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Human Appropriation of Net Primary Production in South Africa, 1961- 2006. A socio-ecological analysis

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Human Appropriation of Net Primary Production in South Africa, 1961- 2006.
A socio-ecological analysis*

von

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** Masterarbeit verfasst an der Universität Wien, Institut für Anthropologie. Diese Arbeit wurde betreut von a.o.Univ.-Prof. Dr. Helmut Haberl.*

Content

List of figures

List of tables

Abstract

During the 20th century the Republic of South Africa experienced fundamental social, political and ecological transitions. The Apartheid regime intensified the severe socio-economical problems with which South Africa is still struggling today and humans transformed natural ecosystems to a wide extent. From 1900 until today, the area under crop production more than tripled and the area under forest plantations grew more than 10-fold. This thesis applies the socio-ecological indicator Human Appropriation of Net Primary Production (HANPP) that aims at measuring human-induced changes in biomass flows resulting from two processes: Anthropogenic harvest and human-induced land conversion (such as land cover change, land use change and human induced soil degradation). HANPP is useful as an integrated indicator of land-use intensity, because it does not only measure changes of biomass flows in ecosystems from land use, but can also be related to the main social and economical driving forces for long-term changes in land cover and land use. HANPP data allow for drawing conclusions on the degree of transformation of natural ecosystems and its implications for factors such as social wealth, biodiversity, sustainable use of natural resources and prospects for a future development of land use. This study quantifies HANPP in South Africa over the period from 1961 to 2006. Despite the rapid changes that South Africa underwent in the observed period, HANPP remained approximately constant, suggesting that over the whole period under investigation humans appropriated around 24% of the total biomass potentially available in each year. However, shifts in patterns of biomass appropriation can be discerned when analyzing pathways of aHANPP separately. HANPP on cropland steadily declined after 1986 and simultaneously aHANPP caused by grazing, harvest of roundwood and fuelwood increased. These results can be interpreted either in context of the green revolution, which initially brought a rise in productivity on agricultural land, or in the background of the economic and political crisis in the 1980ies, which triggered a stagnation in agricultural modernization until 1994, when the country finally had its democratic opening. Rising population numbers and weak agricultural productivity in the past decades resulted in a decreasing aHANPP per head. However, per person demand for agricultural biomass did not decline. As a consequence South Africa became a net-import country of biomass, which means that South African aHANPP is distributed among other countries as well.

Zusammenfassung

"Human Appropriation of Net Primary Production" (HANPP) ist ein Maß für die menschliche Aneignung von Nettoprimärproduktion und wird als sozial-ökologischer Indikator zur Analyse des menschlichen Einflusses auf Ökosysteme eingesetzt. Nettoprimärproduktion (NPP) bezeichnet die Menge an Biomasse, bzw. die Menge an Kohlenstoff, die jährlich von autotrophen Organismen, vor allem von grünen Pflanzen produziert oder fixiert wird, abzüglich jener Menge an Energie, welche diese Organismen für die Erhaltung der eigenen Lebensfunktionen benötigen. Das Konzept von HANPP wurde erstmals von Vitousek et al.

(1986) eingeführt und in zahlreichen Folgestudien erweitert. HANPP-Daten lassen Rückschlüsse auf die Intaktheit von Ökosystemen definierter Gebiete zu, indem sie die Menge an Biomasse die für andere Organismen im Ökosystem zurückbleibt aufzeigen und offenlegen zu welchem Ausmaß und durch welche Pfade natürliche Ökosysteme verändert wurden.

HANPP kann durch zweierlei Wege anthropogen verursacht werden: Der direkte Weg beinhaltet Ernte durch Feld- und Gartenbau, Holzernte und Biomasse die in der menschlichen Viehwirtschaft gegrast wird, der indirekte Weg umfasst Produktivitätsänderungen von Ökosystemen, verursacht durch menschliche Landnutzung, wie zum Beispiel Landtransformation oder Landdegradation.

Die vorliegende Studie analysiert HANPP nach dem Konzept von Haberl et al. (2007), folgende Formeln für die mathematische Berechnung werden dafür verwendet:

$HANPP = \Delta NPP_{lc} + NPP_h$

$\Delta NPP_{lc} = NPP_0 - NPP_{act}$

..wobei ΔNPP_{lc} für den Verlust an NPP durch anthropogene Landnutzung steht und NPP_h für die Biomasse die durch Ernte entzogen wird. NPP_0 ist definiert als die potenzielle Biomasseproduktion eines Ökosystems, also jene, welche ohne menschlichen Einfluss vorherrschen würde. NPP_{act} steht für die gegenwärtig unter menschlicher Landnutzung vorherrschende Produktivität. Außerdem kann HANPP durch die Formel $HANPP=NPP_0-NPP_t$ dargestellt werden, also durch den Unterschied zwischen potenzieller NPP und der Menge an Biomasse, die nach Abzug von Ernte und Landnutzung im Ökosystem zurückbleibt (NPP_t).

Die vorliegende Studie quantifiziert HANPP in der Republik Südafrika in einer Zeitreihe von 1961 bis 2006 und leistet damit einen Beitrag zu den bisherigen länderspezifischen HANPP-Studien (Krausmann, 2001; Kastner, 2009; Schwarzlmüller, 2009; Musel, 2009). Als Datenbasis dienten unterschiedliche statistische Quellen, länderspezifische Studien und Modell-Outputs. Aufgrund der vorhandenen Datenlage war es nur möglich den oberirdischen Teil von HANPP zu analysieren, dieser Umstand wird mit dem Präfix „a" ausgedrückt. Biomasse wird in Kohlenstoffeinheiten angegeben (Kürzel „C"), wobei angenommen wird, dass organische Trockensubstanz zu 50% aus Kohlenstoff besteht.

Da das Ziel dieser Studie eine detaillierte Analyse von aHANPP separat für die unterschiedlichen aNPP-Klassen innerhalb von Südafrika war, war es als ersten Schritt nötig ein konsistentes Landnutzungsdatenset für den gesamten Zeitraum von 1961 bis 2006 zu konstruieren. Da im Rahmen dieser Arbeit durch die alleinige Recherche von historischen und moderneren Landbedeckungsdaten die Erzeugung eines einheitlichen Landbedeckungsbildes von 1961 bis 2006 undurchführbar war, musste ausgehend von rezenteren Daten auf unterschiedliche Interpretationen zur historischen Entwicklung der einzelnen Landbedeckungskategorien zurückgegriffen werden. Lediglich für die Flächen von Wäldern („closed forests"), Ackerland („cultivated areas") und bebauten Gebieten („settlement area"), konnten aufgrund besserer Datenverfügbarkeit, eine komplette Zeitreihendarstellungen der Flächenentwicklung vorgenommen werden, die Errechnung aller verbleibenden Kategorien basiert auf dem NLC 1995- der nationalen Landbedeckungsstudie aus dem Jahr 1994/95 (Fairbanks et al., 2000), kombiniert mit Annahmen zu zeitlichen und geographischen Flächenänderungen. Aus den vorhandenen Daten kombiniert mit ausführlichen

Interpretationen und Überlegungen konnte schließlich das endgültige Landbedeckungsdatenset, bestehend aus 13 Kategorien, die wiederum in vier Landnutzungsklassen eingeteilt werden können, konstruiert werden. Für die Darstellung der $aNPP_0$ Zeitreihe konnte auf vorhandene Outputs des Lund-Potsdam-Jena Global Dynamic Vegetation Modell (LPJ-GDVM: Sitch et al., 2003; Gerten et al., 2004) zurückgegriffen werden. Die $aNPP_{act}$ wurde aus diesen $aNPP_0$ Werten errechnet, indem Produktivitätsverluste verursacht durch Degradation ($\Delta aNPP_{lc}$) von den potenziellen Werten subtrahiert wurden. Die Fläche der „degraded areas" wurde dem NLC 1995 entnommen und man ging davon aus, dass diese Gebiete einen Verlust von 56% der potenziellen $aNPP_0$ erfahren haben (Zika and Erb, 2009). $aNPP_{act}$ auf dem Ackerland wurde direkt aus den Erntedaten errechnet, indem geerntete Biomasse mit „pre-harvest"-Faktoren multipliziert wurde, welche den Verlust von Biomasse durch Pflanzenpathogene oder Seneszenz vor der Ernte mit einbeziehen sollen und somit die komplette oberirdische Biomasse auf kultivierten Flächen darstellen. $aNPP_h$ wurde anhand statistischer Aufzeichnungen unterschiedlicher Departments und durch eigene Berechnungen erarbeitet. $aNPP_h$ auf Ackerland besteht aus dem kommerziellen Teil der Pflanze (dokumentiert in statistischen Aufzeichnungen) und verwendeten und nicht verwendeten Ernterückständen (errechnet durch pflanzenspezifische Ernte-Indices). Die in der Viehwirtschaft gegraste Biomasse wurde durch eine Futterbilanz-Rechnung analysiert. Futterbedarf (jährliche Anzahl an Nutztieren multipliziert mit individuellem Futterbedarf) minus Futterzufuhr (zusammengesetzt aus Ernterückständen, Marktfutter und Futterpflanzen) ergibt die Menge der jährlich gegrasten Biomasse. Holzernte besteht aus der Biomasseentnahme durch die kommerzielle Waldwirtschaft und der Brennholzentnahme individueller Haushalte aus natürlichen Ökosystemen als Quelle für den täglichen Bedarf an Energie. Da die Entnahme von Brennholz gebietsweise unkontrolliert und nicht nachhaltig betrieben wird, stellt sie gleichzeitig eine Bedrohung für die Intaktheit von Savannenökosystemen dar. Industrielle Holzernte umfasst Ernte von kommerziellem Rundholz und Ernteverluste, die anhand von „recovery rates" (Verhältnis kommerzielles Holz zur kompletten Biomasse eines Baumes) berechnet werden.

Da es für Südafrika keine Dokumentationen über den Anteil von anthropogen verursachten Feuern an den gesamten jährlichen Feuern gibt, stellte sich der Punkt „Ernte durch menschlich verursachte Feuer" als problematisch heraus. Darüberhinaus besteht Grund zur Annahme, dass die Anzahl, Stärke und Frequenz von Feuern mit zunehmender menschlicher Besiedelung abnimmt, was eine negative HANPP zu Folge hätte. Wegen dieser Unklarheiten wurde das Thema Feuer in der HANPP-Rechnung ausgeklammert. Nach einer sehr groben Schätzung, basierend auf der Studie von Archibald et al. (2010) könnte die aHANPP unter Berücksichtigung von menschlich verursachten Feuern über den gesamten Zeitraum um etwa 15% pro Jahr höher sein.

Die Geschichte Südafrikas von 1961 bis 2006 war von Ereignissen geprägt, die sich auch in der HANPP Zeitreihe niederschlagen: Die Bevölkerung wuchs um das Dreifache von 18 auf 49 Millionen Einwohner und ein Trend in Richtung Urbanisierung entstand. AIDS/HIV wurde zu einem der zentralen, die wirtschaftliche und gesellschaftliche Entwicklung bedrohenden Faktoren und das Apartheid-Regime richtete die wirtschaftliche Entwicklung bis in die 1990er Jahre systematisch zu Grunde.

aHANPP blieb relativ adynamisch über den gesamten Zeitraum hinweg und bewegte sich in einem Bereich zwischen 70 und 83 Millionen Tonnen Kohlenstoff pro Jahr (durchschnittlich 24% der $aNPP_0$ pro Jahr). Erst bei detaillierterer Betrachtung einzelner aHANPP Ströme werden Auffälligkeiten in einzelnen Perioden innerhalb des analysierten Zeitraums sichtbar:

Die steigende aHANPP auf kultivierten Flächen von 1961 bis 1978 lässt Rückschlüsse auf eine gut funktionierende, expandierende Landwirtschaft zu. Die Ernte auf dem Ackerland stieg kontinuierlich an, was einerseits durch Subventionen durch die Regierung und andererseits durch neue Kultivierungstechniken der „grünen Revolution“ (Einsatz von Bewässerung, Kunstdüngern und Pestiziden) erreicht wurde. Zugleich war der aHANPP Trend auf gegrasten Landbedeckungsklassen rückläufig, denn die steigende Verfügbarkeit von Ernterückständen als Futterquelle, brachte einen schmäleren Bedarf an Beweidung mit sich. Im Gegensatz dazu litt die allgemeine wirtschaftliche Entwicklung schon in diesem Zeitraum unter Regression. Das GDP Wachstum ging um die Hälfte zurück (von 8% in 1961 zu 4% in den späten 70gern).

Von 1979 bis 1994 verschlechterte sich die wirtschaftliche Lage des Landes zusehends. Südafrika kam immer mehr unter internationalen Druck und nach und nach wurden wirtschaftliche Sanktionen der internationalen Gemeinschaft mit dem Ziel das Ende der Apartheid zu erreichen, verschärft. Das Öl-Embargo der OPEC Nationen, fehlendes ausländisches Kapital, ausbleibende Subventionen durch die Regierung, die Rücknahme des Rabatts auf Diesel und damit verbundene steigende Kosten für Dünger und Pestizide, schwächten die Landwirtschaft ab dem Ende der 70-ger Jahre in beträchtlichem Ausmaß. Der Einsatz von Düngern und folglich auch die Produktivität auf dem Ackerland gingen nach 1978 drastisch zurück und gleichzeitig stieg die $aNPP_h$ auf beweideten Flächen. Nach einer längeren Dürreperiode in 1981 war die Kultivierung von potenziellem Ackerland für viele Farmer nicht mehr rentabel und ab 1986 verkleinerte sich daher auch die Fläche der Feld-und Gartenbau Gebiete.

Diese prekären wirtschaftlichen Entwicklungen, gemeinsam mit innerstaatlichen Revolten führten zum Kollaps des Apartheid-Regimes in den frühen 1990ger Jahren und 1994 fanden schließlich die ersten demokratischen Wahlen statt. Nach der demokratischen Öffnung erlebte Südafrika einen Aufschwung des Wirtschaftswachstums und trat der WTO (World Trade Organisation) bei. Trotzdem blieb der landwirtschaftliche Sektor unterentwickelt und erholte sich wegen der weiterhin vorherrschenden Preisverzerrungen und wiederkehrenden Dürreperioden nicht: $aNPP_h$ auf kultivierten Gebieten und landwirtschaftlich bebauten Flächen blieben auf einem niedrigem Niveau. Schwache landwirtschaftliche Produktivität, kombiniert mit dem rasanten Bevölkerungsanstiegs führten zu einer stetigen Verkleinerung der aHANPP pro Kopf über den gesamten Zeitraum hinweg. Der steigende Bedarf an Lebensmitteln musste vermehrt durch Importe gedeckt werden, was bedeutet, dass sich die jährliche Aneignung von Biomasse auf andere Länder ausbreitete und sich die aHANPP auch auf Gebiete außerhalb Südafrikas verlagerte.

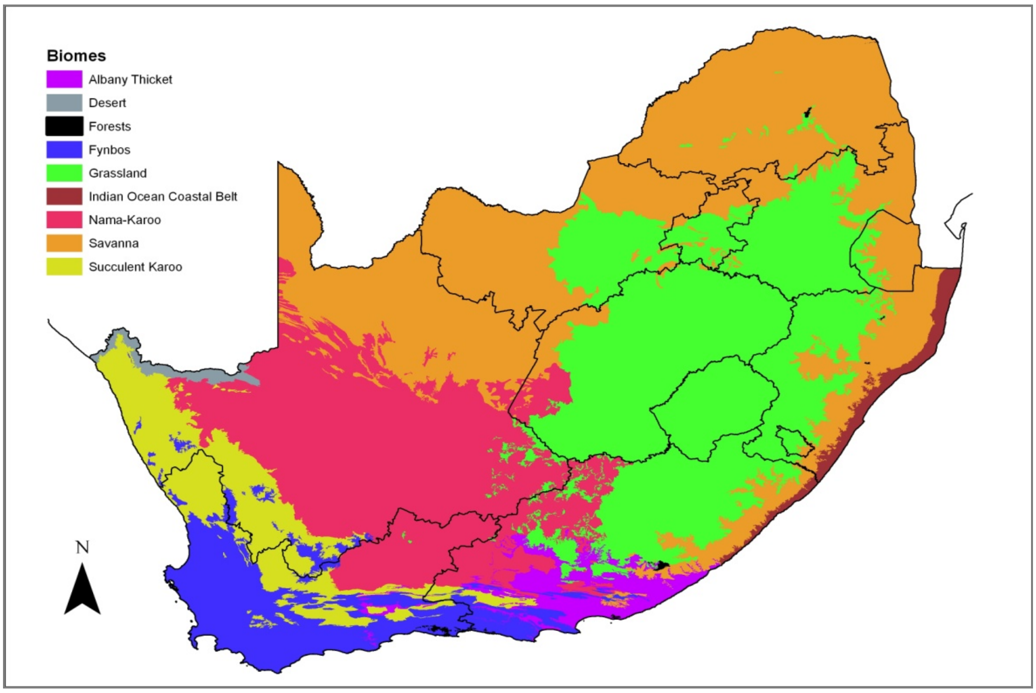
Introduction

During the 20th century the South African land use system underwent fundamental changes. Driven by a rapid population growth, the area under cropland cultivation more than tripled and the need for industrial roundwood, above all triggered by the demand for mining timber, was met by a more than ten-fold increase in the area of forest plantations (Biggs and Scholes, 2002). This study is aimed at analyzing human impacts on natural ecosystems in South Africa, by quantifying the amount of Net Primary Production appropriated by human society in a 45-year period from 1961 to 2006. Net Primary Production (NPP) is defined as the amount of biomass produced by autotrophic, photosynthetic organisms (above all by green plants through photosynthesis) per year minus the amount of energy consumed by these organisms themselves. Human Appropriation of Net Primary Production (HANPP) is defined as an indicator that aims to measure the human induced changes in the availability of NPP in ecosystem, resulting from harvest and land conversion. HANPP therefore shows how anthropogenic land domination reduces the amount of biomass available for all other life forms in the defined area.

The Republic of South Africa (in the following sections abbreviated as RSA) covers an area of 2.1 Mio. km² at the southern most part of the African continent. The country is surrounded by the Indian Ocean in the East and the Atlantic Ocean in the West. The extraordinarily diverse landscapes in terms of vegetation types, climatic and soil conditions and topography result in a wide range of aboveground productivity levels. Annual precipitation varies from less than 100 mm in the little-productive East, where the dry shrub lands of the Nama Karoo, as well as the Succulent Karoo (a small biome of very low productivity, dominated by succulent plants and sparse vegetation cover) and patches of the Namib desert are situated, to more than 1000 mm in the highly productive West, which is home to subtropical forests and fertile grasslands (Lynch, 2004). These fertile grasslands as well as large parts of savanna regions and the thicket biome in the Cape region have been transformed to a high degree as a result of human cultivation and land use practices (Downing, 1978; Macdonald and Crawford, 1988; Hudak, 1999; Biggs and Scholes, 2002; Rouget, 2003).

The Fynbos biome in the Cape region, the most southern part of the country, is a small biome, not bigger than 6300 km², which is classified as a separate floral kingdom due to its outstanding biodiversity of endemic plants. South African topography ranges from wide flat central areas, covering huge parts of the grazing lands, to high mountain ranges that form the so called *High Veld* in the East and South-East, with the Drakensberge mountain range as the most popular one. Figure 1 provides the picture of all in South African biomes.

Figure 1: Biomes of South Africa, Lesotho and Swaziland (Mucina and Rutherford, 2006)



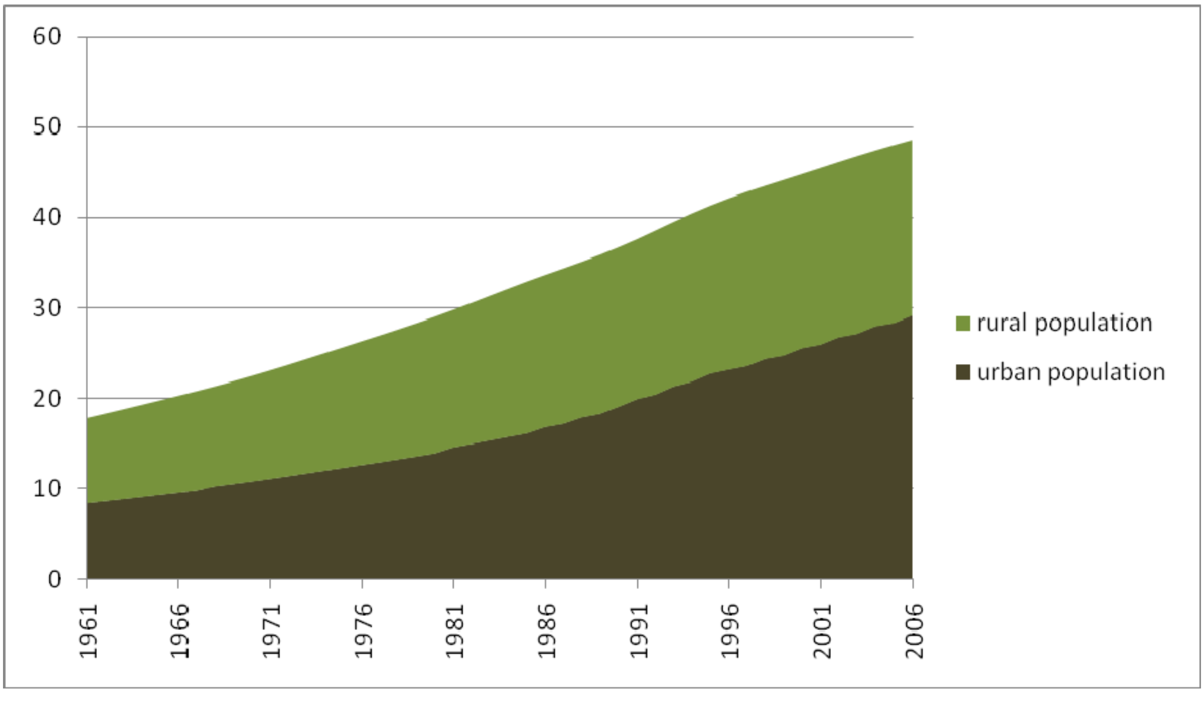
A short summary of South African history gives some context to current land use dynamics: Until the first Dutch settlers, the Boer, as they would later call themselves, arrived at the Cape of Good Hope in the 17th century, they found the region being populated by Koikoi and San pastoralists in the Cape region and the interior of the country. The East, where a more humid climate allowed for crop production, was settled by Bantu-speaking communities (Hall, 1994; Worden, 2000).

After the British landed at the Cape region in 1796 they defeated the Dutch settlers and introduced an English Parliament under British common law. In order to avoid being put under British rule, Boer settlers physically escaped into the North-East during the Great Trek of 1853 (Worden, 2000). The following decades in the second half of the 19th century were characterized by wars between the indigenous tribes and the two colonial powers on land, as well as wars on the control of the diamond and gold deposits discovered in the North. After two bloody Anglo-Boer wars, the British could again manifest their power, and finally, in 1909 South Africa was declared a republic under British control.

Although South African society has been dominated by racial segregation since colonial times, racial policies became legal when the nationalist party won the elections in 1948 and made ways for the official segregation of all non-white people from whites, officially known as Apartheid. Persons defined as “black” suffered most from the new Apartheid laws and orders: From 1959 on, blacks were deprived of their citizenships and were forced to become inhabitants of the new self-governing territories, the so-called Bantustans, also known as homelands, which covered only 13% of the country area and were officially populated by 80% of the South African population. Huge parts of these former homelands are described as degraded due to overpopulation and overgrazing and still the majority of the people living there are poor. It is not the aim of this study to discuss the dark history of Apartheid, which finally ended with the first democratic elections in 1994, in detail, nevertheless it must be mentioned here that during this time of national isolation and systematic demoralization of the non-white population, severe economical, social and environmental problems arose, which still hinder South African progression in terms of social justice, sustainable environmental management and international economic competitiveness today.

In the past five decades South Africa experienced a steep, almost threefold population increase from 18 Mio. people in 1961 to 49 Mio. people in 2006 (FAO, 2006). Simultaneously a trend towards urbanization emerged: in 1961 47% of all inhabitants lived in urban areas, whereas in 2006 this value had increased to 60% (World Bank). Figure 2 presents the demographic development during this time. FAO statistics give higher population values than South Africa's statistical office. The reason for this is that the FAO includes estimates of the population of some of the former homelands, which were considered own states by the Apartheid government and were therefore not accounted for in the official statistics during several years. Like most Sub-Saharan countries, also South Africa is severely affected by HIV/AIDS, especially in rural areas. In 2006, 18.1% of the population between 15 and 49 years of age were infected with the virus (UNAIDS, 2008). This is one of the highest HIV/AIDS prevalence rates in the world. Its devastating effects are not only reflected in tremendous physical and mental suffering of the individuals and their social surroundings, but are also reflected in a regression of the economically active population and as a consequence in a lowering of the overall economic productivity as well (Arndt, 2000).

Figure 2: Population development in Mio. heads from 1961 to 2006

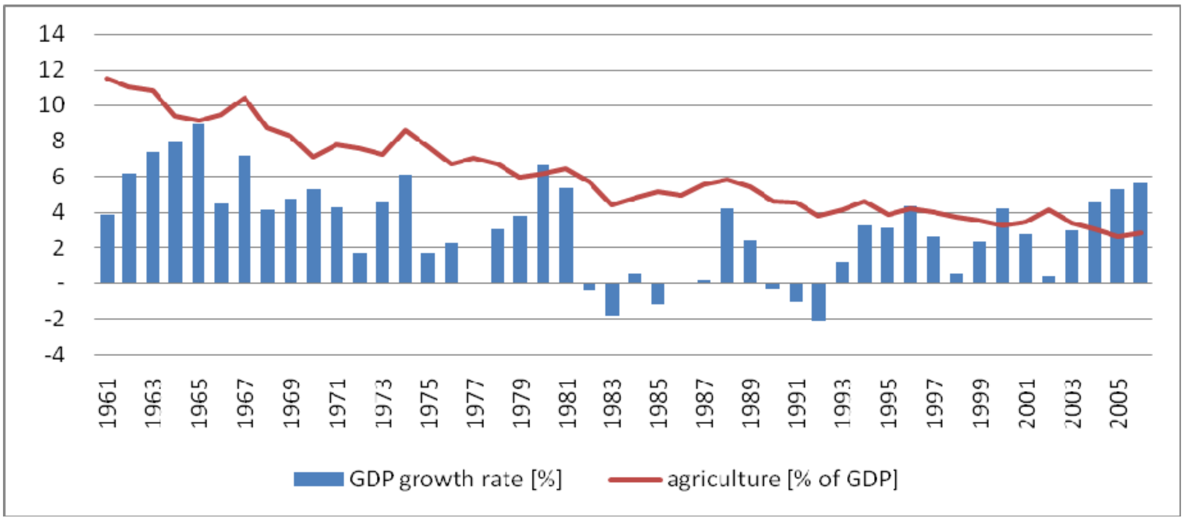


Source: FAO statistical database, world development indicators (World Bank, 2010)

The average population density of South Africa is around 37.6 inhabitants per square meter, with huge differences between the nine provinces: Gauteng is the smallest, but most industrialized and at the same time the most densely populated province with 519.5 persons per km², whereas the Northern Cape has an average population density of around 2.3 persons per km² (STATSA, 2003).

South Africa's international economic performance relies above all on the country's richness of natural resources. Until 2007 South Africa was the largest exporter of gold in the world. At present, South Africa mines 45% of the world's gold reserves, 90% of the platinum metal and 80% of the manganese forages. Although agriculture presents a declining trend in terms of its contribution to the nation's GDP (from 12% of total GDP in 1961 to 3% in 2006), it is still a highly labor-based economic sector and therefore is an important source of local income, playing a crucial role in the prevention of poverty. This is important especially for rural areas, where poverty prevails more significantly than in urban areas. South Africa has inherited striking inequalities in terms of distribution of income and social wealth, as well as severe economic constraints from the Apartheid era, when international sanctions displaced South Africa from the global economic market. In the late 1970ies and more significantly during the 1980ies, the policy of self-sufficiency turned out to be impossible to maintain and the resulting economic crisis could not be solved independently by the Apartheid regime. From the early 1980ies until the mid 1990ies, GDP growth slowed down drastically and even became negative in several years. Only with the onset of democracy in the following years, GDP growth rates recovered slowly to reach again a 6% level in 2006. In terms of per-capita income South Africa belongs to the middle-upper income countries, but at the same time exhibits one of the most unequal distributions of income in the world. Figure 3 presents the picture of GDP growth in South Africa over the observed time period.

Figure 3: GDP growth in South Africa in % from 1961 to 2006



Between 40 and 48% of the population live in poverty (Terreblanche, 2002; Van der Berg and Louw, 2003), with over two thirds of the African population and 35% of the coloureds, compared to a very low share of the Indians and almost zero of the white population being affected (Hoogeveen and Özler, 2005). Due to racial discrimination during the Apartheid regime, when a superior white minority was in possession of most of the economic facilities, the majority of black people still suffer from lower education levels, lower incomes and lower life expectancy compared to the white population.

81% of South Africa's land surface is classified as semi-arid to arid rangelands, only 13% is considered suitable for agricultural crop production and of that, only 22% is highly productive (Schulze, 2007). South Africa consists of a dual agricultural production system: On the one hand the highly productive commercial farming sector produces 95% of the commercially marketed products and covers 87% of the total agricultural land in the RSA (Aliber and Hart, 2009). On the other hand there is a widespread subsistence based production that does not enter the economical market and is still mainly situated in the “former homelands”, the so-called communal areas (STATSA, 2005). Of all provinces, Free State, followed by the Western and the Northern Cape, show the highest concentration of commercial farming (STATSA, 2002). However, the sector of small-scale subsistence agriculture is much smaller in South Africa, than in other sub-Saharan countries.

Almost the entire South African land surface is considered to be grazed by livestock. What may seem as a severe impact on natural ecosystems is indeed only a substitution of natural ungulates with domestic livestock species. There is no evidence for domestic grazers and browsers such as cattle, sheep or goats having more negative effects on biodiversity and carrying capacity of South African ecosystems than natural herbivores (Fritz and Duncan, 1994). However, overgrazing, which is often a result of overstocking and fencing, could alter that picture.

Materials and methods

The concept of HANPP

The human appropriation of net primary production (HANPP) is a socio-ecological indicator that measures the amount of biomass appropriated by humans through two pathways: Anthropogenic harvest and human-induced land conversion (such as land cover change, land use change and human induced soil degradation). HANPP is useful as an integrated indicator of land-use intensity, because it does not only measure changes in of biomass flows in ecosystems from land use, but can also be related to the main social and economic driving forces for long-term changes in land cover and land use. HANPP data allow for drawing conclusions on the degree of transformation of natural ecosystems and its implications for factors such as social wealth, biodiversity, sustainable use of natural resources and prospects for a future development of land use.

For this study I use the HANPP concept as defined by Haberl et al. (2007). HANPP is calculated using the following formulas.

$HANPP = \Delta NPP_{lc} + NPP_h$

$\Delta NPP_{lc} = NPP_0 - NPP_{act}$

ΔNPP_{lc}… Productivity loss due to anthropogenic land conversion

NPP_h……Biomass extracted through anthropogenic harvest

NPP_{act}….Current above- ground productivity

NPP_0..…Potential above- ground productivity

HANPP can also be interpreted as the difference between $aNPP_0$ and the amount of biomass which remains in the ecosystem after anthropogenic land use and land transformation, using the formula:

$HANPP = NPP_0 - NPP_t$

NPP_t…NPP remaining in the ecosystem

I calculate biomass flows in carbon units (in the following abbreviated with C), assuming a carbon content of 50% for all types of dry matter biomass occurring in this calculation. Due to limited data availability and reliability on belowground NPP, HANPP in this study only comprises the appropriation of aboveground biomass (excluding biomass in roots etc.). The aboveground component is indicated by the prefix "a".

Harvested aNPP is calculated applying different methods and assumptions described below. Among others the most important data sources are a wide range of statistical databases. $\Delta aNPP_{lc}$ is calculated either as the difference between the potential productivity of an ecosystem ($aNPP_0$) and the current productivity ($aNPP_{act}$), or directly, when it is considered as the decrease of $aNPP_0$, reflecting the effects of land degradation.

Further information on the HANPP concept is given by Vitousek et al., 1986; Haberl, 1997; Haberl et al., 2001; Schandl et al., 2002; Haberl, 2004c, b, a, 2007; Erb, 2009. In order to trace HANPP in a historical context in detail, it is to account for the extent of anthropogenic transformation of ecosystems. Therefore a consistent land cover data set at a sufficient level of aggregation has to be compiled for the investigated period of time. A range of national land cover data sets for the whole of South Africa exists for more recent years, but when analyzing the respective maps, huge shortcomings in terms of comparability between the maps get apparent. These discrepancies result from differing methods of data collection as well as from differing definitions of land cover classes. Therefore I had to develop a different approach for a suitable land cover data set for the period 2006 back to 1961.

Despite the availability of more recent land cover maps, I decided to work with the national land cover data set from 1994/5 (in the following renamed as NLC 1995) as a starting point. The NLC 1995 turned out to be most suitable for gaining a consistent land cover data set from 1961 to 2006 because it is analyzed in various reports by different authors, above all in the study of (Fairbanks et al., 2000), which was crucial for a wide range of estimation procedures regarding land cover change. The NLC 1995 was compiled by the *Council of Scientific and Industrial Research* (CSIR) the *Agricultural Research Council* (ARC) and the *South African National Defence Force* (SANDF). In order to derive the land cover dataset used here, I chose 13 consistent land cover classes which can be further aggregated to five land use types.

provides an overview of all land use types and land cover classes used in this study, with detailed description in the following sections.

Table 1: Land use and land cover classes with their main sources occurring in this study

Land use class	Land cover category	Sources
Cultivated land	Fallow land	Own calculations
	Annual cropland	STATSA, Daff
	Permanent cropland	FAO, Daff, own calculations
Settlement area	Settlement area	FAO, NLC 1995, own calculations
Forest land	Closed forests	STATSA, Daff
	Open forests	NLC 1995
Grazing land	Grassland	NLC 1995
	Shrub cover	NLC 1995, own calculations
	Sparse herbaceous and sparse shrub cover	NLC 1995, GLC 2000
	Low fynbos	NLC 1995, Acocks (1953)
	Undefined grazing land	Own calculations
	Thicket and bushland	NLC 1995
Unused/unproductive land	Unused/unproductive land	Erb et al. (2007), own calculations

Sources: Erb et al.(2007), Statistics South Africa (STATSA), Department of Agriculture Forestry and Fishery (Daff, 2008a,b), National Land Cover 1994/95 (NLC 1995), Global Land Cover 2000 (JRC 2000), own calculations (with explanations below)

Only for the area of *settlement*, *closed forests* and agricultural cultivation area, change could be calculated on a yearly basis from 1961 to 2006, because only here historical, consistent data was available, either in form of statistical records, or through own calculations (in the case of *settlement).* All other land use categories were assessed by relating the extent of potential biomes in Acocks (1953) to detailed information concerning human-induced land conversion in those biomes (Fairbanks et al., 2000). Fairbanks et al. (2007) give assumptions on the share of areas in the potential biomes (biomes that would prevail without human settlement) that were transformed by the expansion of settlement, closed forests. He combined the spatial data on potential biomes from Acocks (1953) with the spatial data on area of *settlement*, *closed forests* and cropped land from the NLC 1995, to detect the extent of transformed areas in the potential biomes those. As an example, it was estimated that 50% of the total settlement area, 62% of the area of *closed forests* and 50% of the total cultivated land were situated in the potential grassland biome (table 2). Although the area of *closed forests* and cultivated land used in this study differs slightly from the one presented in the NLC 1995, I apply this relations to potential biomes in my calculation as well. Due to a lack of additional data I also assign 50% of the annual increase in settlement area and cultivated area, as well as 62% of the expansion in *closed forests* to *grassland*. I apply the same procedure for all other land categories as well to get a complete picture of land transformation. Table 2 presents the assumptions.

Table 2: Percentage of annual change in area of settlement, closed forests and cultivated land that is assigned to the remaining land cover classes for the whole period under investigation

Drivers of land cover change	Low fynbos	Thicket and bushland	Grassland	Open forests	Shrubland	Sparse herb. or sparse shrubc.	Total change in area
settlement	6	22	50	22	0	0	100
forest area	5	18	62	15	0	0	100
cultivated land	13	18	50	15	2	2	100

The following section discusses in detail how I derived my estimates of land-cover data for each of the categories.

Settlement: Since I use the NLC 1995 as my data source, definition and extent of settlement area follow the NLC 1995. Settlement area includes built-up land, such as houses, infrastructures, parks and other artificial areas. The area of settlement was calculated as per person demand by dividing the sum of urban and rural built-up land from the NLC 1995 by the population number from the FAO statistical database (FAO, 2006). To obtain estimates for the whole period, population data for each year were multiplied by per-capita demand. It may seem problematic in terms of accuracy to calculate settlement area by using a constant per-capita demand factor for the whole period from 1961 to 2006, however, settlement contributes such a small share to the total country area (about 1% in 1995) that any of the resulting errors are of minor importance for the overall result.

Annual cropland: the area extent of annually cropped land is taken from the Abstracts of Agricultural Statistics, which were provided by the Department of Agriculture, Forestry and

Fishery (in the following sections abbreviated as Daff) for the whole period of time. For several crops only production data in metric tons were available in the Abstracts of Agricultural Statistics. To calculate the area covered by these crops, I divided production data from the Abstracts of Agricultural Statistics by their respective yields derived from the FAO statistical data base (FAO, 2006).

***Permanent cropland*:** For permanent crops the *Abstracts if Agricultural Statistics* only provide consistent production data in metric tons. I apply the same procedure as described above to obtain the area development of permanently cropped land and therefore calculate the area extent of permanently cropped land by dividing production data from the *Abstracts of Agricultural Statistics* by yields derived from the FAO statistical database (FAO, 2006).

***Fallow land*:** Fallow land is defined as the difference of total cultivated land and cropped areas. Cultivated land follows the FAO-definition as land planted with annual and permanent crops, as well as artificial pastures. The area of cultivated land for the period 1961 to 1993 is most precisely shown in Biggs et al. (2000), who makes use of district-based statistical data of the agricultural censuses (Statistics South Africa). I did not consider the data on cultivated area reported in the FAO land use database reliable, due to an unreasonably rapid increase in the ratio of fallow land to cropped area from the 1990ies onwards. Cropped areas include annual and permanent crop land.

In the absence of any data, I calculate fallow land in the period 1994-2006 using the mean ratio of cropland to fallow land of the period 1985 to 1993.

***Closed forests*:** This category includes all areas with tree densities over 70%. Forest land consists of both indigenous forests and forest plantations. As forest growth requires certain climate and soil conditions, forest areas in South Africa are limited to the Northern, Eastern and some Southern coastal parts of the country. The *Department of Agriculture, Forestry and Fishery* suggests an area of 5 600 km^2 (0.5% of the total land surface) covered by indigenous forests and for this category, no change in area is considered over the time period. This is supported by the report on indigenous forests provided by the Daff (Stehle, 2007), which sums up and analyses qualitative data in form of travel documents from the 18th century (Thunberg, 1779) as well as quantitative, scientific research results on the physical limitations of forests in South Africa (Geldenhuys, 1994), pointing out that there has been no major increase or decrease in that area and that only small forest patches have been transformed severely. I use the value of 5 600 km^2 documented by the Daff.

The extent of forest plantations was derived from Biggs and Scholes (2002) for the period 1961 to 1979, who used data from the *Agricultural censuses* provided by the *Statistics South Africa*. For the remaining period data were taken from the *forestry and FP industry fact sheets* (Daff, 2008b). According to these databases, afforestation continuously increased over the whole period under investigation. Forest areas grew from 8 000 km^2 in 1961 to 13 000 km^2 in 2006. Other land cover studies have estimated the extent of closed forests by applying remote sensing techniques. This resulted in higher values of forest cover. I consider the statistical datasets to be more accurate for my study, because they cover the whole period under investigation on an annual basis, whereas other studies only cover one point in time. The NLC 1995 for example gives values of 22 000 km2 for the sum of indigenous forests and forest plantations, additionally the NLC 2000 (Daff) reports values of 23 000 km2. Finally the GLC 2000 (JRC, 2003) obtains two land cover classes equal to closed forests that are called Tree Cover, broadleaved, evergreen, covering 9 000 km2 and Tree Cover, broadleaved, deciduous, closed, covering 52 000 km2. However, GLC 2000 area of closed forests should be considered with caution, as values appear rather high compared to the other data sets and it is not clear in how far the definition of closed forests differs from the one I use in my study.

A further argument for preferring statistical data on the extent of closed forests is data completeness over the entire time period, whereas land cover maps only cover one point in time.

Open forests: Here I use the definition of "forest and woodland" in Thompson (1996). It contains all wooded areas obtaining a tree canopy density between 10 and 70%. The characteristic features of these landscapes are single tree layers, combined with a grass herb layer. The woody plants are essentially indigenous species growing under natural or semi-natural conditions, they are above 5 meters high, mainly self-supporting and single stemmed and exhibit a sparse-open to sparse-closed community (Thompson, 1996).

Thicket and bushland**:** Here the vegetation matrix consists of tall, woody, single or multi-stemmed plants that branch at or close to the ground. The density of the canopy cover is above 10% and consists of trees between two and five meters high. Plants are mainly indigenous species and grow under natural or semi-natural conditions, however, this land cover class can be affected by dense encroachment of alien bush (Thompson, 1996).

Shrub cover, Low Fynbos *and* ***Sparse herbaceous or sparse shrub cover:*** These three classes are derived from the land cover category "shrubland and low fynbos" of the NLC 1995, which covers an area of 415 000 km^2 (one third of the entire area of South Africa) and contains three regions of differing levels of aboveground biomass production. To gain a more precise view of HANPP in the RSA it was unavoidable to break down this land cover class into three seperate categories, each with its own level of NPP per unit area and year: *Sparse herbaceous and sparse shrub cover*, derived from the GLC 2000 (JRC, 2003) is the North-Eastern part of the "Shrubland" area. The *low fynbos* area covers the most southern part of the former "shrubland and low fynbos" category. Its potential extent was derived from Acocks (1953). In order to calculate the current extent of *low fynbos* land cover class, I subtracted transformed areas according to Fairbanks et al. (2000) from the potential area of Acocks (1953). The third category, shrub cover, is defined as the remaining part of the NLC 1995- land cover category "shrubland and low fynbos".

In terms of vegetation cover, *shrub cover* is dominated by low (0.2-2 meters), woody, self-supporting, multi-stemmed plants that again branch at, or close to the ground. Trees are rare, around 0.1% of the vegetation cover (Thompson, 1996; derived from definition of "Shrubland and low fynbos"). *Low fynbos* follows the above-described origin and definition of *shrub cover* and is located in the Southern coastal region that obtains higher aboveground productivity than the *shrub cover* and is affected by human land transformation to a higher extent. *Sparse herbaceous and sparse shrub cover* follows the land cover definition of *shrub cover* as well, but is situated in the most unfertile part of shrub land. Its spatial extent and its name are derived from the GLC2000.

Grassland: *Grassland* follows the definition of the NLC 1995 land cover category "Unimproved grassland". It includes all grassland areas with less than 10% tree canopy cover, or shrub canopy cover. The essentially indigenous species which live here are non-woody, rooted, herbaceous plants (Thompson, 1996). Herb land and artificial grassland also belong to this category. Herb land as defined in NLC 1995 includes all vegetation types that consist of non-woody, non-grass-like plants between 0.2 and 2 meters of height and a total tree cover less than 0.1% (Thompson, 1996).

Unused/unproductive land: This land cover class is not part of the aHANPP calculation, because it is not assumed to be exposed to anthropogenic land use and land conversion. Its spatial extent is derived through the following assumptions: (Erb et al., 2007) report two land cover categories for South Africa in the global land cover data set for the year 2000, which are either unused or unproductive. These categories are named "Wilderness" and "Non Productive/Snow" and together cover an area of 87 000 km^2. I assume the same extent for *unused/unproductive land* in my study. However, here these 87 000 km^2 are assumed to contain the entire area of the Kruger National Park (20 000 km^2), which refers to "Wilderness" and the NLC 1995 land cover class "bare rock and soil" (30 000 km^2), which refers to "Non Productive/Snow". The remaining 37 000 km^2 are considered to be situated in the most unproductive parts of the country and they are consequently split from the land cover class *sparse herbaceous and sparse shrub cover*. The Kruger National Park covers the most Eastern parts of the Savanna biome and therefore 90% of these 20 000 km^2 were split from *open forests* and 10% from *thicket and bushland*.

Note that this procedure is only partly accurate in terms of the Kruger NP, because it might underestimate human impacts. Some land conversion occurs even in national parks, such as control of fire or game clearing programs. These effects cam, however, be assumed to be of minor importance within the overall context of my calculation. As the area extent of unused/unproductive land given by Erb et al. (2007) exceeds the sum of all three above mentioned land areas, the last part of *unused/unproductive land* is assumed to be part of the *sparse herbaceous or sparse shrub cover*. This seems plausible, because the north-eastern most parts of this lowly productive land cover category already reach into the Namib desert and can therefore be considered unproductive.

Undefined grazing land: Undefined grazing land is the area that remains after subtracting all land cover categories from the total land area of 1.21 Mio. km^2. This is based on the assumption that all areas except *unused/unproductive land* are potentially grazed by livestock. Undefined grazing land is considered grazed, though to a smaller degree, and I assume that there is some HANPP on this area resulting from livestock grazing.

$aNPP_0$

Data on the potential above-ground net primary production ($aNPP_0$) were taken from the global HANPP study for the year 2000 (Haberl et al., 2007), which applied the model output of the Lund-Potsdam-Jena Dynamic Global Vegetation Model (Sitch et al., 2003) with an improved representation of hydrology (Gerten et al., 2004). $aNPP_0$ data for each land cover class in the RSA were only available for the year 2000 as the 5-year mean of the years 1998-2002. For the remaining years $aNPP_0$ values were only available for the whole country in a ten-year interval (five-year means). The trend in $aNPP_0$ on a yearly basis from 1961 to 2006 was estimated by linear interpolations. This trend in total $aNPP_0$ from 1961 to 2006 was imposed on the $aNPP_0$ values for each land cover class of the year 2000 to derive $aNPP_0$ for each land cover class. The result was a complete picture of $aNPP_0$ from 1961 to 2000 for each land cover category, or for each productivity class respectively.

$aNPP_0$ is likely to show high interannual fluctuations as well, mostly as an effect of varying precipitation. These fluctuations are not visible in the database I used, because as described above, $aNPP_0$ values were not available on an annual basis. However, in years with less favorable climate (meaning years of lower $aNPP_0$), crop harvests are lower, resulting in a lower $aNPP_h$. Nevertheless, lower harvests of crops are likely to be substituted by an increasing $aNPP_h$ of grazed biomass as a source of animal fodder, because feed demand, normally covered by crop residues, has to be covered to a higher amount by grazing then. $aNPP_0$ of *unused/unproductive land* is assumed to be zero.

$aNPP_{act}$, $\Delta aNPP_{lc}$, land degradation

South Africa's land surface is characterized by a huge diversity of climatic, as well as topographic areas and vegetation types which go hand in hand with a wide range of aboveground productivity levels. Country-specific studies of current aNPP appear to be very rare, so as a consequence alternative methods to estimate the $aNPP_{act}$ for all land cover classes used in this study had to be developed. I calculate $\Delta aNPP_{lc}$ as a percentage of $aNPP_0$. $aNPP_{act}$ for all land cover classes other than cropped land, settlement area and closed forests, is calculated by subtracting ΔNPP_{lc} from $aNPP_0$.

I calculated $aNPP_{act}$ on cropland by multiplying harvest on cropland (methods are described in the $aNPP_h$ section below) multiplied by a pre-harvest loss factor of 30% (Oerke et al., 1994; Krausmann et al., 2008). This factor reflects biomass of weeds and biomass losses due to pests and insects before harvest. As no information was available to justify different assumptions, I kept this factor constant throughout the time period analyzed. $aNPP_{act}$ on *fallow land* and in *closed forests* are considered identical to $aNPP_0$. Following the definitions in Haberl et al. (2007), $aNPP_{act}$ of *settlement* is assumed to be one third of $aNPP_0$ of settlement areas. $\Delta aNPP_{lc}$ on *Unused/unproductive land* was assumed to be zero.

For all other land cover classes, change in aboveground biomass production was calculated as follows: One of the main advantages of using the NLC 1995 as a starting point for further calculations was that it detects degraded parts within all land cover classes. Degraded areas are listed separately in the NLC 1995 for each land cover type and they are defined as areas suffering from severe vegetation cover and productivity loss compared to their surrounding areas (Fairbanks et al., 2000). Zika and Erb (2009) suggest in their study on degradation in dry lands that areas suffering from severe degradation experience productivity losses by 56% in a degradation degree of three, which means that potential biomass production is reduced by 56% (degree three is the level of degradation). I apply this approach for my study as well and assume a $\Delta aNPP_{lc}$ level of 56% of the original $aNPP_0$ for areas mapped as degraded in the NLC 1995.

In the land cover data set compiled in this study, degradation is not reported in terms of degraded area, but in terms of a loss in productivity ($\Delta aNPP_{lc}$) compared to the productivity potential ($aNPP_0$) of the degraded area. Due to a lack of data and appropriate methods I consider $\Delta aNPP_{lc}/km^2$ resulting from degradation constant over the whole period under investigation.

$aNPP_h$

Harvest on cropland

Biomass harvest on cropland consists of harvested annual and permanent crops plus harvested crop residues. In this study the *Abstracts of Statistical Agriculture* provided by the *Department of Agriculture, Forestry and Fishery* (Daff, 2008a) were used as a primary source for crop production. Where necessary, these data sets had to be supplemented with additional data from the FAO agricultural production data. The whole above-ground part of annual crops at the time of harvest as well as roots and tubers were considered as $aNPP_h$. For permanent crops, production data of the commercial parts of plants, as well as their annual biomass increment were added to calculate $aNPP_h$.

As agricultural statistics only give values for the production of the commercial parts of crop plants, the following method was applied to calculate $aNPP_h$ on cropland:

Data on primary crop harvest given in fresh weight were first converted into dry matter units using standard factors for water content provided by Watt and Merill (1975) and Löhr (1990). Table 3 presents standard values for water content for all primary crops produced in the RSA from 1961 to 2006.

Table 3: Water content of crops planted in South Africa from 1961 to 2007

commodity	Water content [%]	commodity	Water content [%]
Maize	14	Lentils	11
Wheat	14	Litchis a. o. subtrop. fruit	85
Sorghum	11	Loquats	85
Sugar cane	82	Mangos	82
Apples	85	Naartjes	88
Apricots	85	Oats	14
Avocados	74	Onions	89
Bananas	75	Oranges	86
Barley	14	Other berries	85
Beetroot	88	Other summer fruit	89
Cabbage	92	Other vegetables	80
Carrots	88	Pawpaws	89
Cauliflower	91	Peaches	89
Cherries	80	Pears	83
chicory	90	Pineapples	85
Cow peas	11	Plums	81
Dried tree fruit	20	Potatoes	78
Dried vine fruit	20	Prunes	81
Dry beans	10	Pumpkins	91
Dry peas	2	Quinces	84
Figs	77	Rape	12
Granadillas	85	Rye	14
Grapefruit	88	seed cotton	10
Grapes	81	soya	10
Grean mealies	80	Strawberries	90
Green beans	80	sunflower	7
Green peas	78	Sweet Potatoes	70
Groundnuts	6	Tobacco	10
Guavas	85	Tomatoes	94
Lemons and limes	87	Watermelons and melons	93
		Fodder crops	
		Lucerne	20
		Teff	20

Other hay	20

Source: Watt and Merill (1975), Löhr (1990)

$aNPP_h$ is calculated via crop-specific or crop- aggregate specific harvest indices (HI's) with the harvest index presenting the ratio of aboveground biomass at time of harvest to primary crop harvest:

$aNPP_h$= primary crop harvest / HI

Information on harvest indices (table 4) for Sub-Saharan countries was gathered from standard tables (Evans, 1993; Wirsenius, 2000; Haberl et al. 2007) and wherever possible from country-specific assumptions during personal communications (Nell, pers. comm. 2010). Harvest indices show an increasing trend for several crops from 1961 to 2006 as a result of plant breeding efforts, aimed at increasing the commercially harvestable part of crop plants (Evans, 1993). For maize, wheat and sorghum, more detailed information for recent years could be gathered from experts (Nell, pers. comm., 2010) and in case of maize, from country-specific literature (Esterhuyse et al., 1991). A comparison of country-specific values with values from standard tables showed that for several crops such as maize, wheat and sorghum it HI-values for Western European Countries are more appropriate than those generally applied to Sub-Saharan countries. This is likely to result from the fact that industrialization has progressed further in South Africa than in the rest of Sub-Saharan Africa. For all remaining annual crops for which no information on harvest indices was available, as well as for permanent crops, I applied the mean value of all other harvest indices used in this study. In case of permanent crops, the above-ground component of the plant, calculated via HI is defined as the total annual increment of a plant.

Table 4: Harvest indices for selected years

Commodity	1961	1970	1980	1990	2000	source
Barley	0.32	0.32	0.32	0.33	0.35	s.t.
Beans, Dry	0.69	0.69	0.69	0.69	0.70	s.t.
Cow Peas, Dry	0.69	0.69	0.69	0.69	0.70	s.t.
Groundnuts in shell	0.37	0.42	0.38	0.38	0.40	s.t.
Maize	0.18	0.26	0.34	0.42	0.50	s.t., lit.
Oats	0.27	0.27	0.27	0.20	0.22	s.t.
Peas, Dry	0.69	0.69	0.69	0.69	0.70	s.t.
Potatoes	0.48	0.48	0.48	0.49	0.50	s.t.
Rapeseed	0.27	0.27	0.27	0.28	0.30	s.t.
Rye	0.27	0.27	0.27	0.28	0.30	s.t.
Sorghum	0.18	0.26	0.34	0.42	0.50	s.t., pers. comm.
Soybeans	0.37	0.38	0.39	0.39	0.40	s.t., pers. comm.
Sugar Cane	0.58	0.58	0.58	0.59	0.60	s.t.
Sunflower Seed	0.27	0.30	0.33	0.37	0.40	s.t., pers. comm.
Sweet Potatoes	0.48	0.48	0.48	0.49	0.50	s.t.
Wheat	0.27	0.32	0.38	0.44	0.50	s.t., pers. comm.

HI = primary crop harvest / (primary crop harvest + ***r****esidues);* Sources: s.t.:standard tables from Evans (1993), Wirsenius (2000) and Haberl et al. (2007); lit.: literature (Esterhuyse et al., 1991); pers. comm.: personal communication (Nell, 2010)

I distinguished between recovered, unrecovered and grazed crop residues. All these flows are considered as part of $aNPP_h$ because they comprise biomass which is either extracted from ecosystems or affected or even destroyed by human activity. Unrecovered residues do not enter the socio-economic system and are either left on the field, ploughed into the soil or burned. Burning is only common for sugarcane and for irrigated fields, especially when there are high amounts of low quality residues, such as for wheat. Sugarcane fields are burned directly before harvest to avoid leaves impeding the harvest process. As a consequence crop residues are not available for use in this case (Nell, pers. comm., 2010). Maize and sorghum residues are important sources of animal feed. In both cases stalks and leaves are left on fields and afterwards used as fodder through direct grazing. Unused and unrecovered above-ground biomass parts are either distributed by wind or left on the ground. The high nutritional quality of groundnut hay is responsible for its good reputation as a fodder component. Sunflower plants only obtain small amounts of residues after harvest, heads are welcomed by grazers, offering nutrition rich feed supply, leaves deteriorate quickly.

The mass of crop residues entering the socio-economic system through harvest is calculated by multiplying the amount of crop residues by crop-specific recovery rates (Wirsenius, 2000) listed in table 5.

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Table 5: Recovery rates for selected crop residues

Commodities	Recovery rates
Barley	0.90
Dry beans	0.50
Cow peas	0.50
Groundnuts	0.90
Maize	0.90
Oats	0.90
Dry peas	0.50
Potatoes	0.75
Rape	0.70
Rye	0.90
Sorghum	0.90
Soya	0.90
Sugar cane	0.90
Sunflower	0.50
Sweet potatoes	0.75
Wheat	0.90

Source: Wirsenius (2000)

Grazed Biomass

I calculated grazed biomass as the difference between feed demand and feed supply ("grazing gap"). Livestock numbers were taken from the FAO statistical database (poultry and pig numbers; FAO, 2006) and from the *Abstracts of Agriculutal Statistics* (cattle, goat, sheep, horse and mule numbers). Feed demand was analyzed separately for all livestock species, using the methods described below.

Feed demand for cattle was calculated as a function of the average carcass weight or the average milk production per animal. The formulae used in this study were derived from Krausmann et al. (2008) and the higher result of both formulas was used for the calculation. Annual data on carcass weight was derived from the FAO data base, production of milk was taken from the *Abstracts of Agricultural Statistics*.

Feed $\text{intake}_{\text{milk}}$ [kgDM/head/day] = 0.00155 * milk yield [kg/head/yr] + 4.8375

Feed $\text{intake}_{\text{weight}}$ [kgDM/head/day] = 0.036361 * carcass weight [kg/animal] + 1.702006

For the remaining grazer and browser species sheep, goats, mules, horses and asses constant values for feed demand per head were taken from Haberl et al. (2007).

Feed demand of pigs and poultry was calculated by multiplying the yearly production data of red or white meat and of eggs by efficiency factors for Sub-Saharan countries (feed intake per unit of product output) for the year 2000, which were derived from Haberl et al. (2007). Due to improvements in feed efficiency feed intake per unit of product output was considered 50% higher in 1961 than in 2000. Feed demand was assumed to increase linearly between 1960 and 2001 and to remain constant from 2001 until 2006. Table 6 presents the development of feed demand for all livestock species in several selected years.

Table 6: **Species-specific feed demand [kg DM/head/day] for selected years**

Livestock species	1961	1970	1980	1990	2000	2006
Asses [kg DM/ animal/ day]	6	6	6	6	6	6
Cattle [kg DM/ animal/ day]	8.8	8.6	9.5	10.0	10.1	11.3
Goats [kg DM/ animal/ day]	1.5	1.5	1.5	1.5	1.5	1.5
Horses[kg DM/ animal/ day]	10	10	10	10	10	10
Mules [kg DM/ animal/ day]	6	6	6	6	6	6
Pigs [kg DM/ kg red meat]	13.4	12.4	11.2	10.1	8.9	8.9
Sheep [kg DM/ animal/ day]	1.5	1.5	1.5	1.5	1.5	1.5
Poultry [kg DM/ kg meat]	6	5.5	5.0	4.5	4	4
Poultry [kg DM/ kg eggs]	7.8	7.2	6.7	6.1	5.5	5.5

Feed supply consists of crop residues used for feed, fodder crops and market feed. The share of residues used as fodder to total residues is considered remaining at a constant level of 30% for the whole period under observation. Haberl et al. (2007) suggest this value of 30% for the year 2000 and due to a lack of data I assume it unchanged from 1961 to 2006. A crosscheck during a personal conversation (Nell, pers. comm. 2010) supported this approach. The production data of three types of fodder crops/ non-market feed (lucerne, teff and other hay) were derived from the *Abstracts of Agricultural Statistics* (Daff, 2008a) and were converted into dry matter and carbon units. Market feed consists of processed fodder from animal products and processed feed from primary crop harvest. Data were taken from the FAO statistical database (2006) and converted into dry matter and carbon units. Table 7 presents the water-content of different kinds of market feed utilized in the RSA. As market feed obtains higher nutritional values than non-processed fodder production data was multiplied by a factor of 1.5.

Table 7: **Values on water content used for FAO marked feed**

Market feed	Water content [%]	Market feed	Water content [%]
Barley	14	Soyabean Cake	10
Brans	14	Soyabeans	10
Cereals - Excluding Beer	14	Starchy Roots	75
Cereals, Other	14	Sugar Beet	83
Copra Cake	10	Sugarcrops	70
Cottonseed Cake	10	Sunflowerseed Cake	10
Groundnut Cake	10	Sweet Potatoes	70
Maize	14	Vegetables	95
Millet	12	Vegetables, Other	95
Molasses	33	Wheat	14
Oats	14	Demersal Fish	0
Oilcrops	10	Fish Meal	10
Oilcrops, Other	10	Fish, Body Oil	0
Oilseed Cakes, Other	10	Fish, Seafood	50
Palmkernel Cake	10	Marine Fish, Other	50
Potatoes	78	Meat	50
Pulses	10	Meat Meal	10
Pulses, Other	10	Meat, Other	50
Rape and Mustard Cake	10	Milk - Excluding Butter	87
Roots & Tuber Dry	0	Milk, Skimmed	87
Roots, Other	75	Milk, Whole	87
Rye	14	Offals, Edible	50
Sesameseed Cake	10	Pelagic Fish	50
Sorghum	11	Whey	93

Sources: Watt and Merill (1975), Löhr (1990)

Feed demand of non-grazers is more likely to be covered by market feed than feed demand of grazers, therefore market feed serves non-grazing livestock species first. Surplus market feed, fodder crops and used crop residues are considered to be consumed by grazers. The remaining part of feed demand of grazers is assumed to be covered by grazing. In other words, the amount of annually grazed biomass is calculated as the difference between feed demand of grazers and their market feed supply.

Grazed biomass had to be assigned to the different land cover categories. The share of grazing consumed on these land cover classes depended on their area extend and on their potential of aboveground biomass production. Assumptions on grazing potential of landscapes most severely affected by grazing could be made through the grazing-capacity map (Agriculture maps of South Africa, (ARC, Agriculture Maps of South Africa) and the FAO study on gridded livestocks of the world (FAO, 2007): 49% of grazed biomass was assumed to be harvested on *grassland*, 20% in *thicket and bushland*, 10% in *shrub land*, 9% in *open forests*, 5% in *sparse herbaceous and sparse shrub cover*, 5% in *low fynbos*, 1% in *fallow land* and 1% in *undefined grazing land*. Note that these percentages rely on rather rough estimations and therefore the geographical distribution of grazing assumed in this study should be interpreted cautiously.

Wood harvest

Wood is harvested either as industrial roundwood in forest plantations, or as fuelwood, which is gathered almost exclusively from natural wood sources in the RSA. Fuelwood is mainly collected by rural and peri-urban households to meet their needs for energy as well as for construction materials. A comparison of the data on harvested roundwood provided by the FAO statistical database (2006) with forestry data from the Daff (*FP industrial fact sheets*, Daff, 2008b) showed that FAO data were more appropriate for this study. The advantage of using FAO data was that they are separately documented for coniferous and non-coniferous wood and therefore it was possible to apply wood-specific wood density values and wood recovery rates. Furthermore, the amount of harvested wood turned out to be higher in the *FP industry fact sheets* than documented by the FAO and when considering the potential productivity of South Africa's closed forests, FAO data were more plausible for this study (Haberl, pers. comm., 2010). In terms of the production of non-coniferous pulpwood, values appeared unreasonable high from 2003 to 2006. The 2002-value almost doubled in-between one year, which is not exclusively explainable by expanding forestry area. As a mistake in the statistical record cannot be excluded, I consider the 2002-value for non-coniferouspulpwood constant for the remaining years.

Data on harvest of industrial roundwood given in stacked cubic meters were converted into metric tons and carbon units by applying standard factors on wood density for temperate African countries (Krausmann et al., 2008). As aHANPP considers all aboveground parts of felled trees, data on wood removals were multiplied by wood recovery rates (Pulkki, 1997) in order to achieve the total amount of harvested wood. Table 8 presents an overview on wood density and recovery rates applied in this study. Wood density is given in tons dry matter (DME) per cubic meter and had to be converted into carbon units (by multiplying by a C-content factor of 0.5).

Table 8: Values on wood density and recovery rates for coniferous and non-coniferous wood in the RSA

	coniferous wood	non-coniferous wood
wood density [tDM/m^3]	41	58
recovery rates [%]	54	54

Harvest of fuelwood can almost exclusively be assigned to *open forests* and *thicket and bushland*. No annual statistics on the amount of fuelwood extraction are available for the RSA, however, various authors provide estimations on per-person demand for fuelwood harvest. These studies were often conducted for rural households (Gandar, 1983; Liengme, 1983; Banks et al., 1996), where fuelwood gathering is more common than in urban areas. The International Energy Agency (IEA, 1996) suggested values between 8.4 and 40 Mio. t of fuelwood-consumption per year for the whole RSA. The actual amount of fuelwood from natural ecosystems was not clear though, because a certain amount of bagasse, woodwaste and charcoal was included in the estimation as well. The Department of Minerals and Energy

(DME, 1996) suggests an annually harvested amount of fuel-wood of 9.8 Mio. t DM, or 4.9 Mio. tC respectively, for the whole country (Williams and Shackleton, 2002). I used this value, divided by the population number of the year 1996 (FAO, 2006) and calculated a per-person demand of 0.12 t C/cap/year. This value compares well with the FAO data on fuelwood consumption. Due to a lack of additional data I consider this value constant for the whole period under investigation. I decided to not apply recovery rates on harvested fuel-wood, because the bulk of fuelwood is directly collected from ecosystems and I assume all aboveground parts available for collection in ecosystems to be used as energy source.

Other harvest

Other harvest contains harvest on settlement area through gardening work and park or infrastructure maintenance. It is assumed to be 50% of $aNPP_{act}$ of these areas (Haberl et al., 2007).

Backflows to nature

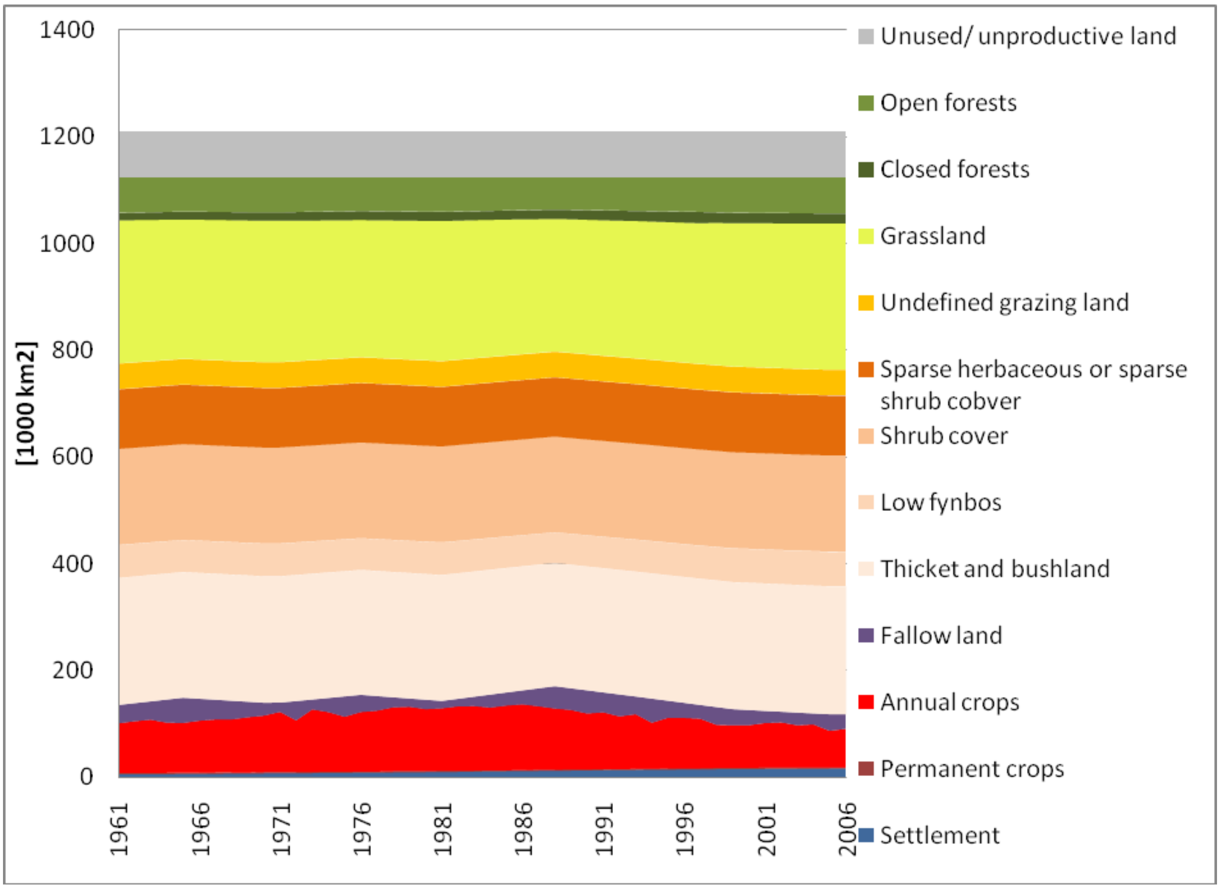
Backflows to nature include all unrecovered crop residues, as well as felling losses and feces dropped by livestock. Unrecovered crop residues were calculated as the difference between the total aboveground part of a plant (calculated via harvest indices) and the commercial part of a plant plus recovered crop residues. Unrecovered wood, which consists of all felling losses, is calculated by multiplying wood harvest by a factor of 0.46 (Pulkki, 1997). In terms of livestock feces I assume that cattle excretes 35% and all other grazers 25% of their annual feed intake and that of this amount, two thirds are dropped on the grazing sites.

Results

Land cover change

Grassland, *thicket and bushland* as well as *shrub cover* contributed the lion`s share to the total South African land surface throughout the investigated time period (Figure 4). Forest land, which includes *closed forest* and *open forests* is of minor importance, whereas grazing land (including all land cover classes except forest land *annual and permanent cropland*, *settlement*, as well as *unused/ unproductive land*) has been dominating the land surface.

Figure 4: Land cover change in South Africa from 1961 to 2006



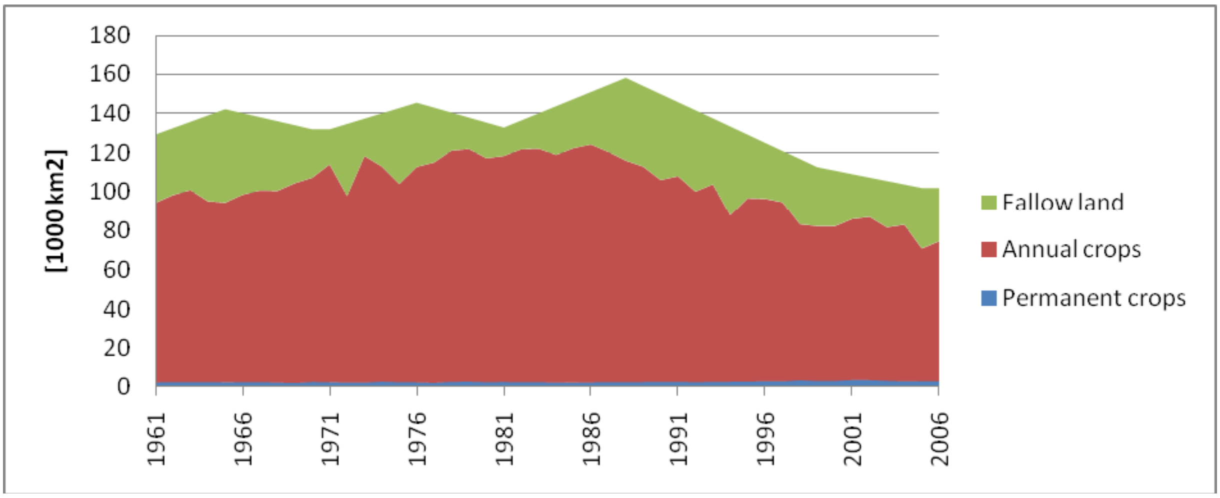
Changes in the area of arable land (including annually and permanently cropped land and fallow land), the spread of settlement area and the spread of forest plantations are responsible for land cover change in South Africa. Land cover change overwhelmingly took place in the more productive regions in the East as well as in the Cape region, along the southern coast of the country (Biggs and Scholes, 2002).

However, cultivated land, settlement area and forest plantations, covered only small parts of the total country surface. In 1988 these three land cover types reached a maximum share of almost 16% of the total land area (mainly due to expanding crop land). In the other years values were mainly near 12%.

Although settlement area increased almost threefold from 6 000 km^2 in 1961 to 16 000 km^2 in 2006, the overall share of settlement area to total land area remained low (0.5% in 1961 and 1.3% in 2006). As a consequence, land cover change due to the expansion of settlement area can be considered of minor importance from 1961 to 2006. A similar scenario was observed in terms of expansion of the area of closed forests, or forest plantations respectively. The area covered by closed forests expanded by 31% during the observed period of time, but only contributed a share between 1.2 (in 1961) and 1.5% (in 2006) to total land surface. As a result, also the area expansion of closed forests does not have major impacts on overall land cover in South Africa.

Cultivation of land (Figure 5) for agricultural crop production is most responsible for land cover change, especially in *grassland*. Until 1988, half of the annual area expansion of cropland was assigned to grasslands area, 18% to *thicket and bushlands*, 15% to *open forests*. The same relations were applied for the declining area of cultivated land after 1988. 50% of the annually "lost" cropland area was reversed into grassland again, 18% into *thicket and bushland*, 15% into *open forests.*

Figure 5: Development of cultivated land in km² from 1961 to 2006

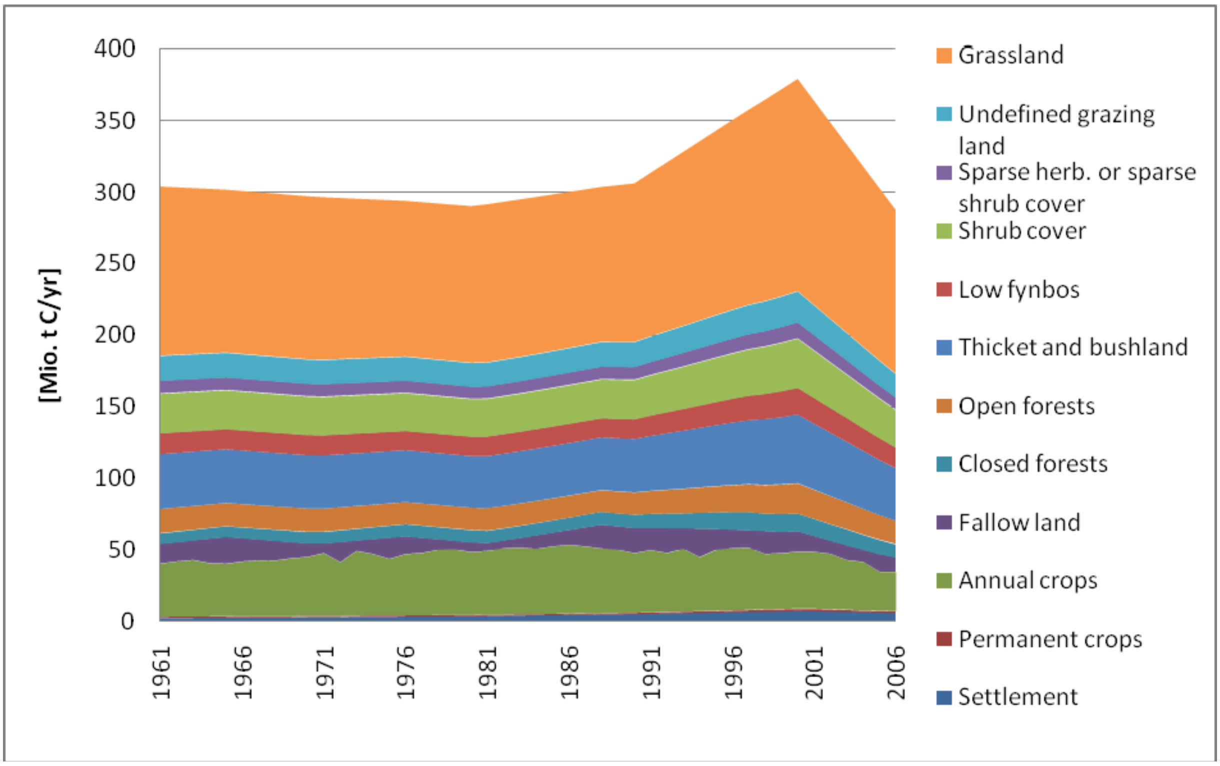


Grassland is the land cover class most severely affected by land cover change. In the period from 1961 to 1988 grassland area declined from 270 000 to 250 000 km², mainly due to the expansion of cultivated area. Due to a decrease in cultivated area from 1988 onwards, grassland reached the initial level of 1961 in the more recent years again, with values around 270 000 km². All other land cover classes only show slight changes in area extent.

NPP_0

According to the results of the LPJ global dynamic vegetation model, the trend in total $aNPP_0$ (the potential above-ground productivity) varies considerably over the investigated time period. It shows a slight decline from 304 Million tons carbon per year (Mio. tC/yr) in 1961 to 288 Mio. tC/yr in 2006 (Figure 6). A major peak of 379 Mio. tC/yr in 2000 can be explained by annual rainfall above average during that period of time.

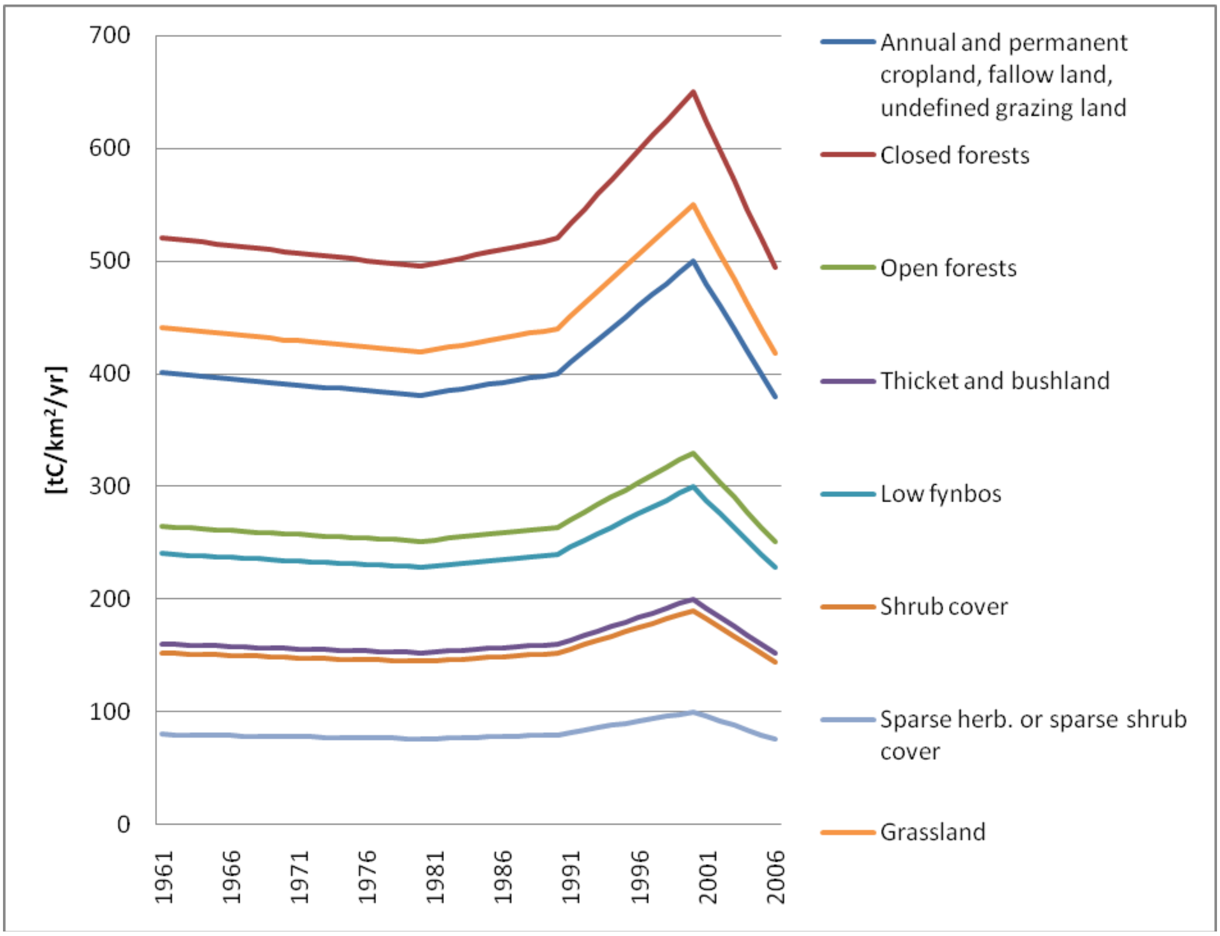
Figure 6: Trend in $aNPP_0$ for the RSA from 1961 to 2006, split into land cover classes



Source: Haberl et al. (2007), own estimations, see text

$aNPP_0$ per unit area and per year for each land cover class follows the trend in total $aNPP_0$, with a peak in the year 2000. In terms of productivity potential a strong East-West gradient gets apparent (Figure 7): *Sparse herbaceous and sparse shrub cover*, situated in the most western parts of the country, obtains the lowest biomass production rates, reaching from 80 to 100 tons carbon per square meter per year (tC/km²/yr) in 2000. Closed forests in the most Eastern parts of the country obtain the highest values of $aNPP_0$ per km^2 from around 560 to 7000 tC/km²/yr (in 2000), followed by *grassland*, *settlement area*, *annual* and *permanent cropland*, *fallow land* and *undefined grazing land*.

Figure 7: $aNPP_0$ for each land cover class

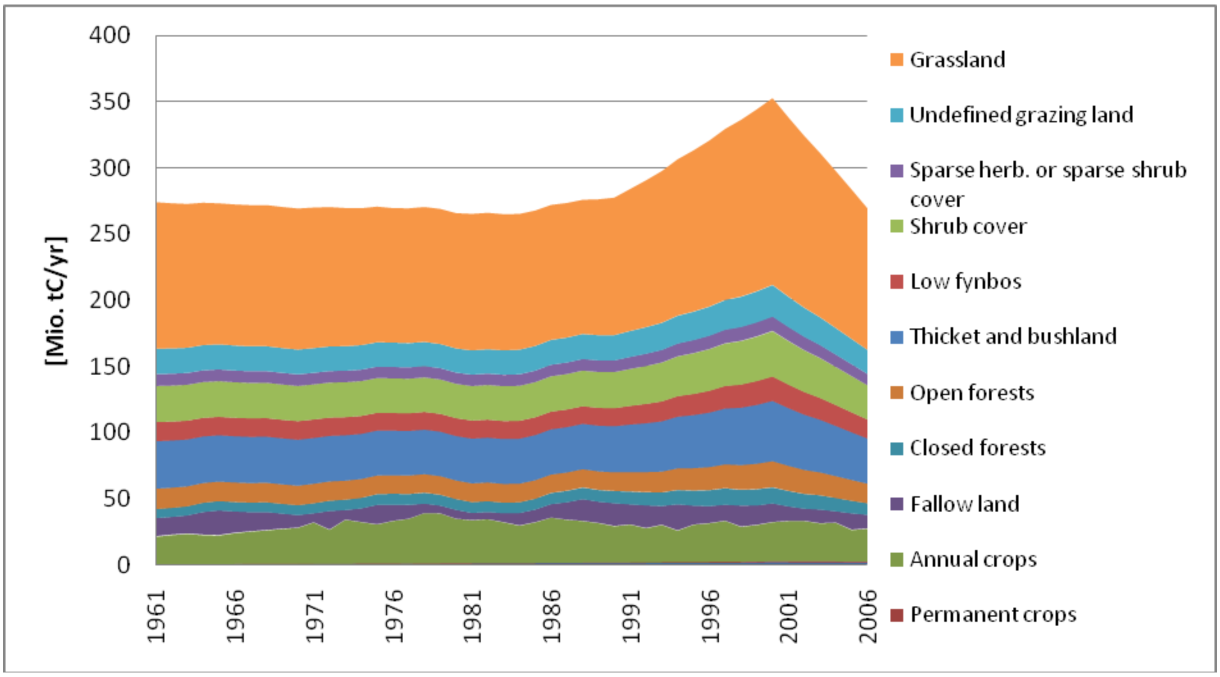


$aNPP_{act}$, $\Delta aNPP_{lc}$

The trend in total $aNPP_{act}$ is similar to the trend in $aNPP_0$ (Figure 8). This is because $aNPP_{act}$ values are derived from the potential aboveground productivity minus land degradation for all land cover classes other than cropland, where $aNPP_{act}$ was calculated directly from harvested biomass.

Values reach from 274 Mio. tC/yr in 1961 to 269 Mio. tC/yr in 2006, with a peak of 350 Mio. tC/yr in 2000. $aNPP_{act}$ for the land cover classes follows the trend in land cover change and as discussed above, this change was not very significant for the whole period under investigation. The rise in $aNPP_{act}$ can be explained by an increase in $aNPP_{act}$ on cropland due to agricultural intensification on the one hand and on the other hand through the fact that $aNPP_{act}$ is derived from $aNPP_0$ (see $aNPP_0$, Figure 6).

Figure 8: aNPP$_{act}$ in the RSA from 1961 to 2006, split into the single land cover classes



A comparison of total aNPP$_{act}$ with aNPP$_0$ per unit area allows analyzing human-induced changes in productivity. Table 9 presents annual aNPP$_0$ and aNPP$_{act}$ values per km² for each land cover class except *closed forests* and *fallow land*, because here no difference between current and potential productivity was considered (Haberl et al., 2007). A decline in productivity due to land degradation was observed for all land cover categories. On *sparse herbaceous and sparse shrub cover* land degradation was too low to be manifested in a visible productivity change. For annual and permanent crops, differences between aNPP$_{act}$ and aNPP$_0$ are more pronounced. On cropped areas, aNPP$_{act}$ values fluctuated more significantly between the years, depending on annual rainfall events, irrigation intensity and the input of fertilizers for crop production. The trend towards a more intensified production system, visible in a rapid growth of aNPP$_{act}$ and aNPP$_h$ values on crop land from the mid 1970ies onwards, came hand in hand with the green revolution, which brought mineral fertilizers, pesticides and advanced irrigation techniques to South Africa. From the mid-1980ies onwards, the aNPP$_{act}$ level on cropland declined again, which is mainly explicable by drier growth periods and by the economic and financial crisis in the 1980ies and early 1990ies (for more details see conclusion). In 1980, aNPP$_{act}$ was even lower than one decade ago. Current productivity recovered again until 2006, when aNPP$_{act}$ per unit of cropped area reached the highest level in-between the whole period observed. Current productivity on the area of permanently cropped land continuously increased from 161 tC/km²/yr in 1961 to 445 tC/km²/yr in 2006. From 2004 onwards the actual productivity even exceeded the potential one, which can be interpreted as an effect of external improvements of growing conditions.

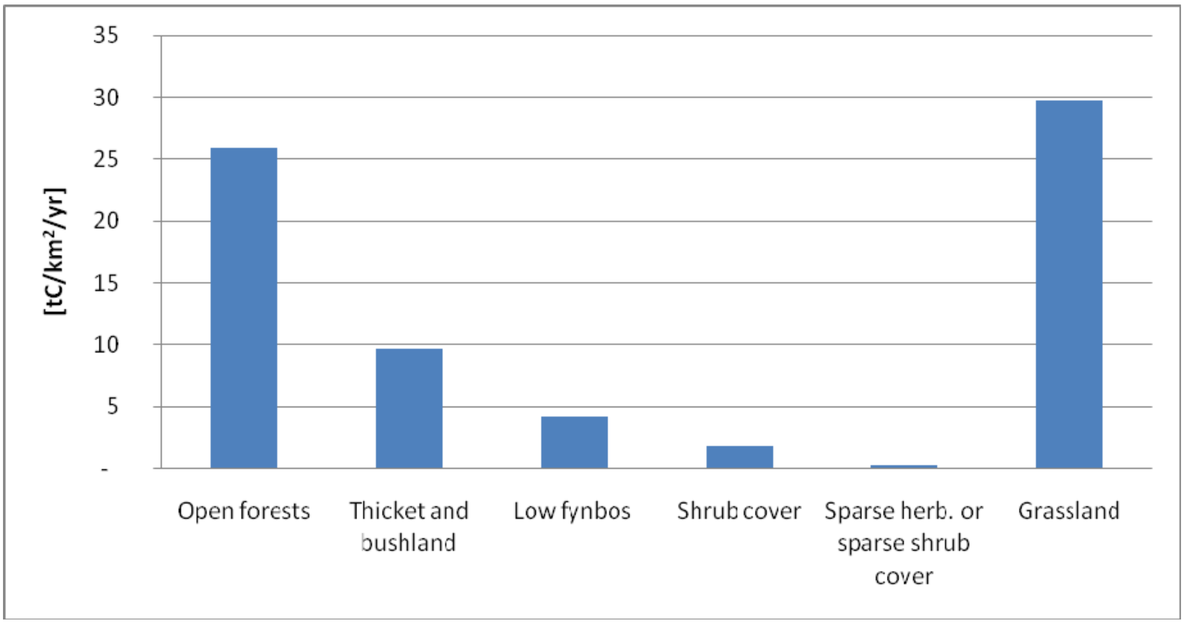
Table 9: $aNPP_{act}$ and $aNPP_0$, for five selected years listed for all land cover categories [tC/km²/yr]

land cover class		1961	1970	1980	1990	2006
Grassland	$aNPP_{act}$	411	400	389	410	388
	$aNPP_0$	441	430	419	440	418
Annual crops	$aNPP_{act}$	221	254	287	260	339
	$aNPP_0$	401	391	381	400	380
Permanent crops	$aNPP_{act}$	161	218	275	343	445
	$aNPP_0$	401	391	381	400	380
Open forests	$aNPP_{act}$	239	232	226	238	225
	$aNPP_0$	264	258	252	264	251
Low fynbos	$aNPP_{act}$	236	230	224	236	224
	$aNPP_0$	240	235	229	240	228
Thicket and bushland	$aNPP_{act}$	151	147	143	150	142
	$aNPP_0$	160	156	152	160	152
Settlement	$aNPP_{act}$	92	100	100	104	103
	$aNPP_0$	401	391	381	400	380
Shrub cover	$aNPP_{act}$	150	147	143	150	143
	$aNPP_0$	152	149	145	152	144
Sparse herb. or sparse shrub cover	$aNPP_{act}$	80	78	76	80	76
	$aNPP_0$	80	78	76	80	76

$\Delta aNPP_{lc}$

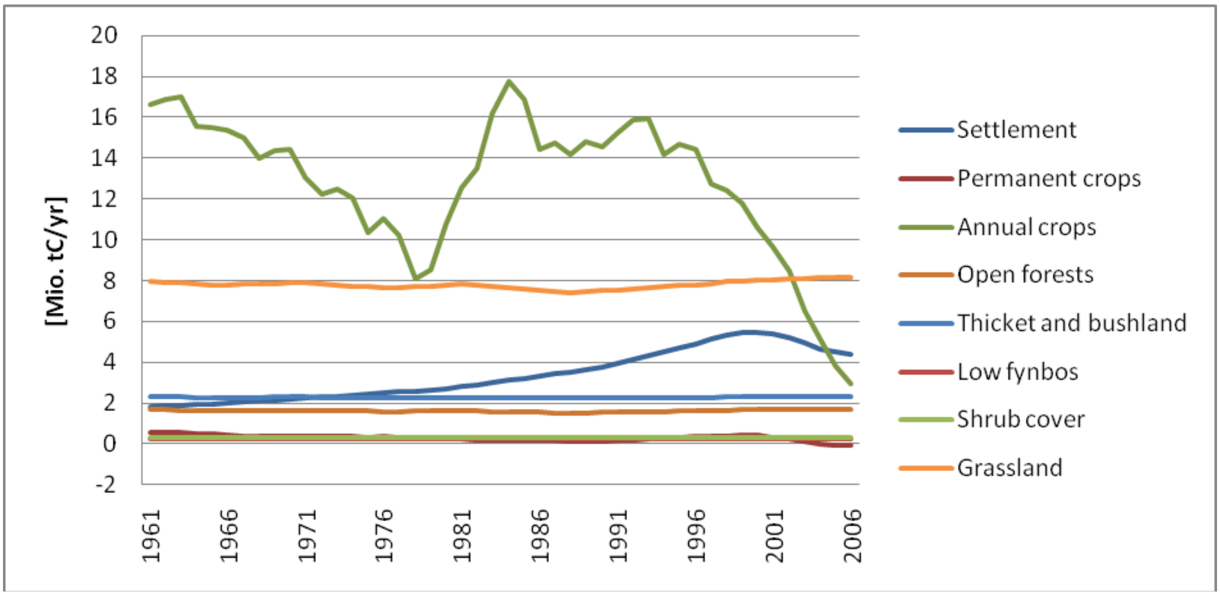
The aboveground productivity potential is most strikingly reduced in *grassland*, the most intensely grazed land cover class. Here, degradation caused $\Delta aNPP_{lc}$ values of 30 tC/km²/yr, which equals an average value of 7.8 Mio. tC/yr. Productivity losses due to degradation on *grassland* are higher than the sum of productivity losses of all remaining land cover classes affected by degradation (Figure 9). *Open forests*, *thicket and bushland*, *shrub cover* and *low fynbos* exhibit values below 1 Mio. tC/yr and $\Delta aNPP_{lc}$ on *sparse herbaceous or sparse shrub cover* almost equals zero.

Figure 9: $\Delta aNPP_{lc}$ for all land cover categories affected by land degradation in (constant value from 1961 to 2006)



The complete picture of $\Delta aNPP_{lc}$ from 1961 to 2006 is presented in Figure 10. $\Delta aNPP_{lc}$ on settlement area increased fourfold from around 1 to 4 Mio. tC/yr, which was as a result of area expansion. Annually cropped land shows high inter-annual fluctuations in $\Delta aNPP_{lc}$ values due to differing yearly amounts of biomass harvest of annual crops. $\Delta aNPP_{lc}$ values were clustered around 16 Mio. tC/yr in the early 1960ies and dropped to around 8 Mio. tC/yr in 1979, followed by a rise towards 18 Mio. tC/yr in the early 1980ies. The trend declined again after 1994 and reached its minimum level of around 3 Mio. tC/yr at the end of the investigated time period. These fluctuations on annually cropped land are related to a strong correlation between $aNNP_{act}$ on cropland and relatively unstable external variables such as annual rainfall and drought, as well as changes in agricultural production due to the use of fertilizers and irrigation. Years of favorable growing conditions exhibit lower $\Delta aNPP_{lc}$ values, because in these years the actual productivity approaches the potential one. The share of $\Delta aNPP_{lc}$ caused by degradation to total $\Delta aNPP_{lc}$ lies between 20 % (in the 1960ies) and 32% (at the end of the time period). Productivity losses due to degradation on *grassland* are higher than the sum of productivity losses of all remaining land cover classes affected by degradation (Figure 10). Here degradation causes $\Delta aNPP_{lc}$ values of around 7.8 Mio. tC/yr. *Open forests*, *thicket and bushland*, *shrub cover* and *low fynbos* exhibit values bebelow 2.3 Mio. tC/yr. $\Delta aNPP_{lc}$ on *sparse herbaceous or sparse shrub cover* almost equals zero.

Figure 10: ΔaNPP$_{lc}$ from 1961 to 2006 for each land cover class



aNPP$_h$

Biomass extraction through anthropogenic harvest rose from around 40 Mio. tC/yr in the 1960ies to more than 51 Mio. tC/yr in 2006. A peak of 46 Mio. tC was observed in 1978, which was the result of above average production of annual crops. Harvest of annual crops (Figure 11 and figure 12) contributes the lion`s share to total harvest. aNPP$_h$ of annual crops increased continuously from 15 Mio. tC in 1961 to around 27 Mio. tC/yr (41% of total aNPP$_h$) in 1978. A declining trend that led to a value of around 20 Mio. tC (30 % of total aNPP$_h$) in 2006 emerged afterwards. Eight years after this peak in the late 1970ies, also the area of cultivated land rapidly declined by 42%. These developments on annually cropped land can be considered rather surprising in the light of a population growth from 18 to 49 Mio. people from 1961 to 2006. Possible explanations for this phenomenon are discussed in the chapter *conclusion*. After a low grazed period from the late 1960ies to the mid 1980ies land use classes most severely affected by grazing (*grassland, open forests, thicket and bushland*) presented a slight increase in harvested NPP (figure 11 and figure 12). *Grassland* shows the second highest values for aNPP$_h$. It contributed around 26% to the total amount of harvested biomass at the beginning and 20% at the end of the observed time period. The amount of grazed biomass is dependent on the amount of harvest on annually cropped land. Little productive periods on cropland imply low availability of crop residues for fodder. The higher the amount of crop residues, the lower the amount of grazed biomass. Gathering of fuelwood increased from 5 Mio. tC/yr in 1961 to almost 13 Mio. tC/yr in 2006. Its effects are most clearly reflected in a steep increase of aNPP$_h$ in *open forests* and *thicket and bushland* (figure 11). Despite new electrification initiatives also for rural areas in the RSA (Wiliams, 2002), no evidence for a declining trend of fuelwood gathering could be found in the literature. Harvest in *closed forests* is almost entirely driven by the forest plantation industry and goes hand in hand with an expanding area of *closed forests*. Harvest of roundwood increased more than fourfold, from 2 Mio. tC/yr in 1961 to almost 8 Mio. tC around 2000 with a slight decline afterwards.

Backflows to nature continuously rose by 23% from 9.5 Mio. tC/yr in 1961 to 17.1 Mio. tC/yr in 2006. Its contribution to total aNPP$_h$ exhibits a steady increase from 21% in 1961 to 26% in 2006. Note, that *backflows to nature* should not be considered an own class of harvested NPP, becase that amount is already counted within the other harvest classes. *Backflows to nature* should rather give a picture of the actual amount of $aNPP_h$ accumulated during harvest events that does not enter the socio-economic system. It turned out that the bulk of total *backflows to nature* consists of livestock feces dropped on grazing sites, increasing from 6.6 Mio. tC/yr in 1961 to 8.2 Mio. tC/yr in 2006. This development shows that the South African land use system underwent a shift towards a more livestock based agriculture. Lifestock based agriculture can increase land use efficiency in countries with little cropland potential, because biomass on grazing land, otherwise not available for the socio-economic system, can be mobilized. Besides, this trend reflects the transition from traditional carbohydrate based nutrition to diets usually preferred in highly developed countries, i.e. a decrease in carbohydrates and an increase in fat and protein consumption (Bourne et al., 2002). Meat consumption per capita increases from 32 kg/cap/year in 1961 to 50 kg/cap/year in 2006 (FAO, 2006). The share of unrecovered crop residues contributing to *backflows to nature* slightly declined after a peak in 1979, reflecting the decreasing trend of production of annual crops. The share of unrecovered wood increased over the whole period under investigation, mainly as a result of the rise in $aNPP_h$ of industrial roundwood.

Figure 11: Harvest of biomass broken down to land cover classes from 1961 to 2006

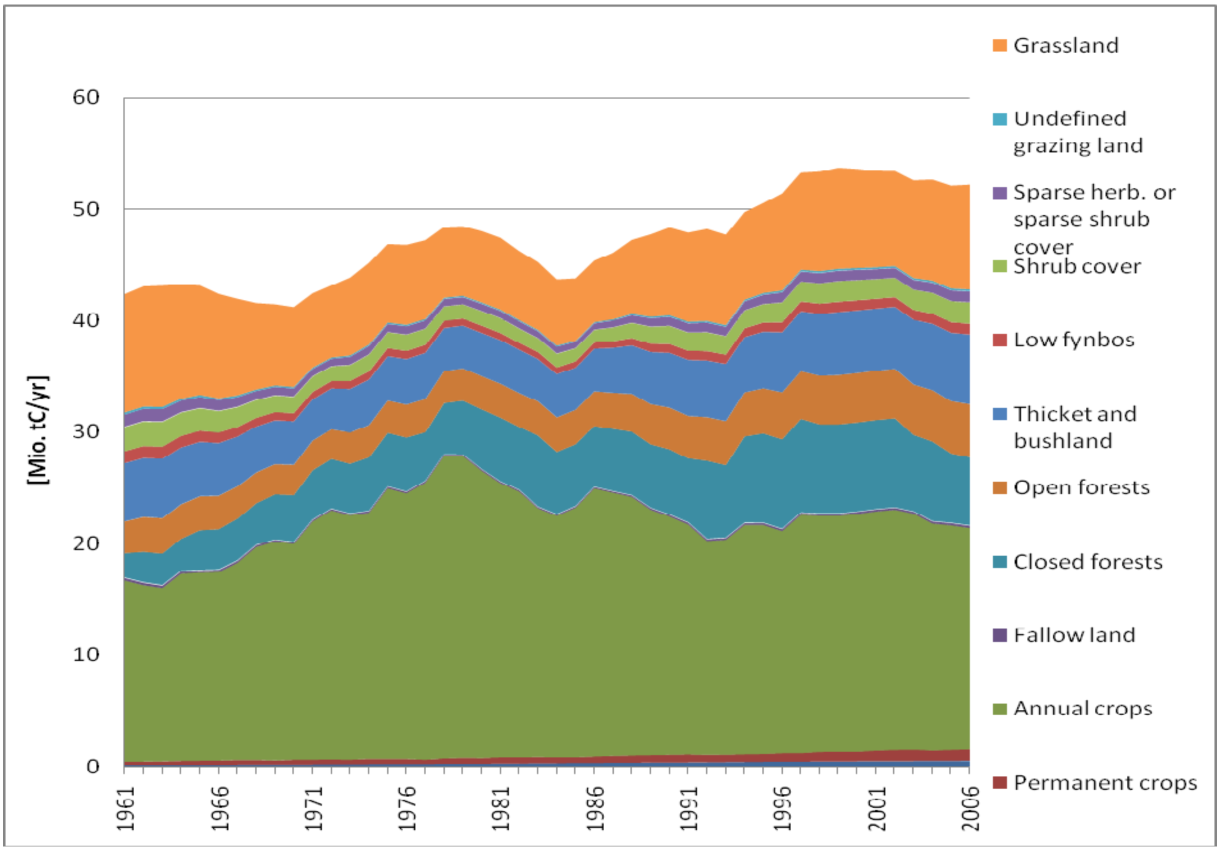
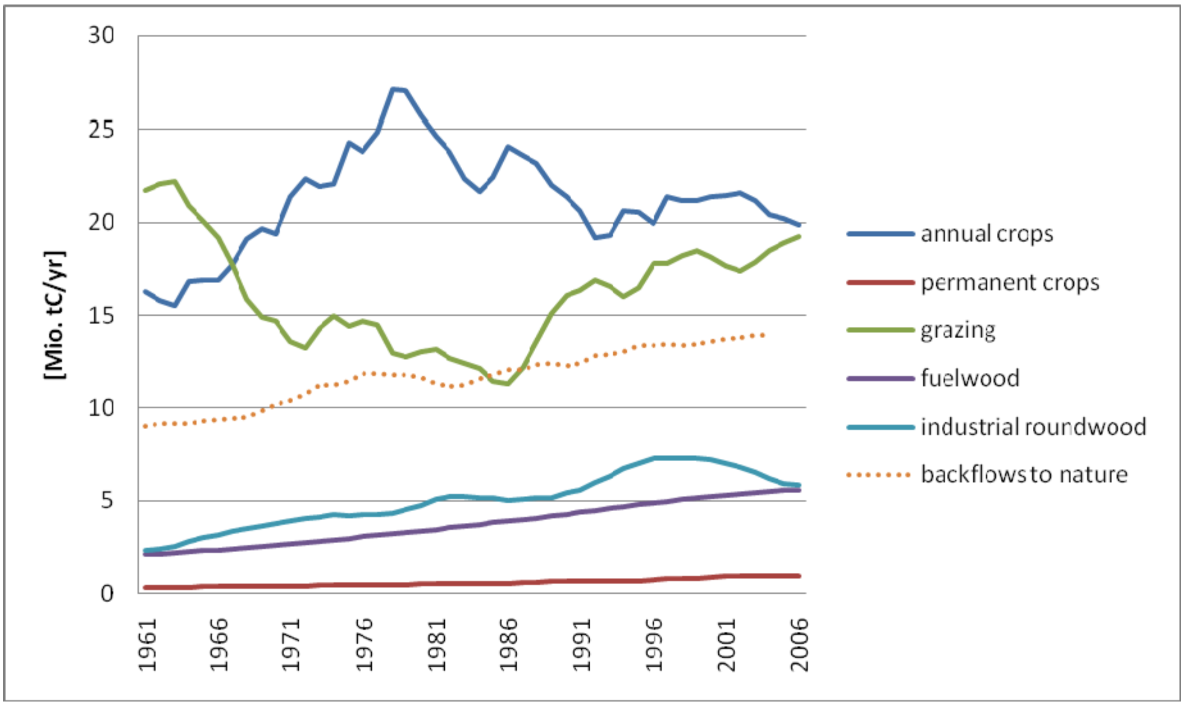
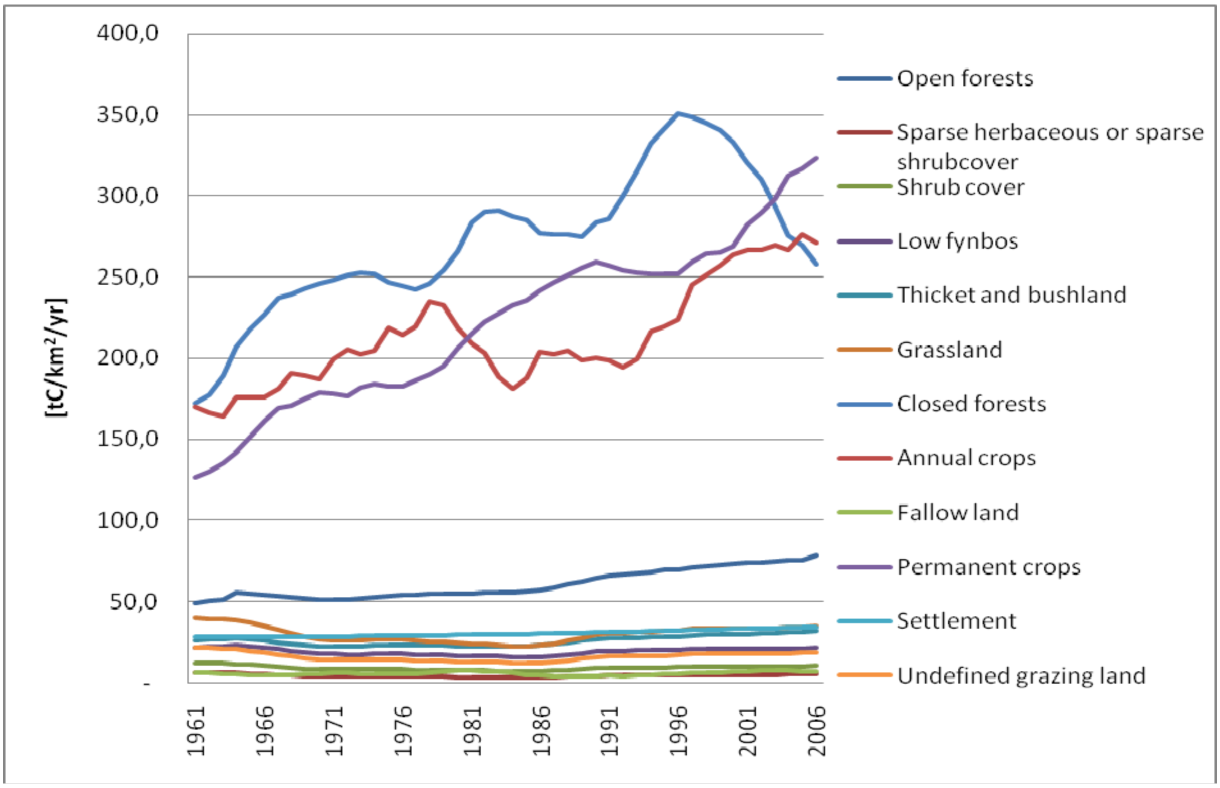


Figure 12: Development of $aNPP_h$ broken down to its components from 1961 to 2006



Harvest per km² broken down to individual land cover classes (Figure 13) remained relatively constant for all land cover categories over the years, except for those heavily affected by anthropogenic land management, such as annual and permanent crops and *closed forests*. On these lands $aNPP_h$ increased substantially. In the case of *closed forests,* even a twofold growth from 190 t C/km² in 1961 to 390 t C/km² in 2000 was observed. This trend declined afterwards to 290 t C/km^2 in 2006. Yields of annual crops continuously rose from 160 t C/km^2 in 1961 to 260 t C/km² in 2006, with a period of low productivity from the 1980ies until the mid 1990ies. Afterwards productivity rapidly rose again. Yields of permanent crops more than doubled from 130 t C/km² to 320 t C/km² during the investigated time period. *Open forests* is not only a heavily grazed land cover class, but also affected by massive fuelwood extraction. Therefore, a rise in harvested biomass from 50 tto 80 tC/km²/yr was found on that land. All remaining land cover classes follow the trend in grazed biomass and stay at a constant level for the whole period observed. Only a slight decreasing trend from the mid 1960ies until the late 1980ies was observed.

Figure 13: Harvest per km² land cover class from 1961 to 2006

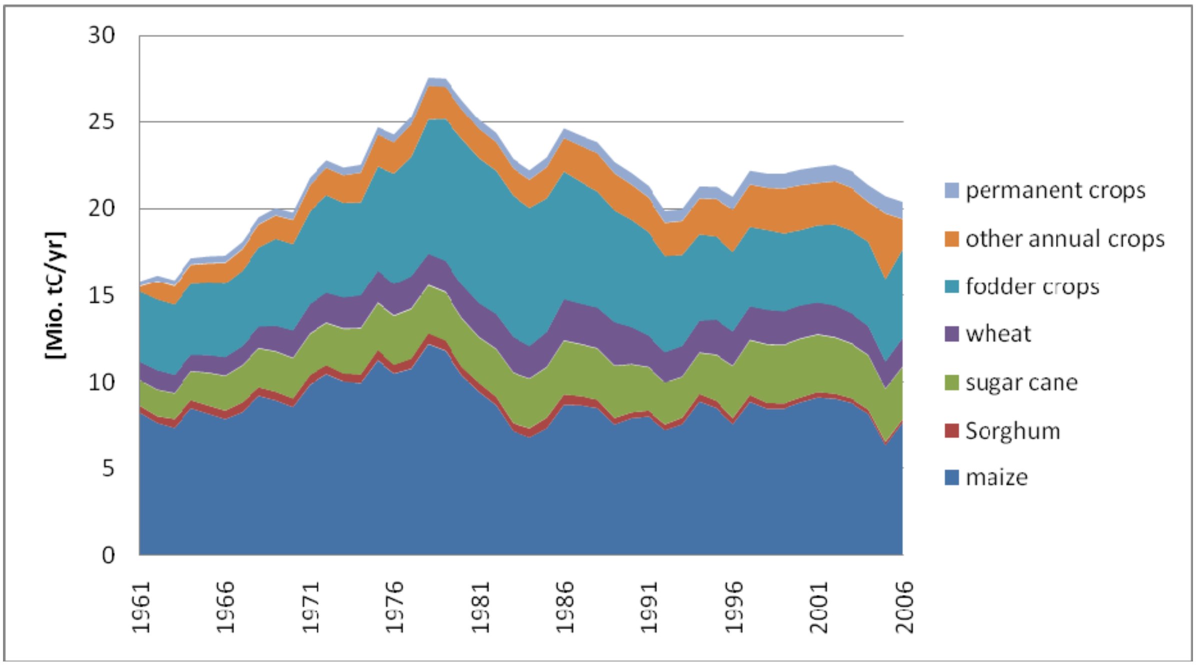


The following section discusses the single components of $aNPP_h$ in more detail.

Harvest on cropland

Figure 14 reports the trends in harvest of crops including fodder crops, broken down to the main crops planted in the RSA from 1961 to 2006. These crops consist of maize, fodder crops, sugar cane and wheat. Total harvest on cropland steadily rose from 16 Mio. tC/yr in 1961 to a peak of 27 Mio. tC/yr in 1978 and afterwards declined until the mid 1990ies. The lowest levels of $aNPP_h$ after 1978 were reached in the early 1990ies, which is mainly explainable by a significant decrease of the two most commonly planted crops: fodder crops and maize. Harvest of fodder cops continuously increased from 4.1 Mio. tC/yr in 1961 to a peak of 8.4 Mio. tC/yr in 1980 and afterwards declined to a value of 5.2 Mio. tC/yr in 2006. Maize harvest rose from 8.3 Mio. tC/yr in 1961 to 11.8 Mio. tC/yr in 1979 and afterwards drastically declined to a level of around 8 Mio. tC/yr. Despite interannual fluctuations in $aNPP_h$,of maize the level of around 8 to 10 Mio. tC/yr remained unchanged until 2006. Within the whole period under investigation, the lowest value of 6.9 Mio. tC/yr was reached in 1984. Years of low $aNPP_h$ of maize in general reflect the effects of drier growing periods such as in the early and mid 1980ies and again in 2004. In terms of crop growing, most of the subsistence farmers especially in rural areas, are highly dependent on relatively drought resistant crops, such as maize (Tadross et al., 2003), because they still use traditional growing techniques. Furthermore, maize is appreciated as the basic staple crop all over the country, because of its high market and nutritional value compared to cereals like sorghum or millet (Fischer et al., 2000). Harvest of all other crops slightly increased only in the early 1990ies a reduction (especially in the case of wheat and sugar cane) was observed. Sorghum played an important role in agriculture of the former homelands. Here, farmers did not have access to modern techniques unlike farmers in the formerly white areas. It is estimated that in the former homelands yields of maize or sorghum were only one third of those achieved in the white areas (Biggs and Scholes, 2002). Besides, several trends in crop harvest are explainable by the political and economical circumstances in several periods under investigation. For details on this topic the chapter *discussion and conclusions* provides further information.

Figure 14: Harvest of the main crops, including fodder crops from 1961 to 2006



Grazed biomass

Total livestock numbers decreased slightly over the observed time period (Figure 15). Cattle, pig and poultry numbers increased, whereas sheep numbers declined by around 30%. After a drastic decline in the number of goats in 1969, stocks remained relatively constant in the following decades. Mules, horses and asses, used as draft animals, initially declined somewhat until the early 1970ies and remained constant in the following years. The effects of these developments on total feed demand are presented in Figure 16. Increasing cattle numbers from 12.6 to 13.9 Million heads from 1961 to 2006 are partly responsible for the total rise in feed demand from 32 to 39 Mio. tC/yr. Besides, the rise in productivity of cattle (in other words the amount of meat and milk produced per animal per year) contributed to the increasing feed demand. In 1961 one milk cow produced 2.6 tons of milk per year and the carcass weight was 177.7 kilograms per animal. Until 2006 these values rose to 3.8 tons of milk per animal and a carcass weight of 263.9 kg per animal. The increasing product output per animal is closely related to the rise in feed demand per animal, which rose by 28%, from 1.6 tC/cap/yr in 1961 to 2.1 tC/cap/yr in 2006. Feed demand per unit of production output was considered constant for sheep and goats over the whole period under observation.

Figure 15: Livestock numbers from 1961 to 2006

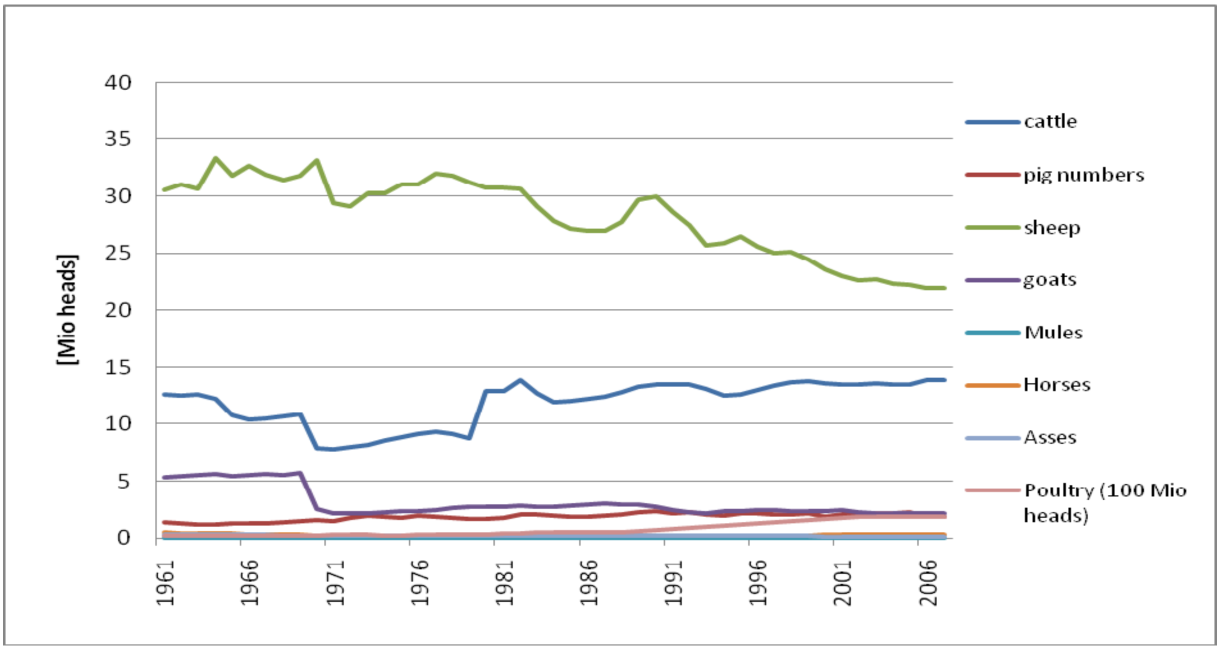
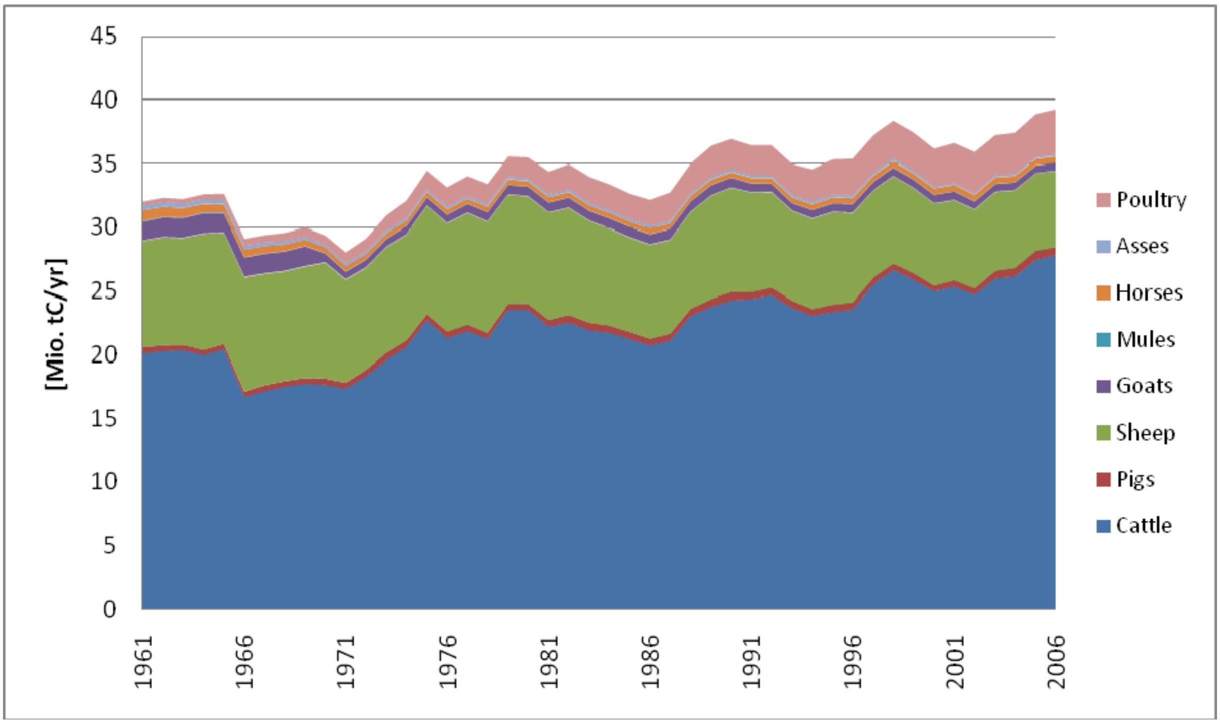


Figure 16: Feed demand for livestock species from 1961 to 2006



Sources: FAOSTAT, own calculations

Feed supply follows the trend of feed demand, with a slight increase from 32.0 Mio. tC/yr in 1961 to 39.3 Mio. tC/yr in 2006 and it shows relatively high inter-annual fluctuations (Figure 17). Due to a smaller share of crop residues, market feed and non-market feed (fodder crops) to total feed supply, the amount of grazed biomass was higher in the 1960ies, compared with the following decades. From the early 1970ies until the mid 1980ies grazing declined. This was the effect of a higher availability of crops residues, an increased consumption of market and non-market feed and a slight decline in total feed demand. Declining amounts of grazed biomass per year can also be interpreted as the rising commercialization and modernization of the livestock industry. From the mid 1980ies onwards, grazing increased again and simultaneously all alternative sources of fodder declined.

Figure 17: Feed supply for livestock species from 1961 to 2006

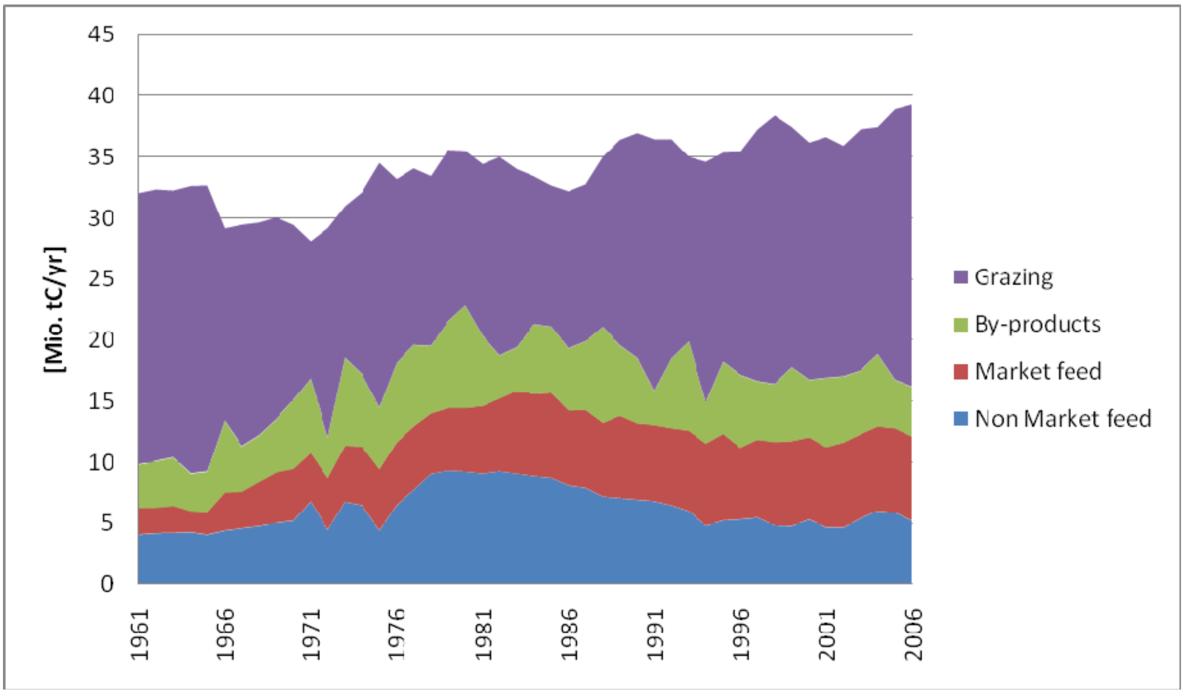
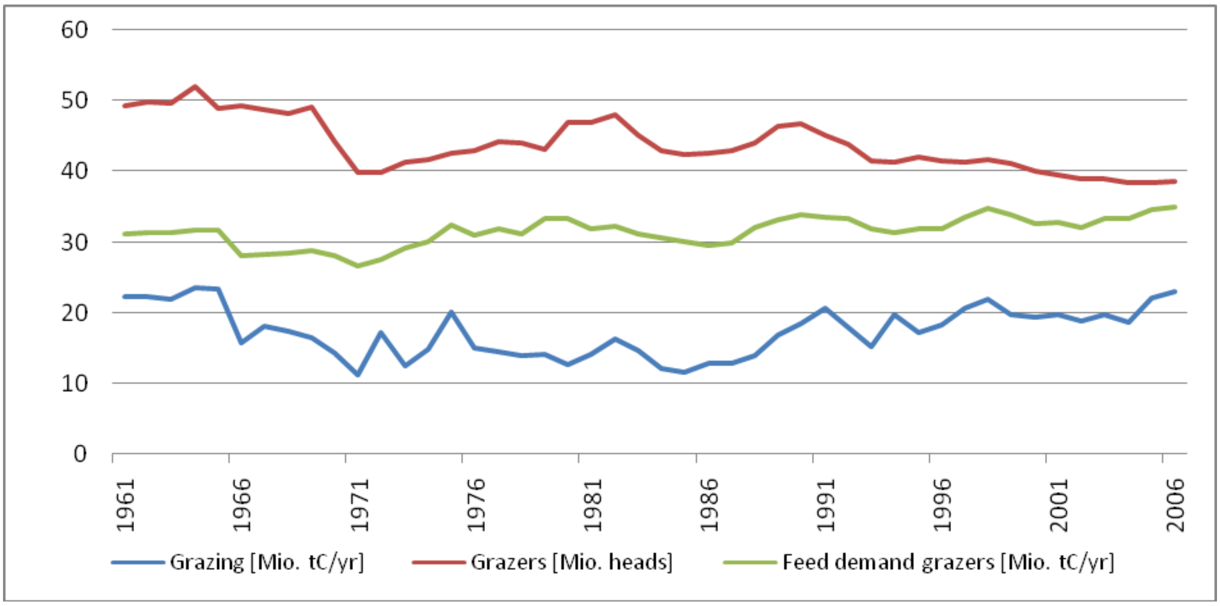


Figure 18 presents an overview of the development of grazing and its components in the RSA (livestock numbers, grazed biomass and feed demand). Although total numbers of grazers slightly declined throughout the time period, feed demand as well as grazed biomass increased. A substitution of sheep and goats with cattle that obtains a higher demand for fodder, as well as the rise in feed demand per cattle offer possible explanations for that (see figure 16 and analysis above).

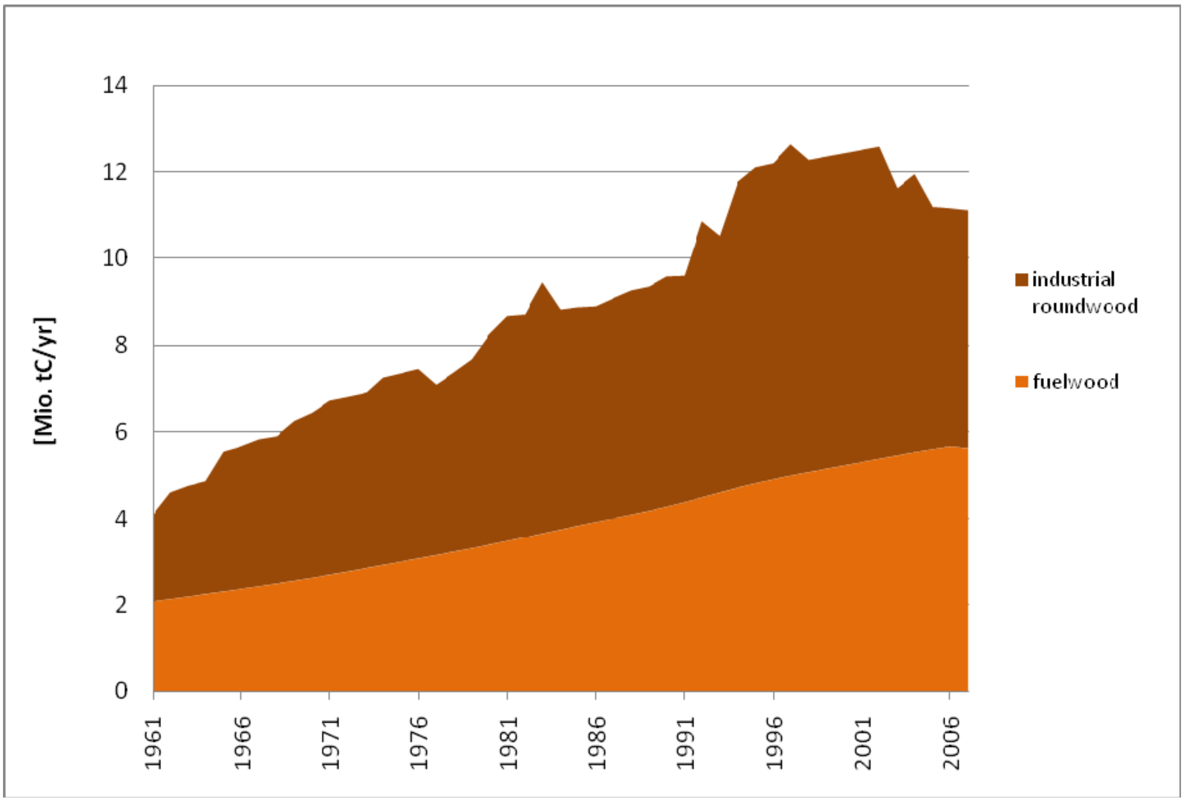
Figure 18: Grazing and its components in the RSA from 1961 to 2006



Harvest of forestry products

Wood harvest increased fourfold from 4 Mio. tC/yr in 1961 to more than 16 Mio. tC/yr in 2006 (Figure 19). As fuelwood collection was calculated as per person demand, the amount of harvested fuelwood reflects the rising population trend. Fuelwood is still the main energy source for most rural families. A report on energy policies in the RSA (IEA, 1996) suggests that still 50% of the rural households use wood as the primary energy for cooking and 58% for heating. No decrease in fuelwood consumption per head is predictable at the moment, because even if electricity makes its way to rural households, energy extracted from wood is considered a "free" ecosystem resource. Therefore, poor rural households will continue to prefer fuelwood to more expensive commercial fuels. Fuelwood collection causes major problems to Savanna-ecosystems. It is considered unsustainable, if yearly extraction of fuelwood exceeds the yearly production of woody biomass (Von Maltitz and Scholes, 1995). Savannah landscapes often suffer from losses of the woody vegetation cover, which has severe impacts on natural habitats and biodiversity. The increasing extraction of industrial roundwood (from 2 Mio. tC/yr in 1961 to around 8 Mio. tC/yr in 2001, with a slight dcline afterwards) follows the trend of expansion of forest plantations and the increasing demand for industrial roundwood in the RSA (Daff, 2005).

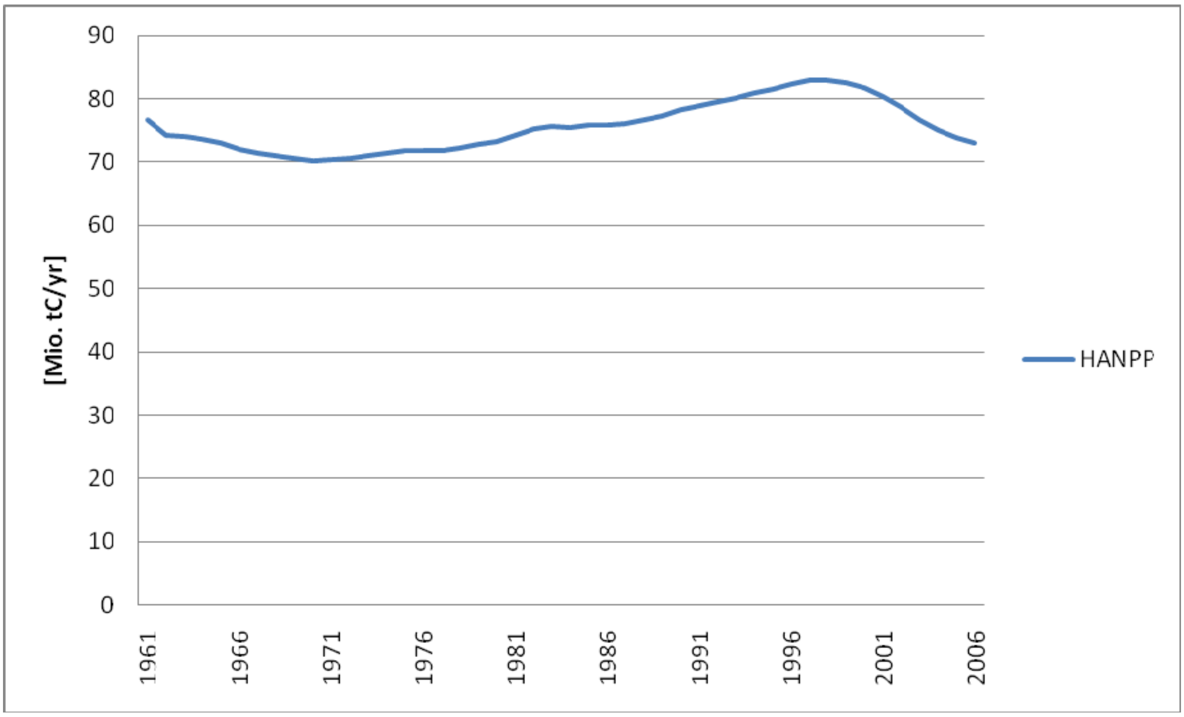
Figure 19: aNPP$_h$ of fuelwood and industrial roundwood


14
12
10
8
6
4
2
0
[Mio. tC/yr]
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
industrial roundwood
fuelwood

aHANPP

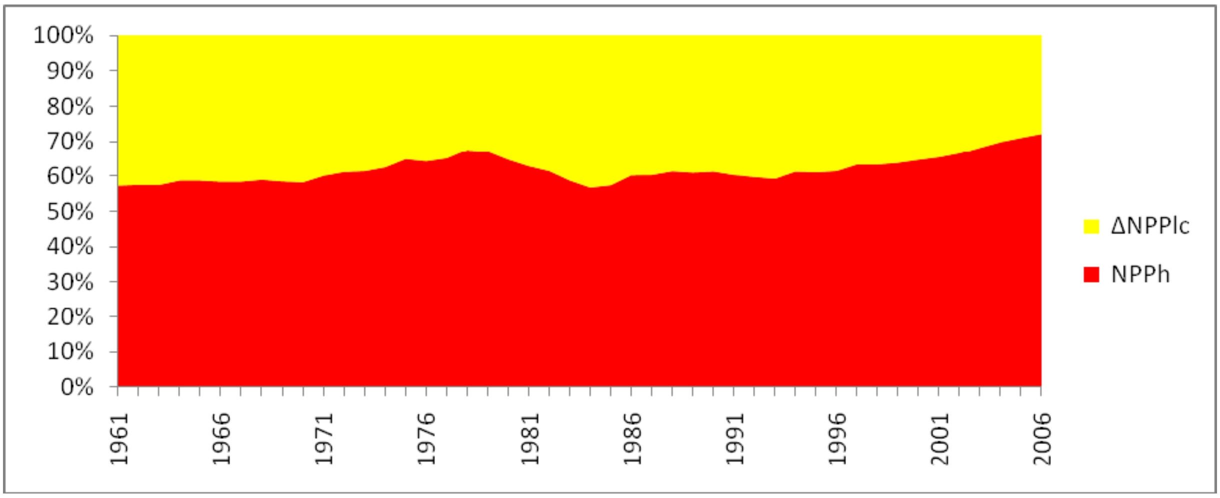
aHANPP in South Africa remained relatively constant from 1961 to 2006, the difference between 1961 and 2006 being less than 1% (Figure 20). Whereas aHANPP initially declined from 74 Mio. tC/yr in 1961 to its lowest level of 70 Mio. tC/yr in 1970, it continuously rose from 1971 to 1998, to reach its highest value of 83 Mio. tC/yr (a rise by 16%). aHANPP afterwards declined again to around 72 Mio. tC/yr at the end of the time period.

Figure 20: Development of aHANPP from 1961 to 2006



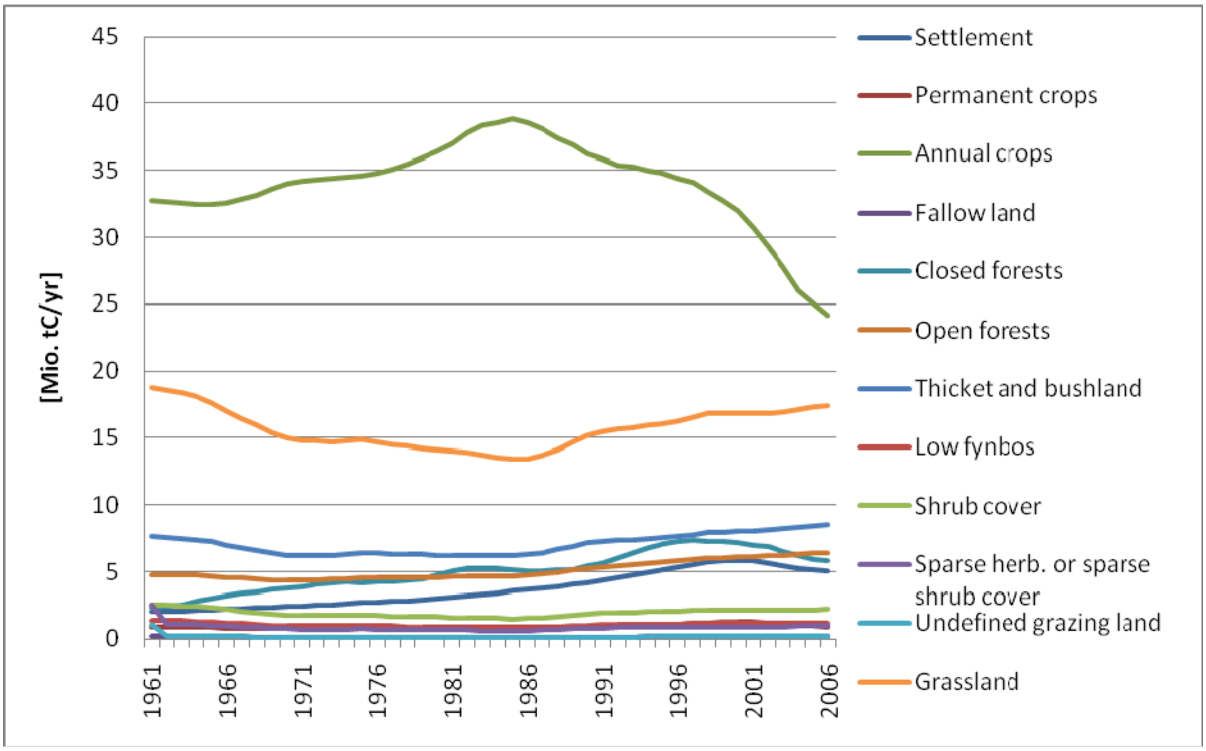
The development of aHANPP is driven more strongly by $aNPP_h$ (Figure 21) than by $\Delta aNPP_{lc}$. At the beginning of the time period under consideration and during a ten year period from 1985 to 1995 $\Delta aNPP_{lc}$ reached values around 42% of aHANPP. In the remaining years, $\Delta aNPP_{lc}$ declined, with the minimum of around 27% of total aHANPP in 2006. The low share of 33% in 1978 can mainly be explained by an overwhelmingly high productivity of annual crops (resulting in low $\Delta aNPP_{lc}$ on agricultural land).

Figure 21: $aNPP_h$ and $\Delta aNPP_{lc}$ as percentage of aHANPP



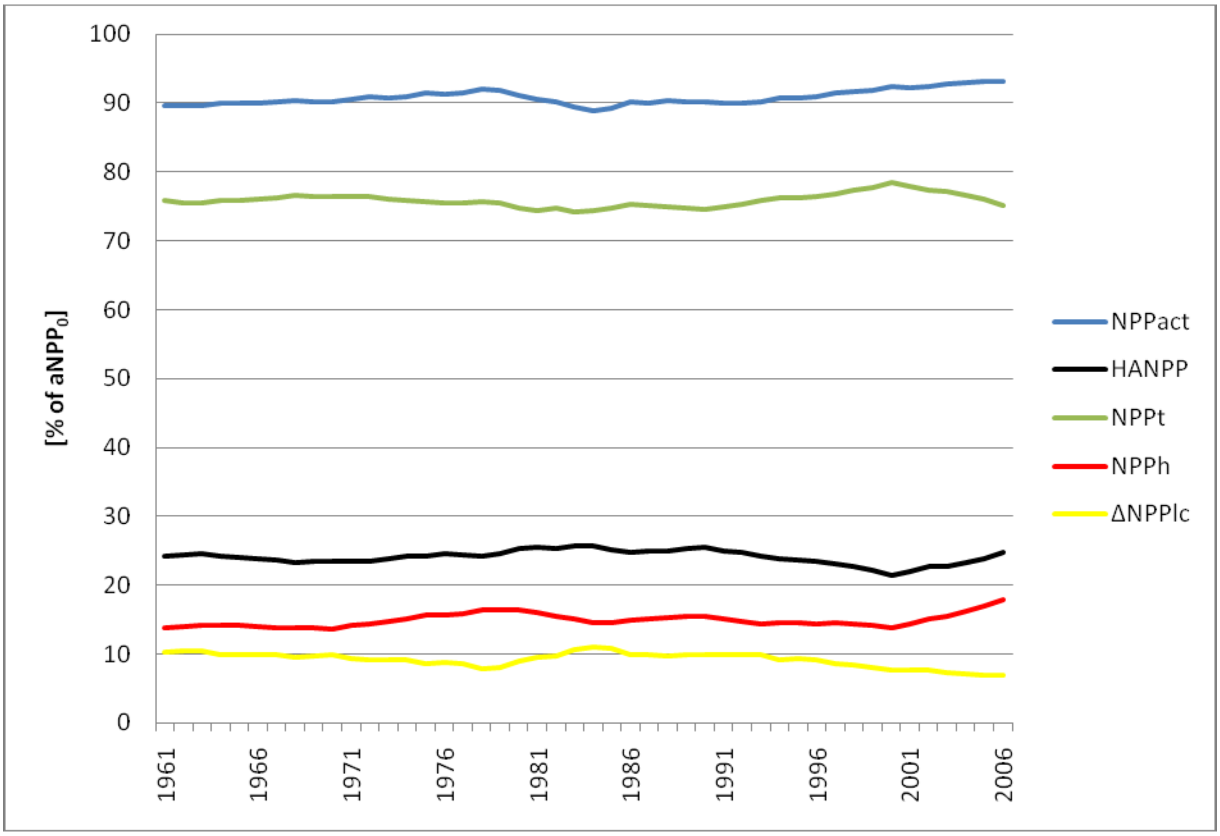
aHANPP on annually cropped land as well as on *grassland* contributes most significantly to total aHANPP. In the late 1980ies the share of aHANPP on grassland plus aHANPP on annual cropland to total aHANPP reached maximum values of around 70% (Figure 22). The reduction of aNPPh of annual crops in the 1990ies was followed by a drastic reduction of aHANPP on annually cropped land. This is also a side-effect of the decrease in annually cropped area after 1985 (Figure 5). In 2006, the lowest value of aHANPP on annually cropped land (24 Mio. tC/yr and 34% of total aHANPP) was reached. The highest value of aHANPP on grassland over the whole period under investigation was 18 Mio. tC/yr in 1961. After a period of rather low aHANPP on *grassland* from 1970 to 1986, the trend increased again to a value of 16 Mio. tC in 2006. aHANPP on *thicket and bushland*, *closed forests*, *open forests* and *settlement* exhibit increasing trends as well, but they do not contribute significantly to total aHANPP. The almost four-fold rise of aHANPP in *closed forest* was most significant among these land cover classes. Here, values increased from 2 to 7.5 Mio. tC/yr., the result of an increase in harvest of roundwood by 75% from 1961 to 2006. aHANPP values rose from 7 Mio. tC in 1961 to 8 Mio. tC in 2006 on *thicket and bushland* and from, 5 to 6 Mio. tC/yr on *open forests*. In contrast to the remaining land cover classes, these land cover categories are affected by the extraction of fuelwood and by livestock grazing at the same time.

Figure 22: Development of aHANPP on land cover classes from 1961 until 2006 in 5-year means



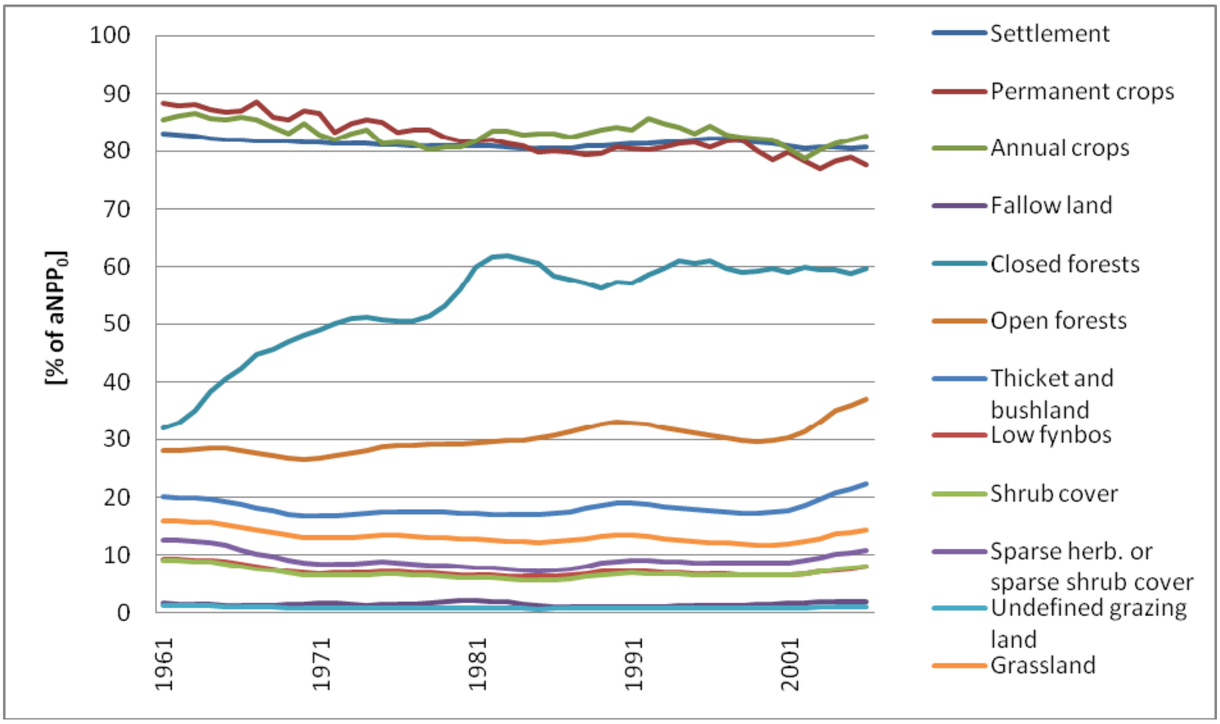
aHANPP as percentage of $aNPP_0$ only increased slightly from 24.2% in 1961 to 24.8% in 2006 (Figure 23) and remained constant over the whole period under investigation. The decline of aHANPP below 21.5% in 2000 was due to the high $aNPP_0$ in that year. $aNPP_{act}$ as percentage of $aNPP_0$ stayed at a constant high level, with only a slight increase from 89.7% in 1961 to 93.1 % in 2006. $aNPP_t$- the amount of biomass that remains in an ecosystem after harvest was between 74% and 79% of $aNPP_0$ throughout the time period. A slight decline from the late 1980-ies to the mid 1990-ies was found, but the trend rose again afterwards to reach its highest level of 78.5% in 2000. This is again, the consequence of extraordinarily high $aNPP_0$ in 2000.

Figure 23: $aNPP_{act}$, aHANPP, $aNPP_t$, $aNPP_h$, $\Delta aNPP_{lc}$ as percentage of $aNPP_0$



aHANPP as percentage of $aNPP_0$ was rather high for several land cover classes, especially for annually and permanently cropped land and for *settlement* (Figure 24) Here, aHANPP declined only slightly over the period under observation, but values remained at high levels between 80 and 90% of $aNPP_0$. As a consequence only a small share of annually produced biomass was left for other organism on annually and permanently cropped land after harvest. On *closed forests* aHANPP as % of $aNPP_0$ increased drastically from 32 to around 60% as a result of a continuous expansion of forest plantations. One reason for this is that the contribution of young forests, not yet harvestable, to total forest area was higher at the beginning than at the end of the time period observed. aHANPP in closed forests appropriated in a sustainable way usually does not exceed 50% of $aNPP_0$ (Haberl, pers. comm. 2010). Therefore there is evidence for an overexploitation of forests in South Africa. However, methodological constraints limit the justification of this assumption and for a final proof further analysis would be necessary. All remaining land cover classes followed the trend in grazed biomass, with aHANPP as % of $aNPP_0$ declining from 1970 until 1989 and with a constant development afterwards. *Open forests* and *thicket and bushland* are considered grazed, as well as severely exposed to the harvest of fuelwood. They therefore obtain high shares of aHANPP to $aNPP_0$ in comparison to the categories that are only grazed alone.

Figure 24: aHANPP as percentage of aNPP$_0$ broken down to the land cover classes from 1961 to 2006



Discussion and Conclusions

Interpretation of the results

In 2006 humans appropriated around 24% of the potential biomass available in South African ecosystems, which equals a value of 72 Mio. tC. Haberl et al. (2007) calculated the same percentage for the global average of the year 2000. 24% appear to be rather low compared to European, especially Western European countries. Schwarzlmüller (2009) reported an aHANPP level of 54% by 2003 for Spain, average Western European aHANPP values are around 46.5%. There is evidence for land degradation playing a substantial role in imposing pressure on the current productivity of South African ecosystems (Hoffman and Ashwell, 1999; Bai and Dent, 2007). However, the quantification of degradation within this aHANPP study was not accomplishable as precisely as desired due to a lack of data and adequate methods. $\Delta aNPP_{lc}$ values in the RSA are between 7 and 11% of total $aNPP_0$ and therefore go well in line with the global value of 5.2%, 7% for Great Britain and 14% in Austria (Krausmann, 2001). Compared with 24% in Spain the South African level seems rather low. $\Delta aNPP_{lc}$ is the cumulative effect of human-induced land conversion, either reducing biomass production of natural ecosystems through unsustainable ways of land use (such as overgrazing, fuelwood depletion, etc..), or, as in case of cropland, maximizing ecosystem outputs in form of anthropogenic harvest, by improving natural growth conditions through modern techniques (such as irrigation, use of fertilizers, crop breeding, etc..). However, intensification of crop production through technical modernization cannot be pursued endlessly, because also ecosystems as well as plant breeding efforts (in order to increase the harvest index of a plant) will reach a state of saturation, when it becomes impossible to absorb anthropogenic inputs anymore. In the case of South Africa, poverty is still a major factor that prohibits intensified agricultural entrepreneurship on small scale, especially in rural districts. Therefore it can be assumed that in these remote and marginal areas agricultural production is still upgradable, provided that there is access to appropriate methods to overcome dry periods. On the other hand, large scale commercial farmers, which already possess 87% of the agricultural land in the RSA, can be considered already utilizing most of the total production potential of cropland. There is evidence that in those core agricultural areas production has been highly intensified in the past (Biggs and Scholes, 2002).

Over the whole period under observation no remarkable dynamics could be identified in the picture of HANPP. However, patterns of biomass appropriation have changed over the past. In order to get a holistic picture of trends influencing HANPP in a certain period of time, trajectories of biomass appropriation have to be analyzed within the background of political economy: The Apartheid regime of South Africa with its policy of economically and geographically repressing the black population was responsible for the incapability to maintain the status of a highly developed nation and to establish the country's aspired self-sufficiency. In terms of agricultural development, economic growth and competitiveness within the international market the international sanctions against the Apartheid regime imposed severe constraints and economic isolation on South Africa. The developments finally led to the financial and economic crisis during the 1970ies and 1980ies. The following section analyzes aHANPP separately for several periods from 1961 to 2006. Furthermore it detects the correlation between the political environment and patterns of aHANPP more precisely.

The trend in aHANPP on cropland from 1961 until 1978 is related to the well performing agricultural economy of the country during that period of time. This is most strikingly visible in the drastic increase of production of annual crops and the expanding area under crop production. Making use of new and advanced cultivation methods of the green revolution and governmental subsidies on agricultural production resulted in this development (FAO, 2005). Especially around the year 1978 a peak in harvest of annual crops could be identified. aHANPP on cropland and *closed forests* rose, whereas aHANPP on grazed land cover categories declined. This is because a rise in aNPPh of annual crops implies a higher amount of crop residues available for fodder. As a consequence, demand for grazed roughage as a source of animal feed declines. The trend towards a reduction of grazed biomass was manifested in the most intensively grazed land cover class *grassland*. Under these circumstances, aHANPP steadily declined until 1978. On the other hand total economical performance in terms of GDP growth had already started to decline from 1965 onwards. GDP growth shrank from 8% in 1965 to below zero in 1977, average annual growth rates were around 4% after 1965. Reasons for that development lie in the complex economical and political system of Apartheid: The rationale of Apartheid was to geographically, politically and socially isolate the black population, through relegating blacks into the self-governed homelands. However, as the manufacturing sector, which was dominated by white entrepreneurs, expanded, huge labor shortages occurred. Although laws, restricting blacks to be employed as skilled workers in the white manufacturing systems, were consequently loosened from 1973 onwards, the situation on the labor market remained critical, segregation went on and economy could not recover. Furthermore an oil embargo, coinciding with declining GDP growth, was imposed on South Africa by the OPEC nations in 1973 (Levy, 1999). This was the onset of economic sanctions, which were aimed at economically pressurizing for an abolition of Apartheid.

The period from 1979 until 1994 (the year of the official end of Apartheid) was not only characterized by the further slow-down in economical performance, but it is also reflected in the trend of agricultural development during that time. After the peak of crop production in 1978, harvest on cropland significantly declined. This trend can probably be partly related to the oil embargo in 1973, which decreased productivity in terms of agriculture and industry (Lundahl, 1984). Furthermore this stagnation in agricultural performance is the result of the removal of governmental subsidies and the rising costs for fossil fuels and fertilizers from the early 1980ies onwards. The rising costs can be directly related to the removal of the rebate on diesel. These financial pressures combined with a protracted drought period in 1981 (FAO, 2005) limited cultivation of little productive areas. Fertilizer input declined by 30% after 1981 (FAO, 2006). Increasing debts led to foreclosures amongst farmers. Large areas of marginal cropland were taken out of crop production and reverted into natural pasture (Simbi and Aliber, 2000). Therefore, the area under crop production also shrank from 1986 onwards (Figure 5).

Due to more stringent financial sanctions from 1985 onwards South Africa faced huge losses of foreign capital, which again severely harmed economic performance. Foreign investors withdrew their investments and companies started to leave the country (Coulibaly, 2009). Consequently GDP growth declined markedly until 1993 (World Bank, 2010; the lowest growth rate of -2% during that time was experienced in 1992). In contrast to the financial sanctions trade sanctions did not reduce exports and imports during that time (Coulibaly, 2009). They rather created price distortions because of a complex system of export tariffs and import subsidies (Hèrault and Thurlow, 2009).

Rising international pressure, resistance movements within the country and the economic catastrophe finally led to the democratic opening. After officially abolishing the Apartheid regime in 1994, South Africa quickly re-entered the global market and joined the World Trade Organization. GDP growth recovered and reached a growth rate of 5% in the late 1990ies (Figure 3). However, the price distortions caused by the complex trade system of Apartheid were still prevailing (Hèrault and Thurlow, 2009) and agriculture remained under-performing. The result was an increase in poverty, especially in rural areas, where the population is highly dependent on agricultural employment. The area under crop production declined further from 1994 until the end of the investigated time period. Still, marginally productive areas are situated in the former homelands, where crop production is very sensitive to climate and soil degradation. People living in these parts of the country often prefer traditional growing techniques or otherwise have no access to fertilizers, pesticides or irrigation methods (Aliber and Hart, 2009), which makes them vulnerable to unfavourable conditions for crop growth. Nevertheless, higher crop yields in the post-Apartheid period allowed for a moderate rise in the production of annual crops. The final slight decrease in harvest of annual crops is related to drought.

Several indicators of agricultural modernization are listed in table 10 for selected years. The development of these indicators reflects the political and economical circumstances described above.

Table 10: Indicators of agricultural modernization

agricultural modernization	1961	1966	1971	1976	1981	1986	1991	1996	2001
Average yield [t C/ha/yr]	1.66	1.76	1.99	2.14	2.09	2.05	2.01	2.25	2.67
irrigated land [% of cropland]	6.27	6.88	7.68	7.74	8.54	9.02	8.22	8.86	9.53
fertilizer consumption [t/km^2/yr agric. land]	2.9	5.6	5.5	14.4	10.4	13.4	13.7	16.6	17.7
draft animals [Mio. heads]	0.86	0.66	0.47	0.45	0.45	0.45	0.45	0.47	0.43

Sources: FAO, own calculation, (World Bank, 2010)

Crop yields increased by 61% during the observed time period (from 1.66 tC/ha/yr in 1961 to 2.67 tC/ha/yr in 2001). The share of irrigated land to total cropland rose from 6.3% in 1961 to 9.5% in 2001. Consumption of fertilizers per land unit was seven times higher in 2001 than in 1961. However, the period of political and financial crisis from the late 1970ies until the early 1990ies exhibits a noticeable stagnation in these trends. Average yields as well as irrigated cropland and fertilizer consumption per unit of cropped land did not increase during that time and decreased in certain years. After an initial decline in the 1960ies stock numbers of draft animals (mules, horses, asses) remained constant. This provides evidence on the cheap labor-based economy of Apartheid. After the democratic opening of the country in 1994 these trends changed towards modernization again (expansion of irrigated land, increasing yields and fertilizer consumption, declining number of draft animals).

Per capita values of aHANPP rapidly declined from 4.1 tons of Carbon per capita and year in 1961 to 1.5 tC/cap/yr in 2006, a decrease of 60%. This is due to a relatively constant level of total aHANPP compared to the massive population growth from 18 to 49 mio. between 1961 and 2006 (see introduction, figure 3). This, however, does not necessarily indicate a proportional increase in land use efficiency or a reduction in per-capita consumption. Analyses of trade flows of South Africa reveals that the decrease of aHANPP/cap/yr can be rather explained by steep rise in imports of goods of the export-oriented economy. Total imports of agricultural biomass increased 13-fold, from 0.4 mio. tons dm per year in 1961 to 6.4 mio. t dm /yr in 2006. Agricultural exports, instead, only grew by a factor 2, from 2.4 mio tdm/yr to 5.5 tdm/yr. Import quantity per person increased from 0.02 t/cap/yr (five-year means from 1961 to 1965) in the early 1960s to around 0.12 t/cap/yr at the end of the investigated time period, while biomass exports decreased from 0.17 to 0.12 t/cap/yr in the same period of time (FAO, 2010). In contrast, exports of forestry products increased drastically from 0.1 to 5. mio. t, while imports only grew from 0.5 to 1.1 mio. t, resuling in significant net-exports.

The amount of imported biomass does not contribute to aHANPP, as HANPP studies only take biomass flows on a defined area, in our case the territory of South Africa, into account. On the contrary, increasing import dependency can be a means to reduce domestic HANPP levels or weaken trajectories that would result in surges of HANPP, because biomass does not have to be produced domestically. In the last decades, South Africa has become a huge importer of agricultural biomass, meaning that its biomass consumption causes NPP appropriation in other countries of the world. The import dependency, of course, closely relates to issues of vulnerability and represents a crucial sustainability challenge for South Africa.

Limits of the study

Due to a lack of data and appropriate methods regarding some aspects of land transformation and carbon flows this study was not able to analyze aHANPP in the RSA as precisely as desired. Two of these aspects are quickly discussed below. With respect to various authors, who have contributed a wide range of scientific research on these fields, it has to be mentioned that high-quality data is available for some points of the recent years. As this study investigates human-induced land use change in a decadal time series, these data sets cannot be applied accurately in this specific context of aHANPP.

Degradation

Land degradation in South Africa turned out to be a rather controversial topic. Several studies consider land degradation a substantial factor for the decline in productivity in South African ecosystems (Hoffman and Ashwell, 1999; Bai and Dent, 2007). Others confirm that human land use, such as overgrazing, plays a crucial role in pressurizing the intactness of ecosystems, but they also point out that no major decrease in ecosystem functions was detected in the past for several study sites mapped as degraded (Wessels et al., 2004; Palmer and Ainslie, 2007). However, it was problematic to find country-specific studies offering quantitative holistic approaches for land degradation. As $\Delta aNPP_{lc}$ values caused by degradation never exceed a level of 13 Mio. tC/yr, there is still a chance for the impact of degradation on biomass production being underestimated in this study. In comparison to the aHANPP trend, which follows a pathway between 70 and 83 Mio. tC/yr, 13 Mio. tC/yr are of limited quantitative importance with respect to the overall result, but still this is a substantial magnitude. Furthermore, there is evidence that I may not have succeeded in appropriately quantifying degradation caused by desertification mainly due to huge discrepancies in quantifying impacts of desertification (Thomas and Middleton, 1994; Nicholson et al., 1998).

Human induced fires

In this study human induced fires could not be considered in the aHANPP calculation. This is mainly due to the fact that it was not possible to quantify the actual contribution of anthropogenic fires to total fires. Archibald et al. (2010) outlined that South African fire regimes are human-driven, in a way that human dominated landscapes show a decline in burnt area fraction as well as fire size. This would rather support a negative aHANPP calculation resulting in a decrease in total aHANPP, which is however not feasible due to a lack of quantitative data on that topic. Within the *South African Greenhouse Gas Inventory*

(UNFCCC, 2009) an eight year remote sensing data set (2000-2008) was analyzed in terms of fire occurrence in different South African ecosystems without distinguishing between human induced fires and fires triggered by lightening. Calculating burned biomass by applying this data set suggests that approximately 9 Mio. tC/yr are burned each year, which would increase aHANPP by around 12% annually. However, as only the biomass burned in human-induced fires is relevant for aHANPP, this figure was not included in my aHANPP calculation.

Further research fields

For further studies on biomass flows in South Africa it would be necessary to develop appropriate assessments on the quantitative impact of human induced fires, as well as quantitative studies on land degradation and its effects on productivity of ecosystems. Furthermore game farming, as a relatively new industry sector, has been gaining more attention in the last years. Due to poor data availability it was not possible to analyze the contribution of production of game meat in the RSA to total aHANPP for the whole period under observation. For now traditional livestock still covers almost the entire anthropogenic need for animal protein, but as the demand for game meat in the national and international market gets stronger, new consequences for South African production systems will arise.

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Annex A

Annex A provides additional figures with results of the aHANPP calculation broken down to the five main land use categories: grazing land (containing *grassland, shrub cover, low fynbos, sparse herbaceous and sparse shrub cover, thicket and bushland*), forest land (containing *closed forest and open forests*), cultivated area (containing *fallow land* and annual and permanent cropped land), settlement area and *unused/ unproductive land*. As aHANPP values for the single land cover classes are often based on rough assumptions, it can be more trustful to investigate the results of aggregated land cover classes. Some additional figures on aHANPP and its components are added here as well.

Figure 25: Land cover change from 1961 to 2006 in 5-year means

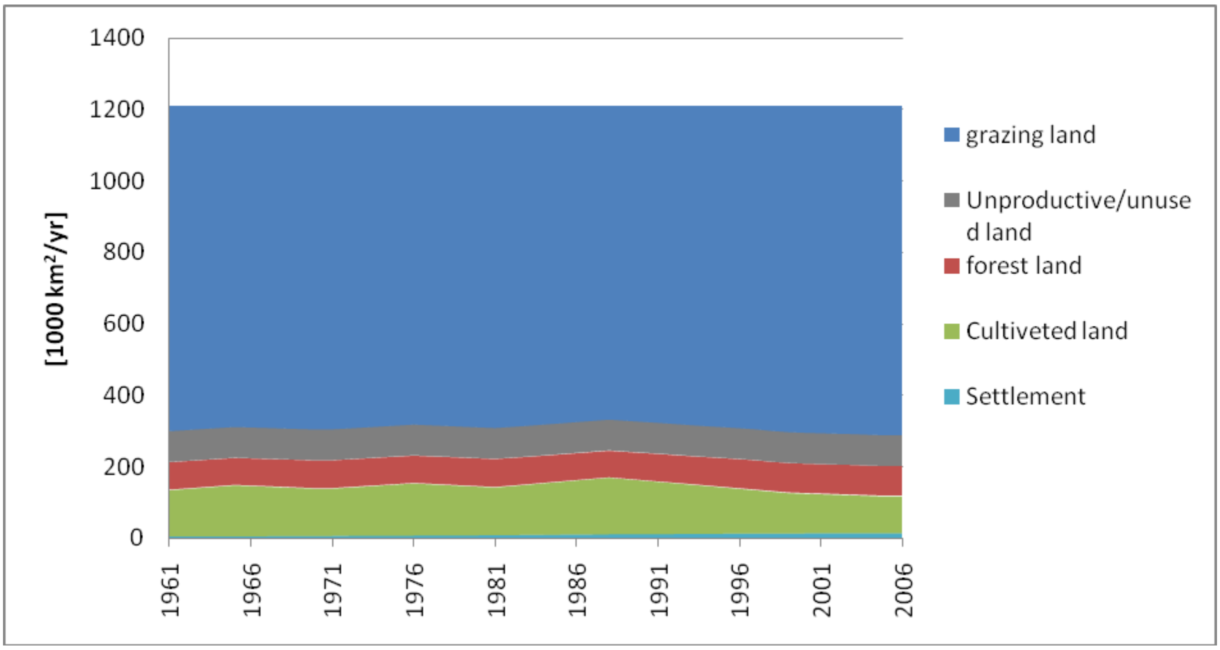


Figure 26: $aNPP_0$ from 1961 to 2006 in 5-year means

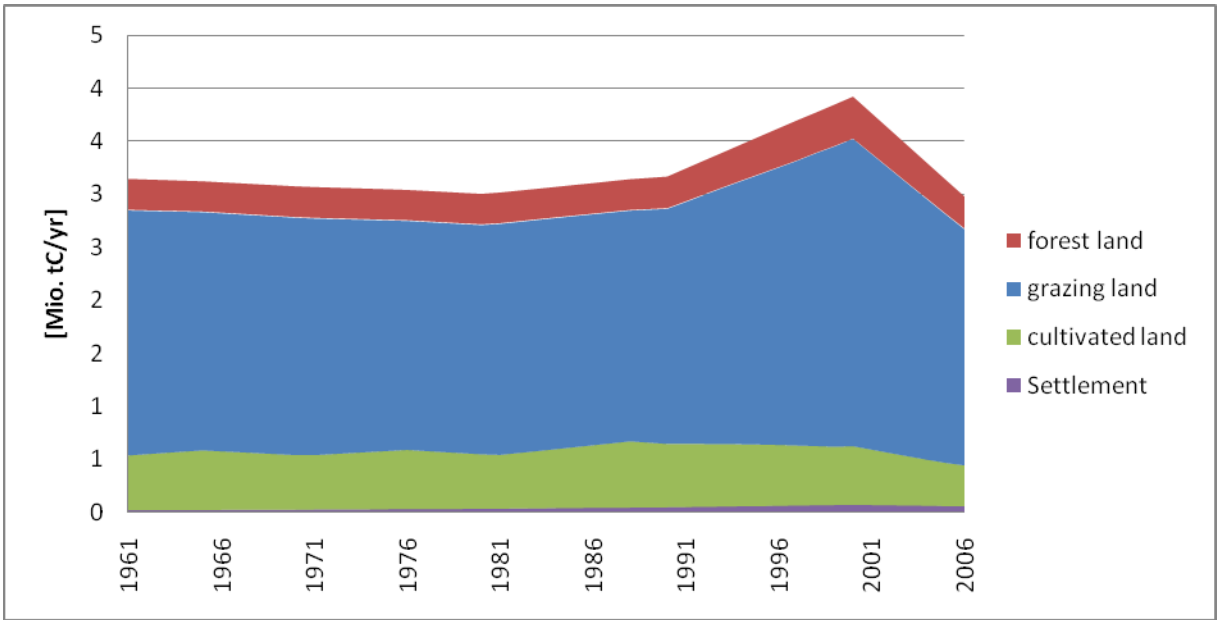


Figure 27: $aNPP_{act}$ from 1961 to 2006 in 5-year means

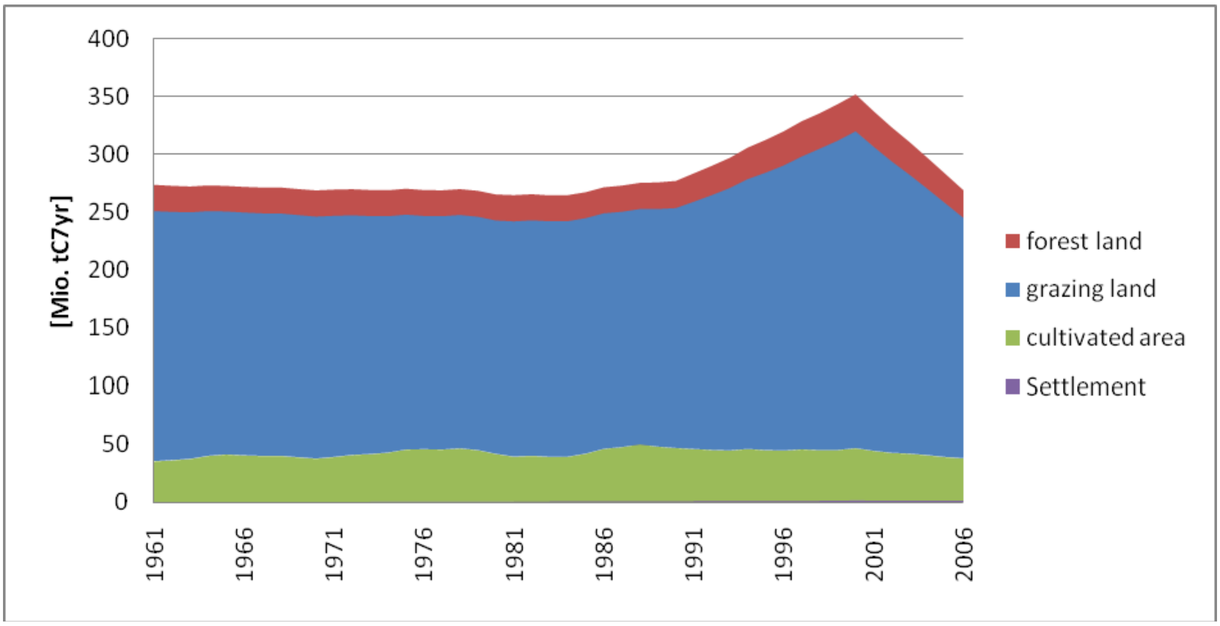


Figure 28: aΔNPP_{lc} from 1961 to 2006 in 5-year means

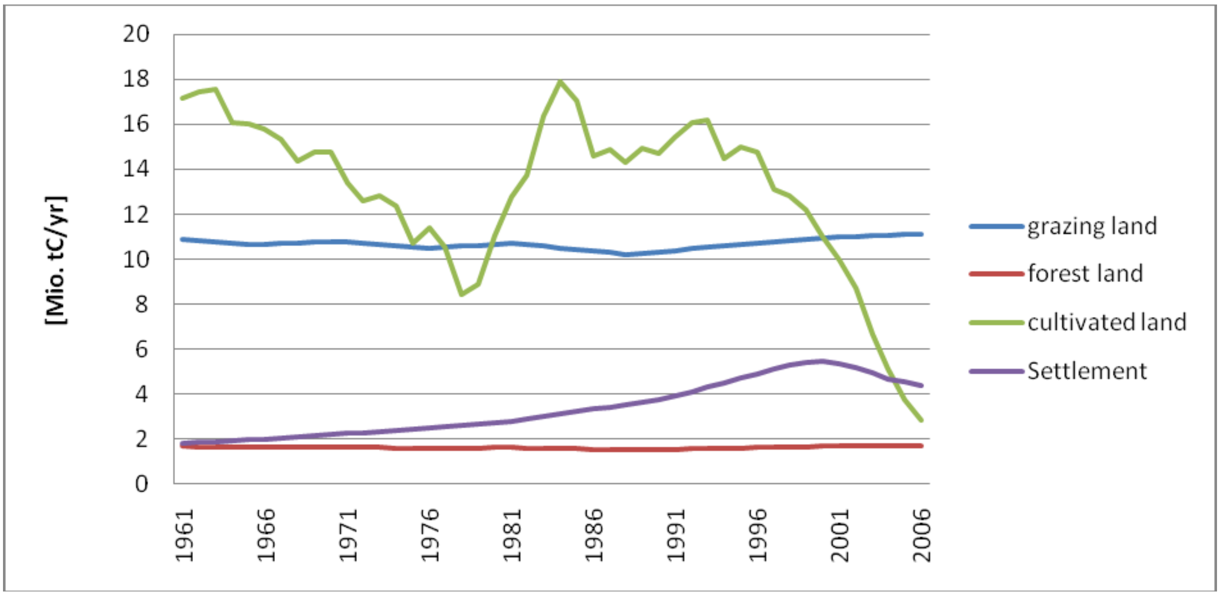


Figure 29: aNPP_h from 1961 to 2006 in 5-year means

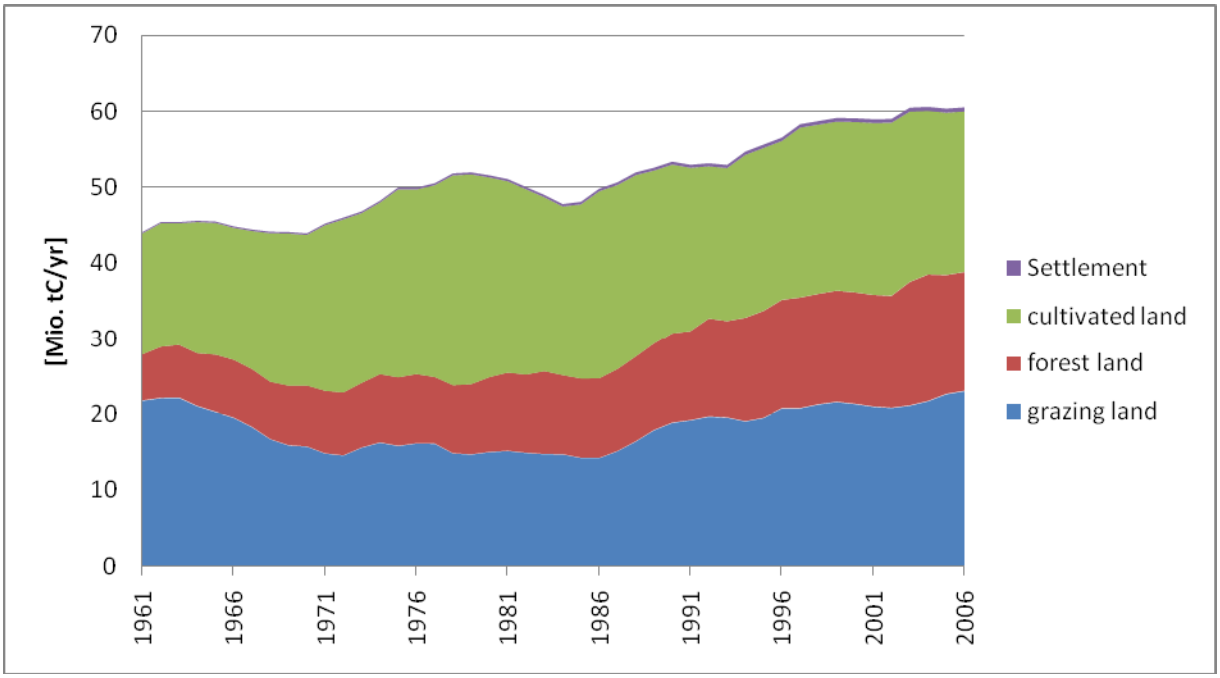


Figure 30: aNPP$_h$/km^2 land use class in from 1961 to 2006, presented in 5-year means

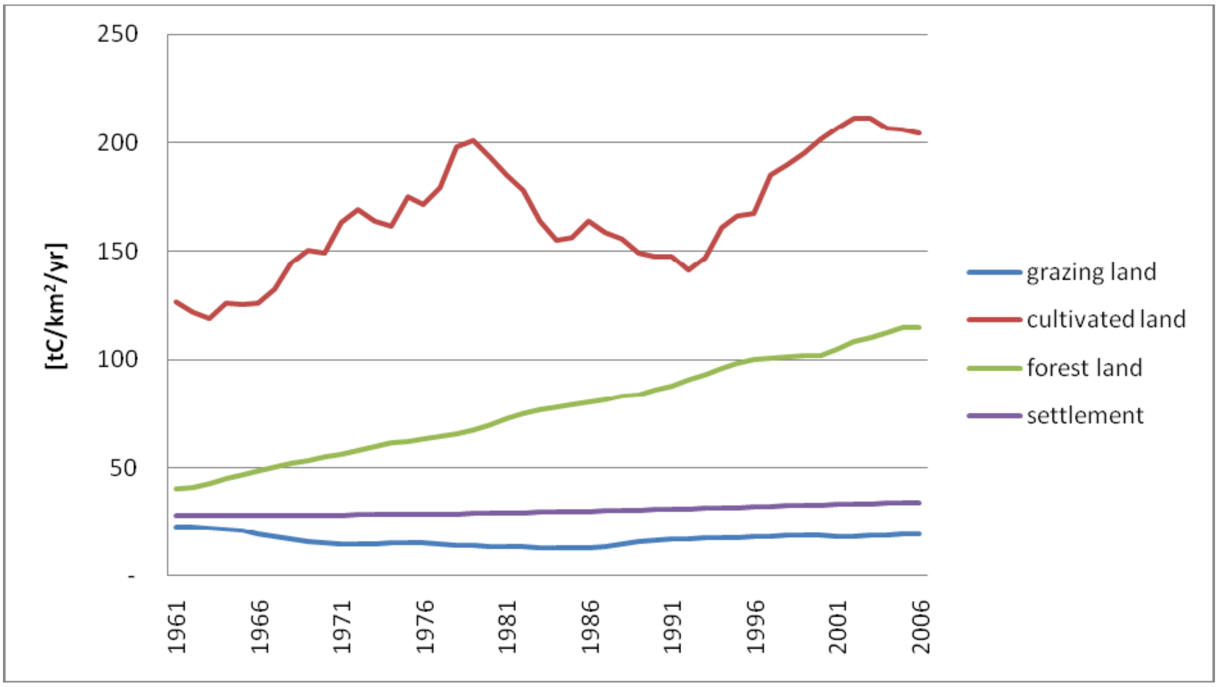


Figure 31: aHANPP development from 1961 to 2006 in 5-year means

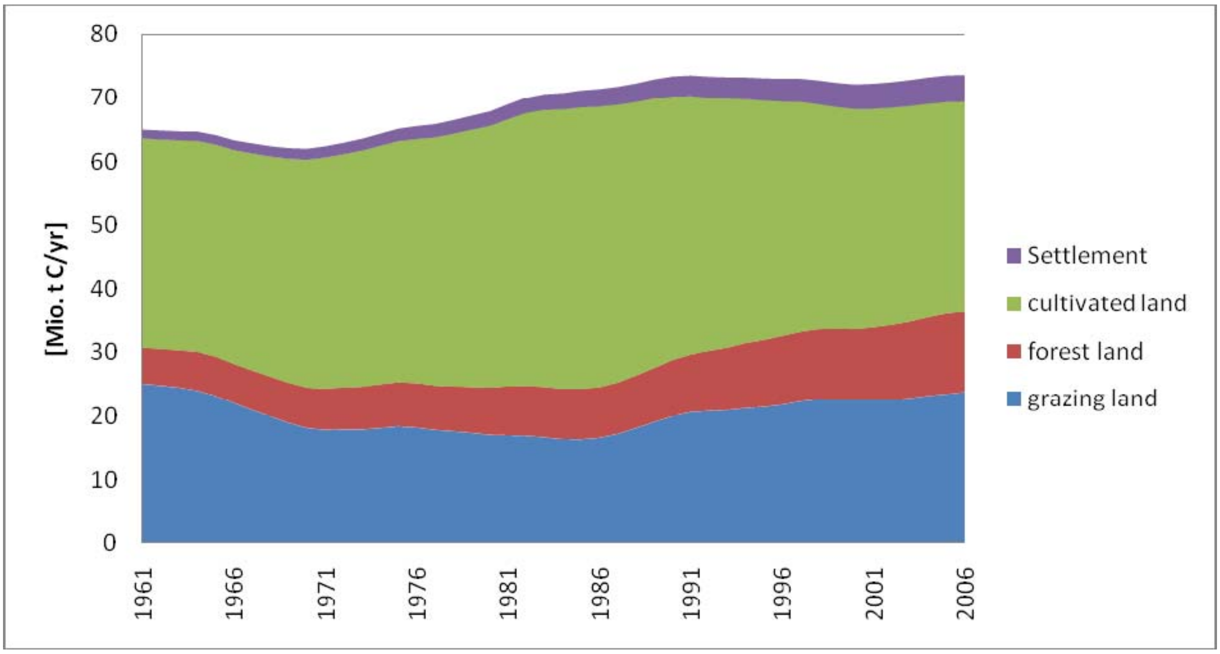


Figure 32: aHANPP as percentage of $aNPP_0$ from 1961 to 2006

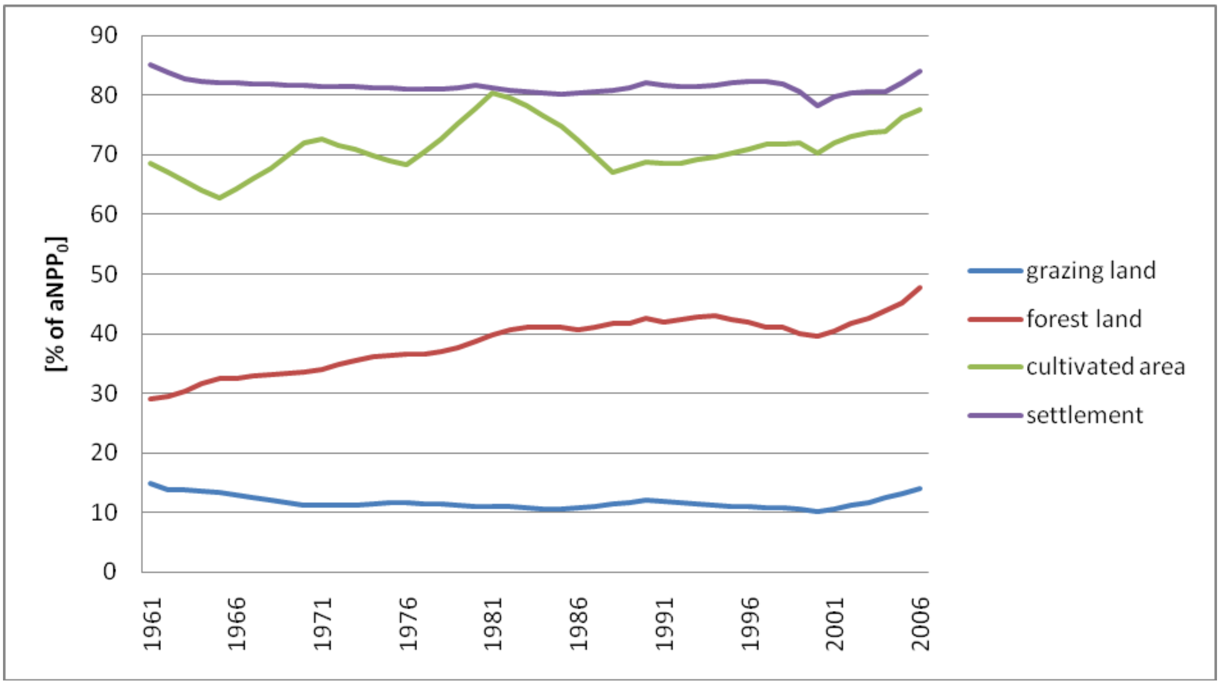
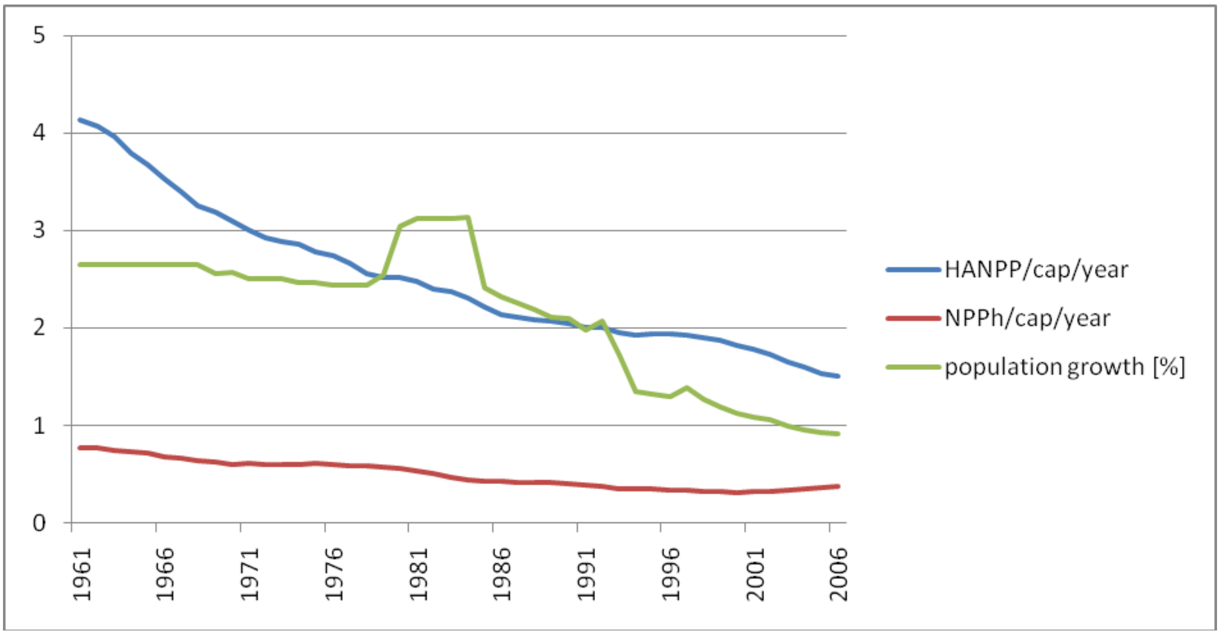


Figure 33: aHANPP/cap/yr, $aNPP_h$/cap/yr and population growth in percent from 1961 to 2006



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