beginning of the sampling period (April) which then gradually decreases as the winter progresses (Fig. 3). Soil N content decreased over time as rainfall increased (Fig. 5). Soils from KRC had significantly higher nitrate and ammonium content than those from Silvermine Nature Reserve ($p=0.053$ and $p=0.047$, $DF=15$). Total N values were also significantly different between KRC and Silvermine Nature Reserve ($p=0.047$, $DF=15$) with KRC generally having greater soil N (Fig. 4). There was no significant difference within sites between burnt and unburnt plots (Fig. 4). Ammonium levels are higher than nitrate in soil, in contrast to the higher nitrate levels in the atmospheric deposition measured.

**Figure 4:** Average of total soil N over the four month sampling period.
Figure 5: Total soil N for Kenilworth Racecourse Conservation Area (rainfall from Cape Town airport weather station) (a) and Silvermine Nature Reserve (excluding rainfall data for July) (b).

Figure 6: Total nitrogen content for the leaves of radishes grown on burnt and unburnt soils of Kenilworth Racecourse Conservation Area (KRC) and Silvermine Nature Reserve (Silv).
Figure 7: Overall biomass of radish plants grown on burnt and unburnt soils of Kenilworth Racecourse Conservation Area (KRC) and Silvermine Nature Reserve (Silv).

Plant nitrogen: radishes

On average, the radishes grown in soil from KRC had significantly higher N content than those grown in soil from the Silvermine site \( (p<0.05, \text{DF}=104, \text{Fig. 6}) \). The radishes grown on the unburnt soil of KRC had a significantly higher N content than those from burnt soil \( (p<0.05, \text{DF}=32) \) while there was no significant difference in N content of radishes grown on burnt and unburnt soil from Silvermine Nature Reserve. In terms of biomass, radish plants grown in the unburnt soil of KRC had significantly smaller biomass than those grown on burnt soils \( (p<0.05, \text{DF}=49) \) while there was no significant difference between burnt and unburnt areas from Silvermine Nature Reserve (Fig. 7). Radishes grown in burnt soil from KRC also had a significantly greater biomass than those from the burnt soil of Silvermine Nature Reserve \( (p=0.058, \text{DF}=57) \), while radishes grown in the unburnt soil of KRC had significantly smaller biomass than those from the unburnt soils of Silvermine Nature Reserve \( (p<0.05, \text{DF}=62) \).
Figure 8: Total nitrogen content for leaves of Restionaceae (a) Ericaceae (b) Proteaceae (c) from Kenilworth Racecourse Conservation Area and Silvermine Nature Reserve.
Plant nitrogen: field plants

Except for the shallow-rooted Restionaceae, the leaf nitrogen content of plants sampled from the field sites show the general trend of those grown at KRC being higher in N than those from Silvermine Nature Reserve, and plants grown in burnt soils often have higher N content than those grown in unburnt soils (Fig. 8). There were no significant differences in leaf N of the Restionaceae between or within sites. The Erica verticillata plants from KRC had a significantly higher N content than E. ericaoides at Silvermine Nature Reserve ($p < 0.05$, DF=7), but there were no significant differences between burnt and unburnt plots for either site. In the Proteaceae, Serruria glomerata collected at KRC had a significantly higher N content than Leucadendron laurorum from Silvermine Nature Reserve ($p < 0.05$, DF=7), but once again, there was no significant difference within sites. Mosses collected in the unburnt plots of both sites had no significant difference in leaf nitrogen (Fig. 9).

![Graph showing nitrogen content over months]

**Figure 9:** Nitrogen content of moss samples collected in the unburnt plots of both sites.
Discussion

Our aim was to quantify the amount of nitrogen deposition that occurs in the Cape Metropolitan area and to discover whether this has an effect on the soils and plants of the natural fynbos that grows in and around the city. N deposition was found to vary greatly within and between sites over the four month sampling period. Previous studies measuring N deposition with bulk collectors (Wilson 2005 unpub.) in the Cape Town area have found bulk N deposition values of over 4kg N ha$^{-1}$ a$^{-1}$ in urban sites such as Kenilworth and areas of Table Mountain near the city, whereas the outlying sites of Silvermine and Tygerberg were found to receive lower N deposition of 2-3kg N ha$^{-1}$ a$^{-1}$. A study performed in the rural area of Malmesbury (Stock and Lewis 1986a) shows similar deposition values of 1.99kg N ha$^{-1}$ a$^{-1}$. This translates to a monthly average of 0.2kg N ha$^{-1}$ in the outlying areas and 0.35kg N ha$^{-1}$ in the urban areas. The results from this study found a monthly average of 2.16kg N ha$^{-1}$ for the urban Kenilworth site and 2.67kg N ha$^{-1}$ for the outlying site of Silvermine. These values are far larger than those found by Wilson (2005) and this probably indicates the greater efficiency of the resin columns as deposition collectors rather than bulk rain collectors. The variability in the monthly deposition between sites (Fig. 2) indicates seasonal trends influenced by the rain and wind. Stock and Lewis (1986a) found that autumn and winter were the seasons in which the largest amount of inorganic N deposition was measured in the outlying area of Malmesbury and suggest that the major source of atmospheric N contaminants is the South Atlantic Ocean rather than terrestrial or industrial sources as autumn and winter are characterised by north-westerly wind bearing rain from the sea rather than the summer south-easterlies. I speculate that the high deposition in the urban area at the beginning of the rainy season is probably due to the air pollution built up over the city being washed out by the first rains of the season. As rainfall amount increases, more atmospheric pollutants are washed out, decreasing the amount of N deposited in the collectors situated in the urban area. Silvermine is located at a higher altitude as well as further away from the city, it is above the inversion layer which traps the air pollution, creating the brown haze that is visible over the city from the mountains early in the morning, so this area may not receive as many washed out nitrates as the city. The large amount of deposition received by the Silvermine site in the second half of the sampling period (June and July) could be attributed to marine particles being deposited by cloud and rain. The Atlantic Ocean to the west of the mountain range is rich in nutrients because of the upwelling system which brings deep sea nutrients to the surface.
nutrients may then be taken into the atmosphere as clouds form. A study in Southern Chile (Weathers et al. 2000) found that cloudwater can deposit up to 2 kg ha\(^{-1}\) a\(^{-1}\) of inorganic N (nitrate\(^{-}\) and ammonium) and 9 kg ha\(^{-1}\) a\(^{-1}\) of organic N compared to less than 1 kg ha\(^{-1}\) a\(^{-1}\) deposited by rainwater. Weathers et al. also suggest that much of the nutrients in the cloud originate in the adjacent highly productive ocean, a system similar to that on the West coast of South Africa. The Silvermine Mountains are often enveloped by cloud and winter rains originate from over the sea in winter as cold fronts are blown in by north-westerly winds.

There was no correlation found between amount of atmospheric N deposition and soil nitrogen levels. The spike in soil N at the beginning of the sampling period could be explained by an increase in mineralization of N by soil microbes with wetter weather, and the decrease caused by uptake by plants through what in the fynbos is the wet growing season, and the leaching of nitrates, washed through the soil by rain. A large proportion of ammonium in the soil may be due to a large amount of mineralization activity occurring in the soil. The N-saturation hypothesis (Matson et al. 2002) predicts that large N additions to soil will increase rates of nitrogen mineralization as more N is available in the organic matter of the soil. As mineralization rates increase nitrifiers in the soil should have greater access to the ammonium which they then oxidise to form nitrate, but this process does not occur instantly after the mineralization. This may be why there is so much ammonium in the soils: mineralization has been triggered by an increase in soil moisture after the winter rains, but the ammonium formed has not yet been converted to nitrate. Wilson et al. (2009) also found that soil N at KRC was greater than that at Silvermine Nature Reserve, and that soil NH\(_4\)-N was greater than NO\(_3\)-N.

Soil nitrogen levels were slightly higher at the urban site and while there was no significant difference in percentage leaf N between sites for shallow rooted Restionaceae, the deeper rooted Ericaceae and Proteaceae had significantly more leaf N in the urban site than the outlying site. Soil N declined over time as the rainy season progressed but this was not echoed by a decline in plant N content.

There were also differences observed in soil N values between the burnt and unburnt areas in each site. Fires release unavailable organic N into the system, making it available to plants shortly after the fire. As time passes, the available N in the burnt soil decreases.
taken up by plants, so that areas which have not been burnt for many years have very little N available. If N deposition has an effect on the soil, areas that have been unburnt for a long time won’t have low N values as expected in an unpolluted site. The unburnt soil at KRC, the urban site, had significantly more N than that of the unburnt site at Silvermine Nature Reserve, the outlying area. The large amount of N in the soil at KRC is not necessarily attributed to deposition. The site is situated in the centre of a frequently fertilised horse racing track, and runoff from the track may have a large effect on the soils of the reserve.

Radish plants were grown as an indication of plant available N in the different soils. We expected to see that plants did better in burnt soils than unburnt soils and that plants at KRC did better than those in Silvermine Nature Reserve. Burnt soils were found to have higher N and in the urban site the radish plants had significantly greater biomass in the burnt soil than the unburnt soil. However, the radishes grown on unburnt soil had the highest nitrogen content. The unburnt site at KRC had higher N than the burnt site because the N is distributed over a smaller biomass. With the higher biomass in the burnt site the radish leaf N is more dispersed.

Both the KRC and Silvermine Nature Reserve sites burnt in 2005 so the soils are at a similar post-burn state so we would expect there to be similar differences in burnt and unburnt soils for the two sites. Why is the performance of the radish plants in the burnt and unburnt soils of KRC so different and Silvermine Nature Reserve so similar? Excess N input could lead to leaching (Matson et al. 2002) of nitrogen from the system, especially in these acid, sandy soils with low organic matter for the nitrates to bind to. Another explanation is that phosphates from marine deposition in Silvermine could lead to the success of plants at Silvermine Nature Reserve as opposed to plants at KRC which might have high N in the burnt site but be limited by phosphorous.

A comparison of leaf percentage N of plants grown in the different sites shows that, except for the shallow-rooted plants from the Restionaceae family, plants from the urban site at KRC had a greater N content. This could be interpreted as a greater availability of N and other nutrients in the soils at KRC, but it must be taken into account that although the plants are from the same families, the different species had different seasonal behaviour. For example, *E. verticillata* was flowering at KRC at the beginning of the sampling period.
Characteristics of mosses which make them useful for biomonitoring include a lack of root system which makes them heavily reliant on wet and dry deposition for their nutrient supply (Wilson et al. 2009). Therefore, bryophyte tissue chemistry is closely related to atmospheric inputs. The species used in this study was classed as 'mixohydric' which means they take up water through both endohydric and exohydric pathways, so their nitrogen content is a reflection of both the soil and the atmospheric deposition. The N concentration in the photosynthetic material of the moss samples is a better comparison of N availability at both sites than the plant samples as the same species occurred in both areas and the mosses were all at the same stage of growth, rehydrating after the dry summer. So it may be concluded that there was no significant difference in N availability to plants in the urban and outlying sites.

Conclusion

The nitrogen deposition measured by the ion exchange resin collectors in this study is far higher than that found by Wilson (2005) using bulk rain water sampling techniques. This is probably be due to the more efficient deposition collection technique, but if it represents an increase in N deposition then we may see increases in the amount of N present in the nitrogen-poor soils of the fynbos region in the future. If nitrogen levels of fynbos soils increase, will the diversity of the fynbos be affected? Greater availability of N may not directly harm the fynbos plants. In fact, it could actually lead to greater diversity in the region as plants which need more nutrient-rich soils move into the area, but these nitrophilous species may eventually invade, outcompeting and excluding the slow-growing fynbos (Bobbink et al. 1998). With climate change, modelled distributions of invasive European annual grasses predict movement into pristine areas of high elevations (Parker-Allie et al. 2009). Such invasion could be related to increased soil nutrients and threatens fynbos diversity by altering fire regimes.

In conclusion, this study finds that there is no clear significant difference between nitrogen deposition in urban and outlying areas of the Cape Town metropolitan area. More in-depth studies with greater sample size are needed to differentiate between deposition caused by
anthropogenic sources and that caused by natural sources such as the ocean. The acidic, sandy soils of the fynbos do not appear to retain extra nitrogen and seasonal high nitrogen values in the soils are not translated into high nitrogen content of fynbos. Leaf nitrogen content is not an ideal measure of comparative performance of plants, and future studies need to use alternative measures, perhaps biomass or growth rate, as well as striving to find common species between sites, a real challenge in the diversity of the fynbos.

References


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**Acknowledgements**

Thanks to Sharon Hall and David Huber of the Arizona State University for methods and advice regarding the resin columns; Dawood Hattas for help with remembering my chemistry; Howard Waldron for the use of his water chemistry lab; Nicky Allsopp of SAEON for advice; Adam West for rainfall data; Tim Aston for letting me tag along to the Silvermine site and much advice and Maya Beukes for use of the Kenilworth Racecourse Conservation Area. Many thanks to Ian Newton from the Archaeology department for rescuing my samples despite chronic machine breakdowns.