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A Nitrogen budget for the Cape Metropolitan Area:

Is Nitrogen enrichment occurring in the soils of remnant patches of lowland fynbos?

Honours Ecology Project

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Abstract

Anthropogenic activities create nitrogenous pollutants which threaten the existence of lowland fynbos, comprising 92 Red Data Book species and 14 Cape Flats endemics. A regional Nitrogen budget was constructed through the collation of existing data for the Cape Metropolitan Area. An NOx inventory has revealed that vehicles emit 66 % of the total NOx emissions into the atmosphere. The maximum potential N deposition is 184 kg N $ha^{-1}yr^{-1}$for the lowlands. Air quality in an industrial area, Goodwood, has revealed that a large proportion of the emissions remain in the air and have the potential to deposit 33 kg N ha^{-1} yr^{-1}. Atmospheric N deposited on unimpacted coastal fynbos is 1.99 kg ha^{-1} yr^{-1}. Thus remnant patches of lowland fynbos are threatened by replacement by grasslands as a result of atmospheric N inputs. Direct measurements of soil N pools are required, since signals of leaching in rivers may be premature as N accumulating in soil pools may not yet have reached saturation point. NH_3 emissions, wet and dry N deposition, and atmospheric transport models are required in order to construct a N budget for the CMA. Thereafter, appropriate preventative strategies can be devised in order to prevent the replacement of remnant patches of lowland fynbos.

Keywords:

Nitrogen budgets, N enrichment, lowland fynbos, N deposition, N emissions.

Introduction

Humans have almost quadrupled in numbers during the 20th century (Smil, 1997). It is estimated that the human population is increasing by 1 billion people every 12 years (Galloway, 1998). Increasing human populations drive the need for increasing food and energy requirements. Nitrogen is fundamental to life since it is a component of the DNA molecule. It controls species composition, diversity, dynamics and functioning of many terrestrial, freshwater and marine ecosystems (Vitousek, 1997). However, nitrogen forms a minor constituent of living matter and remains largely in an unreactive state, making up 78 % of the atmosphere (Smil, 1997). The synthesis of ammonia in 1919, together with other nitrogen rich fertilisers have increased the productivity of land and have effectively allowed for the rapid expansion of the human population (Smil, 1997). The synthesis of ammonia results in the conversion of an increasing amount of unreactive N to reactive, biologically available N thereby altering the global nitrogen cycle. The global N cycle has been altered by human activity to the extent that the amount of anthropogenic N fixation is double that of natural N fixation in terrestrial environments (Jeffries and Maron, 1997). It is predicted that the anthropogenic N fixation rate will increase by approximately 60 % by the year 2020 mainly as a consequence of increased fertiliser use and fossil fuel combustion (Galloway et al 1995). On average only 50 % of applied N fertiliser is removed by crops, the remainder is lost to the atmosphere, or hydrosphere or stored in soil (Galloway et al 1996). Fossil fuel combustion transfers fixed N from long term geological reserves (Vitousek et al 1997) and emits nitrous oxides into the atmosphere. In addition, increasing urbanisation results in increasing transportation in urban areas. Pollutants derived from cars contribute to additional nitrous oxides in the atmosphere (Galloway, 1998). Atmospheric N pollutants are redeposited onto landscapes downwind and downstream.

Over a century ago, the fate of anthropogenic nitrogen was debated. Today, there is widespread consensus that the expansion and intensification of agriculture, industrialisation as well as urbanisation (Holland et al 1997) create nitrogenous pollutants such as ammonia, nitrous oxides and nitrogen dioxide (Galloway, 1998). Nitrogen pollution is receiving a great deal of attention by researchers in Europe and America as nitrogen pollution is not only changing local and global ecosystem processes (Smil, 1997) but is also posing a threat to human health (Erisman et al 1998). Leaching of highly soluble nitrates from heavily fertilised areas can contaminate both surface and groundwater. Toxic levels of nitrates are commonly found in the American corn belt and in groundwater in many parts of western Europe (Smil, 1997). Immobile and persistent nitrogen based compounds increase the acidity of the soil which, may result in the loss of trace nutrients from the soil and the release of heavy metals from the ground into drinking supplies (Smil, 1997). An excess of nitrate can result in contamination of drinking water causing life-threatening methemoglobinemia ('blue baby" disease) in infants (Smil, 1997). Microbes act on nitrogen fertiliser and thereby release nitric oxide, which interacts with other pollutants to produce photochemical smog (Smil, 1997) and acid rain which can be transported hundreds of kilometres downwind of ecosystems (Vitousek et al 1997). Nitrogenous pollutants can result in an increase of respiratory disease, ozone damage to crops, odour problems, changing biodiversity, destruction of the ozone layer, global climate change, corrosion of monuments and engineering materials, and reduced visibility (Erisman et al 1998).

It is expected that nitrogen enrichment may initiate changes in plant tissue chemistry, microbial decomposition processes and rates of herbivory (Jeffries and Maron, 1997). Increasing nutrient availability leads to acidification and eutrophication, which have negative biological effects on the ecosystem (Galloway, 1998). Acidification decreases tree vitality, regenerative capacity and productivity loss by 10 % in Eastern Canada (Kurvits & Marta, 1998). Acidified waters have less wildlife in and around them, greater susceptibility to degradation through UV radiation and an alteration to the nitrogen cycle within lakes, of which the long-term effects are unknown (Erisman et al 1998). Eutrophication of surface waters occurs where growth is limited by nitrogen. It results in shifts in the biological community and a loss of biodiversity (Galloway, 1998).

In terrestrial ecosystems shifts in native ecosystems are caused by nitrogen enrichment when species of low nitrogen tolerance (nitrophobic) cannot compete with faster growing nitrophilous communities (Kurvits & Marta, 1998). Nitrification is increasingly observed in acidic soils (Kurvits & Marta, 1998). The Canadian shield is characterised by poorly buffered, slightly acidic, nutrient poor soils where nitrogen pollution may lead to shifts in species composition from species-rich heathlands to species-poor grasslands and forest (Kurvits & Marta, 1998). Similarly, heathlands in Holland, Britain, Norway and Sweden have been replaced by grasses in response to low levels of N additions. A similar process may be occurring on the slightly acidic, nutrient poor soils of the lowlands of the Cape Flats where remnant patches of species-rich fynbos communities may be replaced by species poor grasslands. Wilson (1999) found that atmospheric N deposition in the Cape lowlands may be a potential cause for grass invasions. However, data remains too sparse and scattered to understand distributions, the fate and impact of anthropogenic N to enable exact predictions of how N enrichment will affect ecosystem processes and the repercussions on human health and vegetational changes (Jeffries and Maron, 1997).

In order to alleviate the problem, regional scale nitrogen budgets are currently being devised in order to evaluate nitrogen fluxes in ecosystems. Furthermore temporal trends of N budgets indicate the sources posing the greatest threats. For example, Galloway et al (1996) analysed the N budget of the North Atlantic Ocean and its watershed. The area was selected based on availability of data and the degree on anthropogenic N disturbance. The primary sources were identified as fertilisers, fossil fuel combustion and legume cultivation. The balance between storage and denitrification losses in watersheds was identified as an area requiring further investigation. Thereafter, the necessary action can be taken to prevent or reduce contamination while highlighting areas requiring research.

The Cape Flats of the South Western Cape, South Africa, is home to acid sand plain fynbos which is a highly endangered lowland heath (McDowell & Low, 1999). It houses 92 Red Data Book species and 14 Cape Flats endemics (Rebelo, 1992). Wilson (1999) found that generally, city sites in the lowlands of the South Western Cape have higher N contents relative to rural sites. Lowland fynbos is particularly susceptible to the negative biological effects of nitrogen pollution because it occurs in remnant patches amongst the urban development of Cape Town (Rebelo, 1992). Currently, the extent to which nitrogen is being added to the ecosystem, the primary sources, the saturation points and critical loads are unknown. Without this information, we cannot make predictions and devise abatement strategies to prevent the loss of the highly endangered fynbos and other potentially hazardous effects of nitrogen pollution. Thus, the aim of this project is to (i) investigate whether N fixed by anthropogenic activities is accumulating in the lowlands of the Cape Metropolitan Area through the construction of a regional N budget (ii) identify the sources of the primary contributors to N enhancement and how these are likely to change in the near future (iii) identify the steps required in order to undertake a task of this nature as there has been no documented research dealing with regional scale nitrogen pollution and the potential threats to lowland fynbos of the Cape Flats of South Western Cape, prior to this project.

Methods and Materials

Study area

I attempted to construct a regional N budget for the Cape Metropolitan Area of the South Western Cape, South Africa. The Cape Metropolitan Area is located west of the 19° East longtitude and 34° South latitude (CMC). The entire catchment of the Kuils, Bottelary and Eerste River systems does not fall within the boundaries of the CMA. Only the lower courses of the rivers fall within the CMA boundary, but have been included in the analysis as the catchment drains the Southern parts of the Cape Flats area which is a part of the geographical area of study. The area under investigation can be seen in Figure 1.

Constructing the N budget for the CMA

I collected data from various sources in order to establish temporal trends of activities affecting N levels in the CMA (refer to Appendix A). Although limited by data availability I attempted to construct a regional N budget. The budget consists of inputs and outputs. Inputs are factors which directly and indirectly add N into the system whereas outputs are a measure of excess N leaving the system, which indicates levels of N accumulation in soils of lowland fynbos. Since there are no measurements of temporal trends of soil N pools in the lowlands of the Cape Flats, we have no direct indication of the N status of the soil and how this may be changing through time. Wilson's (1999), comparative analysis of whether city sites are relatively more susceptible to grass invasion than rural sites does not indicate time trends and contaminant sources. This project is a collation of data which may serve as an indication of potential change in the soil N pool through analysis of the N inputs and outputs through time. I focused on N inputs which are likely to influence soil nutrient concentrations of the natural remnants of fynbos in the lowlands.

Inputs

The urban sprawl of Cape Town is a consequence of increasing human populations of the Cape Flats. In order to indicate the rising populations of humans in the CMA, I included population census data, obtained from the Cape Metropolitan Council, because threats to remnant patches of lowland fynbos are closely associated with increasing human populations. Apart from threats of complete destruction of remnant patches as a result of the increasing need for housing, industrial and educational facilities (McDowell & Low, 1990), human threats to the existence of remnant patches are compounded by human activities which create atmospheric N pollutants.

Agricultural sources

Increasing urbanisation and industrialisation reduce the amount of arable land, which necessitates the intensive use of fertiliser, in order to maintain productivity to meet food demands (Shukla et al 1996). The use of fertiliser is not confined to the physical delimitations of agricultural areas. Jobst (1996) found that areas in close proximity to agricultural areas had relatively high levels of non-native annual grass infestations relative to areas in close proximity to indigenous vegetation. Gaseous emissions of N (NH_3 and N_2O) from fertilisers are transported by the wind, depending on wind conditions as well as the atmospheric lifetimes of the pollutants, and deposited on terrestrial and freshwater ecosystems. Large components of the Cape Flats landscape are utilised for agricultural purposes where N based fertiliser additions contribute to the soil and atmospheric N pools. Remnant patches of fynbos are therefore indirectly threatened by fertiliser additions through atmospheric N deposition. In order to assess the degree of threat through additions of N based fertiliser in the CMA, I collected statistics of fertiliser sales in the CMA. The data was obtained from the Fertiliser Society of South Africa (FSSA) but sales for only three magisterial districts were available, Cape Town, Somerset West and Strand. These values account only for inorganic fertilisers.

Atmospheric ammonia emissions from fertiliser is only one component of the total ammonia emissions. In the United Kingdom, the primary sources of ammonia emissions are from livestock housing and waste storage, landspreading of livestock wastes, livestock grazing and fertiliser application to agricultural and horticultural crops and grasslands (Dragosits, 1998). In Australia, Denmead (1990) found that the air above a grazed pasture was up to ten times richer in NH_3 than normal air but natural fields emitted the largest proportion of 0.65 Tg NH_3 yr^{-1} (Tg = 10^{12}g), excreta from domestic animals emitted 0.65 Tg N yr^{-1}, fertilised fields emitted 0.13 Tg N yr^{-1}, biomass burning emitted 0.12 Tg N yr^{-1}, coal burning emitted 0.07 Tg N yr^{-1}, excreta from fertilised fields emitted 0.13 Tg N $yr^{-1}$and excreta from wild animals emitted 0.03 Tg N yr^{-1}. Ammonia emissions are not monitored in the CMA and we could not estimate the ammonia inputs into the atmosphere which may then be redeposited onto landscapes. NH_3 emissions require our attention. We should investigate the method of fertiliser use and application as the timing, season, storage and method of application, which influence the amount of N leached and NH_3 volatilised.

Since fertilisation is moving towards the utilisation of urea, because of ease of transport and application (Cooper, 2000 pers comm), we should investigate the effects of NH_3 emissions from urea and predict its effects on leaching and N pollution. Unfortunately, I was unable to obtain temporal trends of livestock numbers in the CMA which would have indicated a component of atmospheric NH_3 emissions. Fortunately, NH_3 measurements are made in freshwater systems which could serve as an indication of temporal patterns. In addition, NOx is also an atmospheric pollutant.

Air pollution studies in the CMA

Global air emissions of NOx, where $NO_X = NO + NO_2$, have shown that road transport and power plants account for 70 % whereas biomass burning accounts for 20 % of the total anthropogenic NOx emissions (Olivier et al 1998). Increasing human populations within the CMA, result in increasing transportation which increases traffic pollution. In order to determine the temporal trends of road transportation in the CMA and the implications for atmospheric NOx, I collected data on the number of vehicle registrations in the CMA, which include CA, CY, CEY, CFM and CFR.x. This data was obtained from the Cape Metropolitan Council, state of the environment report website.

"Brown haze"

In the CMA, brown haze episodes are result of an inversion layer associated with calm conditions. It prevents the dilution of emitted pollutants and prevents mixing with the upper atmosphere. This means that pollutants are emitted into a smaller air mass where air velocity is insufficient for dilution (Wicking-Baird et al 1997). Thus the lowlands are subjected to high concentrations of pollutants until midday when the pollutants are slowly dispersed by wind currents. An NOx inventory for the CMA was compiled by the Energy Research Institute of the University of Cape Town (Wicking-Baird et al 1997). The following information based on the NOx inventory is taken from Wicking-Baird et al (1997). The inventory provides a detailed analysis of the NOx constituents and source emissions of the "brown haze" of the CMA for the time period of July 1995 - August 1996. It is based on a source apportionment. Source apportionment is the quantification of the relative contribution of each emission source to the pollutants collected at ambient sites (or receptor). It requires the collection of data concerning the chemical species making up particles from the sources and the ambient locations. The source sampling was based on a study done by Mintek and the Desert Research Institute. The following sources were characterised: various soils, road dust, sea salt, coal fired boiler, oil fired boiler, Caltex oil fired boiler, Caltex gas fired boiler, Caltex furnace, Caltex fluidised catalytic cracker unit, Kynock Ammonium nitrate emissions, diesel combustion, petrol combustion, wood fires, grass fires and tyre burning. Source apportionment was carried out using the Chemical Mass Balance Model. The method is accepted by the United States Environmental Protection Agency.

The chemical data was validated by repeat tests done by different organisations carrying out chemical analysis. Emission inventories were obtained by multiplying fuel consumption by emission factors. Fuel consumption of the entire Cape Metropole was obtained from various sources estimated from other parameters (Wicking-Baird et al 1997), the details of which have not been specified or referenced. Emissions from large point sources were sometimes obtained directly from the industries. However, accuracy of the information is difficult to establish since it was derived from a variety of sources. Furthermore, many emission factors were derived from international sources instead of from research conducted under local conditions. It is therefore expected that some of these values may not be accurate. The fuel use data is also not certain because of assumptions made to reach 'best estimates'. Infrequent events such as very large fires which produce large amounts of emissions were not included because of its variable nature and the difficulties of quantifying emissions. Nevertheless, the inventory is the best available source for identifying potential significant sources constituting the brown haze of the CMA.

Potential N deposition based on emission data

Based on the emissions inventory I converted the amount of NOx tons per year to kilograms per year and divided by the total area of 2159 km^2 of the CMA (CMC). This indicates the maximum bulk (wet and dry) N deposition on land and freshwater systems, which could occur in the CMA, assuming that the total emissions are deposited directly onto the land. Furthermore, I calculated the area of the CMA without mountainous regions and the Peninsula since these areas are less unlikely to be influenced by N deposition relative to the lowlands (appendix B). This was achieved through weighing of a map of the entire CMA, thereafter reweighing the same map but the mountainous portions and the Peninsula were cut out. Thus the maximum N deposition was recalculated based on more realistic patterns of N deposition.

In addition, based on vehicle registration data for the same time period (July 1995 - August 1996), the amount of NOx that was emitted by vehicles in that particular year was calculated as well as a constant estimate of the amount N deposited per car on the lowlands and the temporal trends of vehicular N deposition based on projected and past statistics (Appendix C). These calculations are based on the assumption that the N emitted from each car is equal and does not increase with increasing age of the vehicle.

The emissions given by the NOx inventory will not be proportional to the amount of N deposited on terrestrial and freshwater ecosystems for the following reasons: primary emissions will have differing dispersion mechanisms from each source as pollutants are emitted at different times, different heights and positions (Wicking-Baird et al 1997) in the geographical landscape. Emissions above the inversion layer may take a longer period of time to reach the ground (Wicking-Baird et al 1997) and may even be deposited in a completely different geographical location. These values do not include N imports and exports amongst neighbouring areas which means that it does not account for loss and gains as a result of local and global meteorological patterns. Most primary emissions undergo phase and/or chemical transformations for example NOx converts to nitrates and certain emissions are seasonal and therefore only contribute to the haze at certain times of the year (Wicking-Baird, 1997).

Air quality data

In light of the above, I obtained air quality data for Goodwood and the CBD from the CMC (Figure 1). The air quality is sampled at Goodwood because of existing air monitoring equipment, electricity and security of the equipment (CMC). I selected Goodwood because it is located on acid sand plains and is relatively close to the Central Cape Flats area as well as the Kuils River relative to other air quality sampling stations. For the purposes of this study, air quality at Goodwood serves as a representation of suburban air quality influenced by industrial activity, which may affect lowland fynbos patches. Air quality sampled in the CBD of Cape Town, allows for the comparison of air quality of areas influenced by high concentrations of traffic pollution and areas affected more by industrial activity on the lowlands in Goodwood. Unfortunately, data for air quality at Cape Point of the Southern Peninsula was not available*. It would have served as an ideal control since the air is relatively unimpacted by anthropogenic N sources.

*E. Brunke from the atmospheric research station at Cape Point (CSIR), was contacted but data was not provided.

Potential N deposition based on air quality data

Using the NOx quantities present in the atmosphere at Goodwood, I calculated the potential N deposition per hectare for the same time period (August 1995 - July 1996) as the emissions inventory. As a result of dispersion factors such as wind, particle size and the resultant settling velocity, gaseous measurements of NOx cannot be converted into amounts of N deposited per unit land. Nevertheless, based on the following assumptions, we were able to calculate an estimate of potential bulk N deposition (dry and wet) per unit land. Bulk deposition is the amount of N that could be deposited on terrestrial and freshwater systems as in the form of dry and wet deposition. Dry deposition is the transfer of gaseous pollutants from the atmosphere to the earths surface by absorption or adsorption washout and rainout (Tyson et al 1988). Wet deposition is the transferal of pollutants from the atmosphere to the earths surface by washout and rainout processes (Tyson et al 1988). The following assumptions were made: (i) a boundary layer of a 100 metres prevails and remains constant throughout the year, (ii) all the NOx is deposited onto the land directly below, without chemical reactions with water and other compounds and the exportation by wind, (iii) all N washed out after a rain event is immediately recharged the following day. The calculations are as follows (Appendix D):

a.) conversion of NOx μgm^{-3} to kilograms by multiplying by 10^{-9}
b.) multiplication by the air column (100m)
c.) multiplication by 10000 to convert to hectares
d.) multiplication by the number of days in the month
e.) summing up the N deposited for each month to estimate the N deposition per year.

These results were then compared with N deposition, based on the inventory emissions calculations for the same time period.

Outputs

Increased N input could increase the size of soil N pools but the capacity of soil to store N is limited (Skeffington et al 1988). This limit is described as the saturation point and once saturation point is reached, leaching of nitrates occurs. N saturation has many definitions, most of which describe the declining ability of an ecosystem to retain added N (Aber, 1989). The issue of interest of this project is the accumulation of N in the soil. The extent of N accumulation in the soil can be measured by measurement of leached nitrates into freshwater and groundwater sources. Since N leaves the terrestrial landscape upon saturation, these terrestrial N losses to hydrological systems are considered as outputs. However, anthropogenic river N can be a result of direct fertiliser additions, industrial and domestic pollution or the deposition of atmospheric N inputs directly into the river. Wind currents especially in summer may result in large quantities of N exportation to neighbouring provinces or countries, depending on the wind and pollutant.

According to meteorological zones of Cape Town as defined by Wicking-Baird et al (1997), north westerly winds in winter disperse the central business district (CBD) pollution in a north westerly direction (Wicking-Baird et al 1997). Traffic pollution in the central business district (CBD) is bound to be most intense as a result of car densities. Thus pollution emanating from the CBD may be transported and dispersed over the Southern parts of the Cape Flats and the Sand river catchment. Furthermore, pollution over the suburban areas parallel to the Peninsula mountain chain such as Wynberg, is dispersed downwards as a result of downdrafts induced by the local topography (Wicking-Baird, 1997). Depending on the extent and magnitude of the downdrafts, the pollutants derived from these areas as a result of residential and traffic emissions, may affect the lower lying areas of concern. The Central Cape Flats area has a concentration of industrial activity. The air quality sampling station at Goodwood is found in this meteorological zone. The Kuils, Bottelary and Eerste rivers system flows through intense agricultural landscapes and is subjected to atmospheric N inputs as a result of the wind patterns explained. Furthermore, it is in close proximity to industrial activities concentrated in the central Cape Flats. Thus nutrient concentrations of this system may indicate the degree of anthropogenic N inputs into the system. I therefore compared the concentrations of NOx and NH_3 of the Kuils, Bottelary and Eerste river with nutrient concentrations of the Sand river.

The Sand river is geographically located on the Western flank of False Bay. Based on wind patterns and land-use activity in the catchment, the Sand river is relatively unimpacted by intense agricultural and industrial activity. However, traffic pollution from the CBD may influence N concentrations of the Sand river catchment. Nutrient concentrations of rivers are further complicated by direct industrial, human and animal waste inputs into the system. In order to analyse the effect of atmospheric industrial, agricultural and traffic pollution, I selected sampling points which are least likely to be influenced by sewage. The relative location of the catchments can be seen in Figure 1.

Output analysis

Sampling stations of the Sand, Kuils, Bottelary and Eerste Rivers were matched up with 1: 50 000 topographical land-use maps in order to identify the land-use drained by tributaries as well as elevation above sea level. Careful selection of particular sampling points was made in order to avoid sewage and other direct inputs into the river. In order to investigate the effect of the inversion on atmospheric N deposition, data at sampling stations of the upper, middle and lower courses of the rivers were analysed. One would predict that the upper reaches of the rivers are less impacted by N deposition from the inversion layer because a greater volume of pollutants concentrated over the lowlands. Furthermore, I utilised data collected at sampling stations along the rivers that would potentially reflect the effect of agriculture through the process of leaching and suburban land-use on N concentrations of the river. Data for sampling points located in relatively unimpacted N habitats served as controls and relative to the Kuils, Bottelary and Eerste rivers, the Sand river served as a control. If signs of leaching are not evident in water quality of the Kuils, Bottelary and Eerste river, which receives N additions through fertiliser additions, then it is unlikely that fynbos soils subjected to only atmospheric N inputs would be leaching N.

The variation of selected sampling stations from the Sand River and Kuils, Bottelary and Eerste system was analysed in order to compare the N concentrations of the two river systems. Figures 2 and 3 shows the location of the selected sampling stations. The Kuils, Bottelary and Eerste rivers are components of a single river system draining the Cape Flats catchment area. The data is normally distributed and has similar variances, I therefore analysed the variation of N of winter medians for the years 1991, 1995 and 1999, using an analysis of variance (ANOVA). Post Hoc analysis was used to determine the significantly different variables, Statistica 2000. Winter medians were used because of winter rains which wash N from the atmosphere into rivers as well as from soil into rivers and groundwater. Because only winter means were used it was not necessary to standardise N concentrations to flow rates which follows seasonal variations.

The data available for groundwater quality represents a 'snapshot' of reality which is ineffective in an attempt to establish temporal trends of N outputs. Sampling of groundwater quality occurred at various locations and lacks continuity.

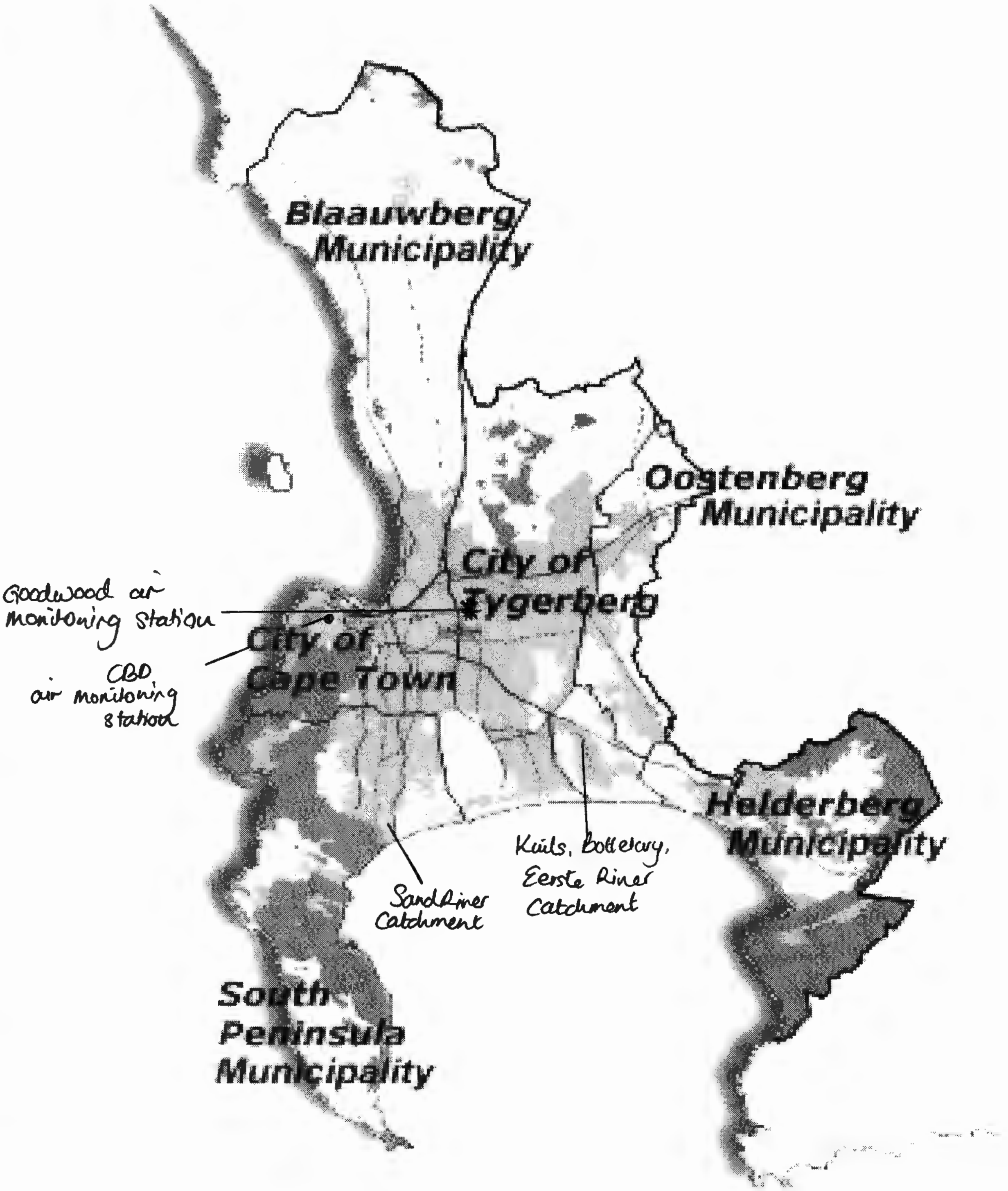

Figure 1. Map showing the Cape Metropolitan Area of the south-western Cape, South Africa.The location of air quality sampling stations in Goodwood and the CBD, location of the Sand river and the Kuils, Bottelary and Eerste river catchments are indicated on the map.

Taken from: www.ngo.grida.no/soesa

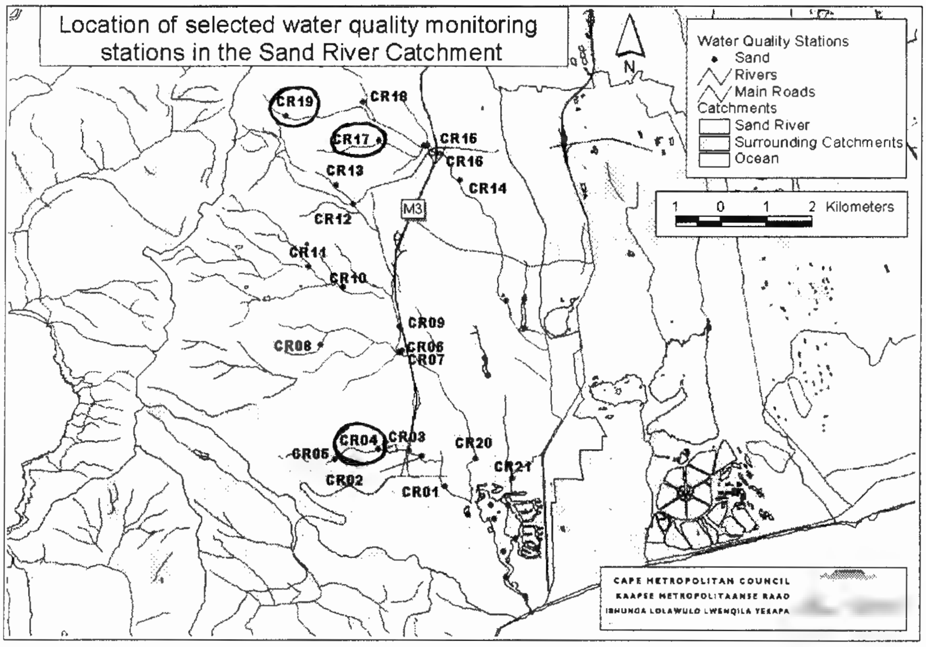

Figure 2. Map showing the locations of sampling stations along the Sand River. Sampling stations selected, for the purposes of this study, are circled in black.

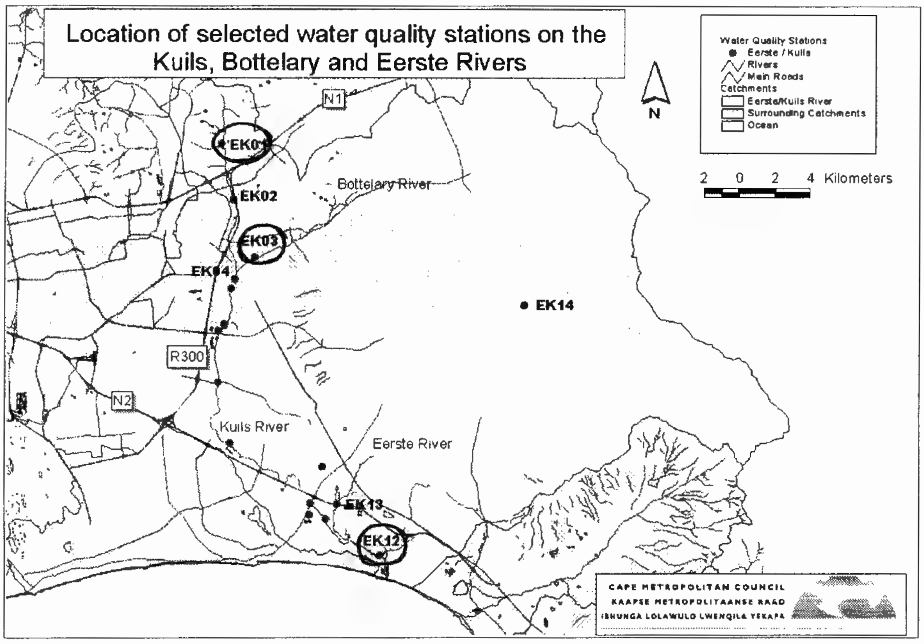

Figure 3. Map showing the locations of sampling stations along the Kuils, Bottelary and Eerste rivers. Sampling stations selected, for the purposes of this study, are circled in black.

Results

Inputs:

Population

Population data shows that human numbers within the CMA are rapidly increasing through time and are projected to continue rising as time proceeds (Figure 4). In the early 1900's there were approximately 250 000 inhabitants in the currently designated CMA. The population began to rise exponentially to approximately 2 500 000 inhabitants in 1990. Human populations in the CMA are rising and will continue to do so in the near future.

Fertiliser

The N based use of fertiliser in the magisterial districts of Cape Town, Somerset West and Strand fluctuate widely over the ten year time period of 1989-1999 (Figure 5). However, the pattern of decreasing fertiliser use in urban areas is beginning to show. As fertiliser sales in Cape Town and Somerset West decrease, the fertiliser sales in Strand are gradually rising. The sales for Strand are well below that of Cape Town and Somerset West.

Transport

Vehicle registrations for the CMA have increased exponentially over the later part of the last decade and are projected to continue increasing in the near future (Figure 6).

Atmospheric NOx

The primary contributions of atmospheric NOx of the brown haze in Cape Town are cars, contributing to 66 % of the total emissions, while industry only contributes to 25 %. Table 1 depicts the results from an analysis done by the Energy Research Institute of the University of Cape Town (Wicking-Baird et al 1997) and of N deposition calculations for the entire CMA and the CMA excluding the mountainous areas and the Peninsula.

Table 1. NOx emissions inventory for the Cape Metropolitan Area for July 1995 – August 1996, compiled by Wicking-Baird et al (1997). Emission rates NOx (tons/year) were converted to maximum N deposition (kg N ha^{-1} yr^{-1}) for the same time period, for the entire CMA (215900 hectares) and for areas excluding mountainous terrain and the Peninsula (154217 hectares).

SECTOR	SOURCE EMISSIONS	EMISSION RATES Tons NOx yr^{-1}	POTENTIAL CMA DEPOSITION: kg N ha^{-1} yr^{-1}	POTENTIAL LOWLAND DEPOSITION: kg N ha^{-1} yr^{-1}
Residential	Coal	15	0.1	0.1
	Paraffin	61	0.3	0.4
	Liquid Petroleum Gas	31	0.1	0.2
	Wood	542	2.5	3.5
Transport	Petrol vehicles	16848	78.0	109.3
	Diesel vehicles	1781	8.2	11.5
	Aviation fuel	576	2.7	3.7
	Ship diesel	739	3.4	4.8
	Ship bunker oil	582	2.7	3.8
Industry and commerce	Coal	1875	8.7	12.2
	Heavy fuel oil	695	3.2	4.5
	FFS Fuels	154	0.7	1.0
	Diesel	900	4.2	5.8
	Power paraffin	7	0.0	0.0
	Caltex	1643	7.6	10.7
	Kynoch	888	4.1	5.8
	Athlone power station	893	4.1	5.8
Other	Tyre burning	13	0.1	0.1
	Medical incineration	2	0.0	0.0
	Wildfires	107	0.5	10.7
Total		**28352**	**131.3**	**183.8**

Air quality of Goodwood and the CBD

NOx concentrations at Goodwood are lower than those found in the city (Figure 7). NOx concentrations in the city increased from 1984 to 1993 thereafter decreasing till 1997, after which they began to increase again. NOx concentrations in Goodwood show a declining trends since monitoring began in 1992. NOx concentrations in Goodwood and the city follow distinct seasonal patterns where high concentrations are found in winter and low concentrations are found in summer. Potential bulk N deposition based on air quality in Goodwood and the city, is lower but of a similar magnitude relative to calculations based on the emissions inventory. Bulk deposition in the city is 91 kg N ha^{-1} yr^{-1} and in Goodwood is 33 kg N ha^{-1} yr^{-1} for the time period August 1995 - July 1996.

Terrestrial and atmospheric N inputs

Table 2. Temporal patterns for N inputs of the CMA. Vehicle registrations and the corresponding maximum kg N ha-1 yr^{-1} deposited on land and freshwater ecosystems, based on emissions inventory for July 1995 - August 1996. Fertilisers sales for the magisterial districts Cape Town, Somerset West and Strand.

INPUTS	**1990**	**1995**	**2000**	**2010**
Fertiliser sales:				
(metric tonnes)				
Somerset West	262	273	203	ND
Strand	1	5	9	ND
Cape Town	439	133	62	ND
Vehicles registrations:				
N deposition (kg N ha^{-1} yr^{-1})	97	120	111	129

Outputs

Comparison of water quality of the Kuils, Bottelary, Eerste and Sand Rivers

Two way ANOVA tests shows that there are no significant differences between NH_3 concentrations of the different sampling stations along and between the Kuils, Bottelary and Eerste rivers are not significantly higher than concentrations in the Sand River, ($p = 0.875782$) (Table 3). There are no apparent temporal trends indicating leaching from agricultural or fynbos soils. However, the Kuils, Bottelary and Eerste sampling station at 150 metres above sea level has significantly higher nitrite and nitrate concentrations relative to other sampling stations as well as the Sand river where ($p = 0.000000$) but there does not appear to be any temporal trends. Unfortunately, the output data does not reflect any reliable trend of N concentrations in the rivers and does not indicate any effects on N based fertiliser additions in the Kuils, Bottelary, Eerste system. Furthermore lowland streams of neither the Kuils, Bottelary, Eerste system nor the Sand river show any indication of elevated N concentrations.

Table 3. Temporal trends of ammonia and nitrite and nitrate concentrations for the Kuils, Bottelary, Eerste system (Ek) and the Sand river (Cr) at the upper, middle and lower course of the river and the land-use it discharges through for the 1991-1999 time period.

Sampling station	Elevation (m) asl.	Land-use	Ammonia (mg/l)			Nitrite and nitrate (mg/l)		
			1991	1995	1999	1991	1995	1999
Ek01	300	Agriculture, vineyards, residential	0.1	0.1	0.2	1.8	1.2	0.7
Ek03	150	Agriculture, vineyards	0.1	0.1	0.2	0.1	0.1	11.2*
Ek12	50	Agriculture, vineyards	0.1	0.1	0.2	1	1.3	2.7
Cr19	200	Vineyards	ND	0.1	0.1	ND	2.7	1.1
Cr17	60	Residential	ND	0.7	0.1	ND	0.3	0.4
Cr04	20	Agriculture, urban	ND	0.1	0.3	ND	0.6	0.5

ANOVA for NOx: df = 47, f = 14.80, p = 0.000000; Tukey HSD test, *$P<0.05$, Tukey HSD test NH_3: df = 47, f = 0.40, p = 0.40

Cape Flats Acquifer

The Cape Flats aquifer is recharged from precipitation within the Catchment which ranges from 500 to 800 mm across the Cape Flats. According to Gerber (1980), taken from Conrad, 1995, the precipitation recharge is 154 x 10^6 m^3 per annum, where the Kuils Rivers estimated contribution is 0.5 x 10^6 m^3 per annum. Thus the water quality of rivers within the catchment influence groundwater quality but wet deposition through precipitation may be the most influential factor. It appears that research has focused on recharge capacity and resource potential regardless of the findings of Bertram (1989) taken from Conrad, 1995, which showed that high concentrations of nitrate and potassium in the Phillipi area are a direct reflection of approximately 400 tons of annual fertiliser additions. As land-use patterns change, atmospheric N pollutants increase and agricultural practices intensify, it seems obvious that the groundwater sources face contamination. Groundwater should therefore be sampled at least on a monthly basis and over fixed locations of the landscape in order to reveal the fate of the groundwater quality given that anthropogenic activities continue unchecked.

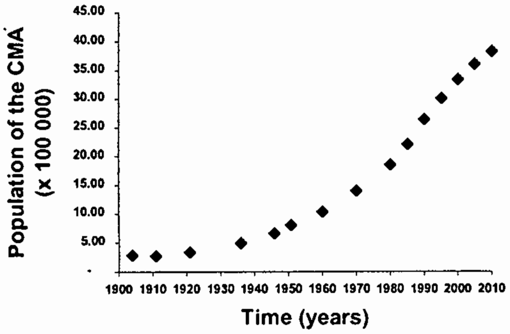

Figure 4. Temporal trends of population growth in the Cape Metropolitan Area from 1900 and projected growth until 2010.

Data source: CMC

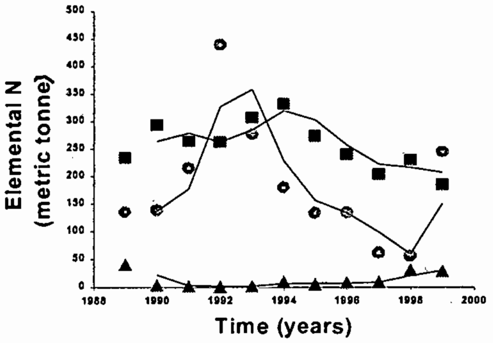

Figure 5. Temporal trends of N based fertiliser use for the magisterial districts of Cape Town (circles), Somerset West (squares) and Strand (triangles) of the CMA.

Data source: FSSA

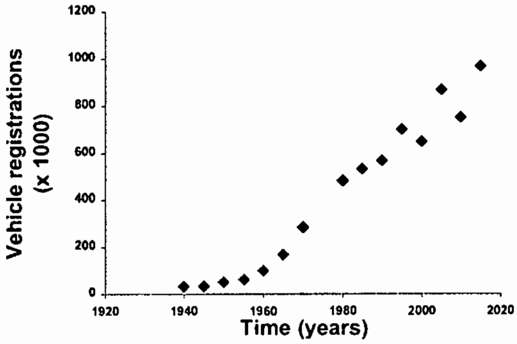

Figure 6. Temporal trends of vehicle registrations for the Cape Metropolitan Area and projected values for 2020.

Data source:
www.ngo.grida.no/soesa

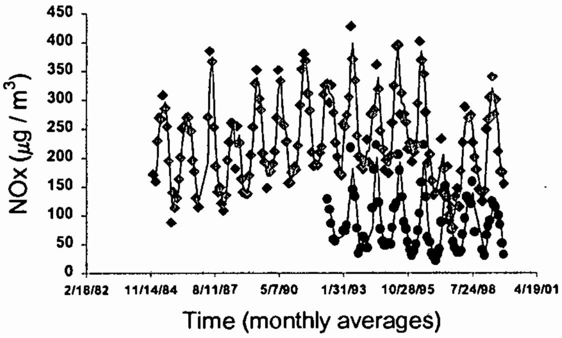

Figure 7. Temporal trends of air quality sampled at Goodwood (circles) and in the CBD (diamonds) of the CMA.

Data source: CMC

Discussion

What is the magnitude of N inputs in the CMA?

According to the results of this study, potential N deposition in the CMA is 131 kg N ha^{-1} yr^{-1}. Of the CMA, the lowlands are susceptible to N deposition whereas the Peninsula and the mountainous areas are relatively unimpacted. Maximum potential N deposition on the lowlands is 184 kg N ha^{-1} yr^{-1} based on N emissions rates. The actual air quality at Goodwood and the CBD of Cape Town shows the variability of the potential N deposition as a result of localised land-use patterns where activities in the city result in greater atmospheric N concentrations (Fig. 7). N deposition based on air quality data in the CBD is 91 kg N ha^{-1} yr^{-1} and in the industrial and suburban area of Goodwood is 33 kg N ha^{-1} yr^{-1}. There is a large degree of uncertainty concerning the fate of N emissions but it appears that a large proportion of the N emissions appear to remain in the atmosphere and eventually accumulate in soils. Stock & Lewis (1986) found that the total N inputs through precipitation in a coastal fynbos environment, relatively free of anthropogenic N sources, is 1.99 kg N ha^{-1} yr^{-1}. The difference between N deposition of impacted and relatively unimpacted sites suggest that lowland fynbos is currently being impacted by atmospheric N inputs. Atmospheric N inputs ranging between 30 - 60 kg N ha^{-1} yr^{-1} have replaced *Calluna* and *Erica* dominated heathlands in the Netherlands with grassy vegetation dominated by *Deschampsia flexuosa* or *Molinia coerulea* (Heil & Diemont, 1983). Bulk NO_3 deposition in the industrial areas of South Africa, Mphumalanga, range from 4 - 6 kg $ha^{-1}yr^{-1}$in 1985 (Tyson et al 1988). However, these regions are not subjected to temperate inversions and has low values of NO_3 deposition relative to the CMA. Atmospheric N inputs in the CMA, in particular the lowlands, are of a sufficient magnitude to transform lowland patches of rare and endemic fynbos into species poor grasslands. These results support the findings of Wilson (1999) which suggest that the invasion of alien grasses on the Cape Flats is attributed to atmospheric N inputs and N levels in the CBD are higher relative to rural areas.

N deposition in the CBD is 3 times greater than that of an industrial area of Goodwood (Fig. 7). The expansion of urban areas will catalyse the rate of N accumulation in fynbos soils and replacement of fynbos. Thus urban development and expansion pose an increasingly large threat of N accumulation in the soils of surrounding areas such as the remnant patches of lowland fynbos. In order to explain elevated levels of N deposition in the city, we need to consider the sources of N inputs.

What are the primary sources of atmospheric N inputs?

The NOx inventory, Wicking-Baird et al (1997) (Table 1), reveals that vehicle emissions constitute 66 % whereas industry constitutes only 25 % of the total NOx emissions in the CMA. These percentages translate to 121 kg N ha^{-1} yr^{-1} and 47 kg N ha^{-1} yr^{-1} of atmospheric N lowland inputs from vehicles and industry respectively. Thus pollution emitted by high traffic density in the CBD supercedes concentrations of N pollutant emitted by industries in Goodwood.

Approximately 50 % of commuters travel by private vehicles. The higher income areas comprise of the largest proportion of private commuting. However, the middle and lower income areas have the highest absolute number of cars and travel the greatest distances to places of work (CMC). Thus most of the vehicles utilised for private commuting are those vehicles traveling the greatest distances on a daily basis, and therefore emit the most NOx and SO_2 into the atmosphere. Based on increasing human populations and the match of increasing vehicle registrations, we can expect to find a corresponding increase in human and vehicle numbers in future (Fig. 6, 8 and Table 2). Based on current N deposition estimates, it is inevitable that vehicles emissions in future will result in the replacement of remnant patches of fynbos by grasslands.

Until alternative means of energy sources are devised and are economical and pollutant free, we need to strive for alternative means of transport through the improvement and greater utilisation of public transport, decentralisation of business districts should be emphasised in land-use plans in order to reduce traffic density and strict roadworthy maintenance regulations should be implemented.

Fossils fuels emissions are second to vehicles but to my knowledge, temporal trends of fossil fuel emissions in the CMA have not been documented. However, it is possible that Koeberg's use of atomic energy have drastically reduced fossil fuel emissions in the CMA and it is possible that fossil fuel emissions may be decreasing in the CMA. Further investigation is required.

We urgently require models of atmospheric transportation and deposition of pollutants under local conditions, in order to identify the fate of N emissions and the communities most threatened by N deposition. Predictions of the fate of N emissions and the identification of potential hotspots for N deposition will be more informative and precise. The cumulative effects of peaks in NOx concentration in winter (Fig. 7), frequent temperature inversions (Wicking-Baird et al 1997), stable atmospheric conditions relative to summer where the south-easterly winds may export pollutants, and high winter rainfall, highlight the need for monitoring wet deposition as rain may be a key element in contributing to soil N pools in the CMA. Thus it is essential that we monitor wet and dry deposition.

An enormous amount of research is required before we can determine the degree of N accumulation in soils. There remains a high degree of uncertainty of the actual amounts of N entering soil and the effect of temperature inversions on soil N contents. Wet and dry deposition of N should be research priorities as it directly influences terrestrial processes such as vegetation changes as well as freshwater and groundwater quality.

How do agricultural activities contribute to N inputs?

Smil, (1997) found that the use of fertiliser during the 20th century has been matched by a parallel increase in world population. Agriculture in the CMA is concentrated in the south-east area around the Helderberg mountains (CMC). Figure 5 illustrates the decline of agricultural practises in relatively more urbanised areas and the increase of fertiliser sales in remaining arable areas. These trends require further investigation as fertiliser sales are not an adequate measure of fertiliser drift, NH_3 emissions or actual amounts of N additions to the systems since consumption patterns are not necessarily a reflection of utilisation patterns.

Before we can determine the extent to which agricultural activities contribute to atmospheric N we require monitoring of NH_3 emissions in the CMA. An inventory similar to the NOx inventory devised by Wicking-Baird et al (1997) is required. Denmead, (1990) found that NH_3 is a primary source of pollution in agricultural areas (including feedlots) in Australia. In fact, NH_3 has been identified as one of the main threats to vitality and biodiversity in Dutch nature areas because of spatial proximity to agricultural areas (Bleeker & Erisman, 1998). We should investigate spatial relationships between sensitive ecosystems and agricultural landscapes.

Is N leaching from soils?

Neither the Sand river nor the Kuils, Bottelary and Eerste rivers are showing signs of NH_3 leaching from soils. This means that soil pools of natural vegetation and cultivated land are not signaling trends of N leaching and are unimpacted in terms of NH_3 emissions from fertilisers (Table 3). The lack of evidence of leaching from soils does not imply that N enrichment is not occurring. It merely implies that soils may not yet have reached saturation point after which leaching would occur. Soil may still be accumulating N and because fynbos soils are low in nitrogen, the time taken for saturation point may be prolonged. Furthermore, N may be leaching at a constant rate over the time period for which it was monitored and is therefore not detectable as a trend. Finally, N accumulations may be utilised by invasive species, thereby preventing leaching from occurring and thus the method used in this study is not adequate to assess the degree of N accumulation in soils. We require direct measurements of soil N levels impacting lowland fynbos species and its temporal changes through time, which may allow us to predict the timing of contamination of fynbos soils and devise preventative strategies.

The inversion layer which occurs over the lowlands has not enriched N concentrations of the lower reaches of the Sand river. Thus soils of fynbos are not showing any indication of N leaching. However, the Bottelary river has significantly enriched NOx concentrations at 150 metres above sea level. Both agricultural activities and the inversion layer may have increased N levels. It is possible that algal growth utilises the additional N resulting in decreased values downstream. Evidence for leaching is sparse and if any, may only be occurring in the Bottelary river. Distinguishing between atmospheric N deposition and agricultural N inputs is difficult. In addition it is difficult to interpret N concentrations of values without comparisons with N concentrations of relatively pristine rivers flowing over similar geological bedrock. Pristine rivers, for example the Buffels Wes river which flows through the Cape of Good Hope Nature Reserve, should be monitored so that the nutrient status can be used as a control when assessing the nutrient status of rivers influenced by anthropogenic inputs. The location of water quality sampling stations should be reconsidered. The current sampling stations appear to be located close to roadways for sampling convenience. Pollutants from cars may therefore provide a skewed result of land-use effects on water quality. Furthermore, we should document the grounds on which the sampling stations are established as this has not occurred in the past (Haskins, C. 2000 pers. Comm).

The occurrence of rain during winter, when atmospheric N concentrations are greatest (Figure 7), may be reducing the rate of N accumulation on land while threatening freshwater and groundwater supplies. Research on groundwater has focused on recharge capacity leaving very sparse data pertaining to water quality. Since the Kuils, Bottelary, Eerste system is a source of groundwater recharge, as a result of intensive agriculture, we can deduce that N concentrations in the Cape Flats acquifer are bound to accumulate to potentially harmful levels in future. However, the primary recharge source is that of precipitation (Gerber, 1980 taken form Conrad, 1995). We therefore urgently require research of wet deposition. Groundwater should be monitored on a continuous basis in order to determine temporal trends pertaining to nutrient status. This should be done in close proximity to agricultural areas as well as other land-use types such as golf courses and botanical gardens which add N to the system. Research should account for heterogeneity of land-use as well as acquifer conditions. This will enable us to determine the rate of nutrient accumulation and predict the potential timing of groundwater contamination in order to devise preventative strategies.

Conclusion

Increasing human populations are threatening the existence of the fynbos ecosystems in the lowlands of the Cape Metropolitan Area through the creation of increasing amounts of N pollutants. Vehicles emit 66 % of the total NOx emissions in the CMA and are currently posing the greatest threat to N accumulation in fynbos soils. The maximum N deposition of 184 kg N $ha^{-1}yr^{-1}$ on the lowlands, based on emissions in the CMA is comparable with N quantities present in air at Goodwood of 33 kg N $ha^{-1}yr^{-1}$. These results indicate that lowland fynbos soils are being impacted by N pollution as only 1.99 kg N $ha^{-1}yr^{-1}$ was derived from atmospheric N inputs for unimpacted coastal fynbos. The remnant patches of lowland fynbos are therefore threatened by replacement of species poor grasslands. NOx emissions will increase as the number of vehicles increase in future unless, we improve public transport and decentralise urban areas. NH_3 emissions require monitoring in order to assess the effect of agricultural activities on soil N pools. Thus there is still a large degree of uncertainty with respect to amounts of N entering fynbos soil pools but based on the results of this project, fynbos is being impacted by atmospheric N additions. More direct measurements of soil N pools and temporal patterns of changing soil N contents are required. Wet and dry deposition measurements as well as atmospheric models depicting the transport and fate of N pollutants are urgently required to aid in the construction of a regional N budget for the CMA and the development of strategies preventing the replacement of remnant patches of lowland fynbos by grasslands.

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Appendices

Appendix A

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Appendix B

	tons/yr	kg/yr	kg/ha/yr	kg/ha/yr
		1000	**215900**	**154214**
coal	15	15000	0.1	0.1
paraffin	61	61000	0.3	0.4
lpg	31	31000	0.1	0.2
wood	542	542000	2.5	3.5
petrol vehicles	16848	16848000	78.0	109.3
diesel vehicles	1781	1781000	8.2	11.5
aviation fuel	576	576000	2.7	3.7
ship diesel	739	739000	3.4	4.8
ship bunker oil	582	582000	2.7	3.8
coal	1875	1875000	8.7	12.2
hfo	695	695000	3.2	4.5
ffs fuels	154	154000	0.7	1.0
diesel	900	900000	4.2	5.8
power parafin	7	7000	0.0	0.0
caltex	1643	1643000	7.6	10.7
kynoch	888	888000	4.1	5.8
athlone power station	893	893000	4.1	5.8
tyre burning	13	13000	0.1	0.1
medical incineration	2	2000	0.0	0.0
wildfires	107	107000	0.5	0.7
TOTAL	**28352**	**28352000**	**131.3**	**183.8**

weight of total cma = 0.7g
weight of cma - mountainous area = 0.6g
weight of cma - mountainous area and - peninsula = 0.5g
therefore mountains and peninsula account for 28.57 % of the CMA
THUS 71.43 % OF THE AREA OF CMA: 215900 HECTARES = 154217 HECTARES

Appendix C

1995	700000 vehicles		kg/ha/yr
2000	650000		NO MNT/NO PENINSULA
		PETROL	109.3
1996	705000	DIESEL	11.5
			120.8

max N deposited by vehicl	120.8	each car deposits = 0.000171347
total vehicles IN 1995-6	705000	

total vehicle registrations:	0.000171348	
1990	567000	97.15404
1995	700000	119.9433
2000	650000	111.3759
2005	867000	148.5583
2010	750000	128.5106

weight of total cma = 0.7g
weight of cma - mountainous area = 0.6g
weight of cma - mountainous area and - peninsula = 0.5g

therefore mountains and peninsula account for 28.57 % of the CMA
THUS 71.43 % OF THE TOTAL AREA OF CMA: 215900 HECTARES = 154217 HECTARES

Appendix D

city

month	NOx	in kg	in air colm	in air colm	days/mont	kg/ha/mnth
	ug/m3	*10^-9	kg/m2	kg/ha		
			100	*10000		
aug	312	0.0000003120	0.0000312	0.312	31	8.25
sep	275	0.0000002750	0.0000275	0.275	30	8.12
oct	262	0.0000002620	0.0000262	0.262	31	6.45
nov	215	0.0000002150	0.0000215	0.215	30	6.98
dec	225	0.0000002250	0.0000225	0.225	31	5.95
jan	192	0.0000001920	0.0000192	0.192	31	5.88
feb	210	0.0000002100	0.000021	0.21	28	6.69
mar	223	0.0000002230	0.0000223	0.223	30	8.82
april	294	0.0000002940	0.0000294	0.294	30	12.43
may	401	0.0000004010	0.0000401	0.401	31	11.07
june	369	0.0000003690	0.0000369	0.369	30	10.70
july	345	0.0000003450	0.0000345	0.345	31	0.00
kg N /ha/yr						91.34

air colm	
40	36.53
50	45.67
100	91.34
150	137
200	182.67
250	228.34
500	456.68
750	685.01
1000	913.35

goodwood

month	NOx ug/m3	in kg *10^-9 /1000000000	in air colm kg/m2 1000	in air colm kg/ha *10000	days/mont	kg/ha/mnth
aug	131	0.000000131	0.000131	1.31	31	40.61
sep	89	0.000000089	0.000089	0.89	30	26.7
oct	76	0.000000076	0.000076	0.76	31	23.56
nov	54	0.000000054	0.000054	0.54	30	16.2
dec	40	0.00000004	0.00004	0.4	31	12.4
jan	31	0.000000031	0.000031	0.31	31	9.61
feb	38	0.000000038	0.000038	0.38	28	10.64
mar	50	0.00000005	0.00005	0.5	30	15
april	73	0.000000073	0.000073	0.73	30	21.9
may	103	0.000000103	0.000103	1.03	31	31.93
june	157	0.000000157	0.000157	1.57	30	47.1
july	222	0.000000222	0.000222	2.22	31	68.82
	Kg N ha yr					324.47

air colm	
40	12.98
50	16.22
100	32.447
150	48.6705
200	64.894
250	81.1175
500	162.235
750	243.3525
1000	324.47