Modeling Carbon Sinks and Sources in semi-arid Environments for a Land Degradation Assessment Approach

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Abstract

Contrary to wetlands or moderate climates, the understanding of carbon exchange between ecosystem and atmosphere in arid and semi-arid environments is more challenging due to the sensible feedback of terrestrial ecosystems to environmental variability. Especially in the savannah regions of South Africa the biomes are strongly affected on the one hand by low and sporadic precipitation and on the other hand by intense land use of livestock farming. This leads to wide degraded areas under the process of desertification and the loss of huge carbon stocks in soil and vegetation. To quantify the carbon sinks and sources in these regions we ran our dynamic vegetation model BETHY/DLR for South Africa which generates maps of Net Primary Productivity, NPP, in spatial resolution of 1 km. These results can help assessing the status and development of land degradation for the whole country of South Africa.

1. Introduction

Land degradation in arid or semi-arid areas is affected by different components from biophysical and socio-economic factors (Hoffman and Todd 2000). Soil degradation is mainly caused by wind and water erosion as well as soil acidification and salinisation. The degradation in vegetation is driven by the loss of cover, change in species composition, alien plant invasion, bush encroachment and deforestation. Intense livestock farming also contributes significantly to the encroachment of the regional vegetation (Perkins and Thomas 1993, Dougill et. al. 1999)

The challenging but crucial assessment of the desertification process in African regions has already been subject of several scientific investigations (Abel and Blaikie 1989, Ringrose et. al. 1999, Stringer and Reed 2007; Wessels et. al. 2004, 2008). Most of these activities have been on a regional scale and addressed only for single biomes. So there is still lack of a national attempt for the assessment of land degradation in southern Africa concerning the variety of biomes in the country.

Generally the first problem for land degradation assessment is an objective definition of the term ‘land degradation’ itself. In the United Nations Convention to Combat Desertification (UNCCD), composed in 1994 by an Intergovernmental Negotiation Committee (INCD), land degradation is defined as the ‘reduction or loss, in arid, semi-arid and sub-humid areas, of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as:

(i) soil erosion caused by wind and/or water;
(ii) deterioration of the physical, chemical and biological or economic properties of soil; and
(iii) long-term loss of natural vegetation;' (UNCCD 1994)

They further defined desertification as the 'land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities'. In principle land degradation is correlated with a loss of biological and economical productivity due to soil erosion, salinization, crusting, loss of soil fertility or depletion of seed banks. The vegetation cover especially its biodiversity and/or its density (LeHouerou 1996) are influenced. For Syrian dry lands Evans and Geerken (2004) developed an approach to distinguish for semi-arid areas between climate and human-induced degradation. Low annual rainfalls of less than 200 mm and high inter-annual variability determine the climate of Syrian dry lands. On the other side, semi-nomadic herders move to these areas to graze animals and to cultivate barely.

Instead of facing all the patterns of a definition for land degradation, as described by e.g. the UNCCD (1994), the study of Hoffman and Todd (2000) attempted to reflect people's perception of the status of the environment in areas they are working in, like agricultural extension officers or resource conservation technicians. From a survey, carried out for the 367 magisterial districts of South Africa, they could elaborate a map showing the incidence of land degradation for the whole country, with KwaZulu-Natal, Limpopo and the Northern and Eastern Cape being mostly affected.

A quantitative method for assessing actual land degradation using remote sensing data was tested by Wessels et al. (2008). The authors tested the "local NPP Scaling (LNS) method, where the growth season sum NDVI (∑NDVI), a surrogate for productivity, of each pixel was expressed relative to the highest values (90th percentile) of ∑NDVI observed in all pixels falling within the same land capability unit (LCU)." They concluded that "the LNS method is a valuable tool for mapping land degradation at a regional scale".

Instead of using NDVI sums it will be possible to derive a scaling method where the productivity of the plants is applied as a measure for desertification. With our dynamic vegetation model BETHY/DLR the Net Primary Productivity (NPP) is derived from satellite and meteorological data sets. Values of NPP in arid and semi-arid areas can be an indicator for degraded land. Further development of the NPP values over several years can be used to assess the process of land degradation in these areas. The following descriptions are especially concerned with the desertification problematic in South Africa.

2. Model description

The dynamic vegetation model BETHY/DLR (Biosphere Energy Transfer Hydrology Model) (Wisskirchen 2005), is a modification of the JSBACH (Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg) (Knorr 1997) scheme which is included in the ECHAM5 (the HAMburg version of the ECMWF model) global atmosphere circulation model (Roeckner et. al. 2003). There it is used for calculating the contributions from the biosphere-atmosphere exchange. At the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR) BETHY/DLR is driven for simulations of the carbon exchange and the water balance between biosphere and atmosphere. For this study the model was adapted for drought conditions and specific biomes in arid and semi-arid areas.

We are computing the Net Primary Productivity (NPP) for different regions on regional to national scales. The model is driven by remote sensing data and meteorological input data on a spatial resolution of 1 km in time steps of one hour. (See Figure 1 for a schematic overview of the used input data and internal model processes.)

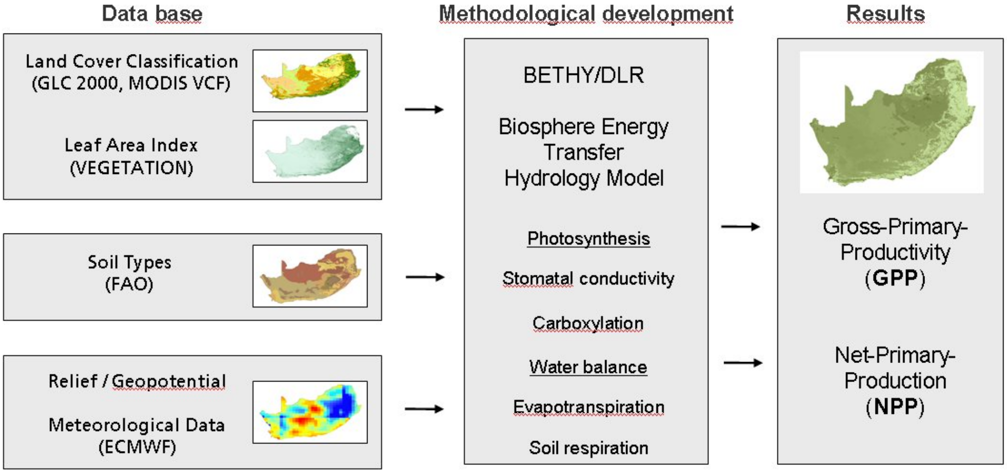

Figure 1: Model Scheme: Input database, model components and results

The BETHY/DLR model uses a two-flux scheme to approximate the radiation absorption in the canopy. Photosynthesis is integrated using a combined approach of Farquhar (1980) and Collatz (1992). The enzyme kinetics, which are parameterized on leaf level, are distinguished to C3 and C4 plants. This is important, since C3 and C4 plants have significant differences in their way of carbon-fixation. C4 plants are highly adapted to hot and dry conditions as they can be found in southern Africa.

In a second step the photosynthesis rate is extrapolated from leaf to canopy level, taking into account both, the canopy structure as well as the interaction between soil, atmosphere and vegetation. Stomatal and canopy conductance, evapotranspiration and soil water balance are included. Water stress is considered by calculating the demand for evapotranspiration using the Penman-Monteith approach (Monteith 1965) against the Federer (1979) criteria which assumes that evapotranspiration cannot be greater than a certain soil water supply via roots.

The output is given by time series of NPP in daily steps with the resolution and projection of the land cover classification (1 km x 1 km, latitude – longitude projection with WGS84 (World Geodetic System 1984) datum).

The driving parameters of the BETHY/DLR model are two sets of remote sensing data (derived from SPOT-VEGETATION), meteorological data (provided by the European Centre for Medium range Weather Forecasts, ECMWF) and further dataset concerning i.e. soil type information and altitude.

Time series of the Leaf Area Index (LAI) are used to initiate the phenology of vegetation. They are based on CYCLOPES 10 day composite datasets, which can be downloaded from the POSTEL (Pole d'Observation des Surfaces continentales par TELedetection) databank. For each pixel a time series analysis has to be applied in order to eliminate data gaps and outliers (see Figure 2).

For the purpose of this study the method of the harmonic analysis (HA) is used. The HA belongs to the method of "least squares", whose most famous member is the Fourier transformation. At DFD this method is used for operational processing the Global Ozone Monitoring Experiment (GOME) (Dech 1998). It was adapted for the use of LAI data.

The CYCLOPES dataset also provides information of land cover and land use and is available as Global Land Cover 2000 (GLC2000). The Land Cover Classification System (LCCS) of FAO of the United Nations was used for the derivation of the GLC2000 (Bartholome et al. 2002; DiGregorio and Jansen 2001). With GLC2000 a classification with 22 different land cover classes is available which is representative for the year 2000. The global CYCLOPES and GLC2000 data are each available in tiles of 10° x 10° as maps in rectangular projection with an information of latitude and longitude with WGS84 date.
In order to make the GLC2000 usable for NPP modelling with BETHY/DLR, the 22 GLC2000 vegetation classes have to be translated to the actual 33 inherent BETHY/DLR vegetation classes, which can be regarded as vegetation types. Each vegetation type is linked with biochemical parameters as e.g. the maximum carboxylation rate or the maximum electron transport rate representing light and dark reaction of photosynthesis. The parameterisation of BETHY/DLR allow translating one GLC2000 class to fractions of two vegetation types, using the fraction of cover information provided by the MODIS Vegetation Continuous Fields (MODIS-VCF) product.

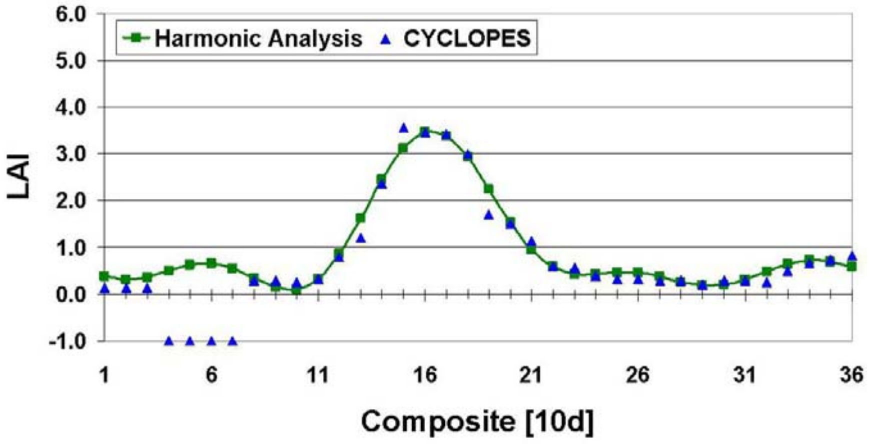

Figure 2: LAI plot representing arable vegetation. The CYCLOPES data (blue) show gaps that need to be filled by applying the Harmonic Analysis to produce a continuous set of 36 reliable LAI values (green) for one year of simulation.

In addition to remote sensing data BETHY/DLR needs meteorological data input. The ECMWF provides the needed data in a spatial resolution of 0.25° x 0.25° with a temporal resolution of up to four times a day. These are model analysis of 2 m air temperature, wind speed at 10 m above ground, the soil water content of the four upper layers and cloud cover. Daily values of precipitation are derived from the ERA40-reanalysis. From this the daily mean, minimum and maximum of temperature are calculated, as well as the daily mean of cloud cover over all three strata (high, medium and low) and the water vapour pressure. The daily temperature values are scaled with the difference of ECMWF and ETOP-elevation and the temperature gradient of the U.S. Standard Atmosphere, which is -0.65 K per 100 m.
The daily average of photosynthetic active radiation (PAR) is determined from global radiation. This is calculated with the approach taken by Burridge and Gadd (1974) from Stull (1988). The idea is to take the

geographical coordinates of the day and year, and a transmission, which depends on the degree of cloudiness. Daily average of cloud cover is calculated as weighted sum of each cloud strata. Global radiation is calculated for each location in the time step of one hour. The volumetric soil water content is only needed for initializing the soil water budged of the model. Afterwards it is calculated independently, according to the hydrological boundary conditions. Investigations of Wisskirchen (2005) have shown that in general a transient phase of one year is needed to reach equilibrium. In the current version stable conditions are determined dynamically.

With this model we are able to simulate the development of sinks and sources for carbon depending on the geographical and meteorological conditions of the considered region. Further development of the model, which includes the implementation of a phenology model, allocation schemes for the distribution of carbon fixation in plants and finally a method for data assimilation, will lead us to predict the future distribution of carbon sinks and sources. In this context our focus will be on future land use/land cover changes, especially regarding land degradation in semi-arid areas.

3. Results

One main result of our simulations for this study is an annual map for South Africa (including Lesotho and Swaziland) showing yearly NPP sums for each pixel, representing one square kilometre. Figure 3 shows this map for the year 2003.

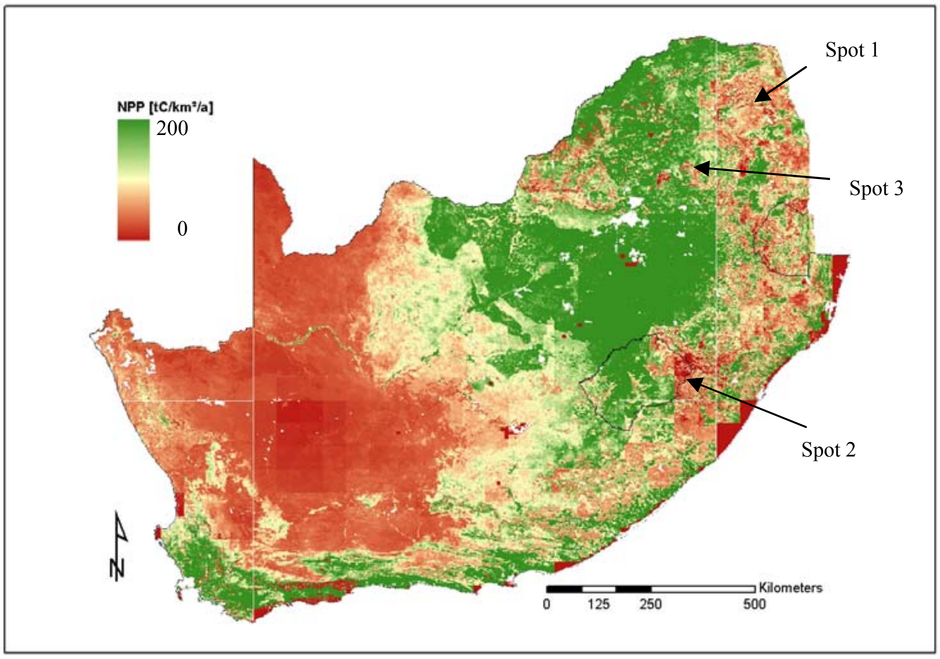

Figure 3: Map of annual NPP sums for the year 2003. Values are reaching from 0 (red) to 200 (green) tC/km²/a.

For the following discussion of the results, three single spots are chosen, which generally represent the values and distributions in the surrounding region with comparable climatic and vegetative conditions. There are low values about several tons of carbon, per square kilometre and year, denoted in red, mean values of about 100 tC/km²/a in sandy colours and higher values of 200 tC/km²/a and above are shown in green. The latter high values are mostly coupled with arable land use (as in the regions near Pretoria and Johannesburg) or dense forest areas (as along the southern coastal line). There is a decline from the east to the west to mean values in Free State and North West, and to low values in Northern and Western Cape. This distribution is correlating with the distribution of precipitation rates, which is the one reason for sparse vegetation in the eastern part of South Africa. It can also be seen the transition from high to lower productivity crossing the Drakensberge from west to east reaching the savannah regions in Kruger National Park.

In Figure 4 the distribution of the NPP is shown for the vegetation period of 2002/2003 for two spots (depicted in Figure 3) in western South Africa, for deciduous broadleaved trees in Swaziland (left; spot 2) and deciduous shrubland in Limpopo (right; spot 1).
The important input values are precipitation rates, the LAI and mean temperature distribution. These data turn the balance for the plant being a weaker or stronger carbon sink. Using the LAI for information about the health and growth status is also important for distinguishing between different plant types. The heterogeneity in the NPP values e.g. in the district of KwaZulu-Natal or Limpopo, where precipitation rates are high, can be ascribed by the different LAI distributions of the various plant types.

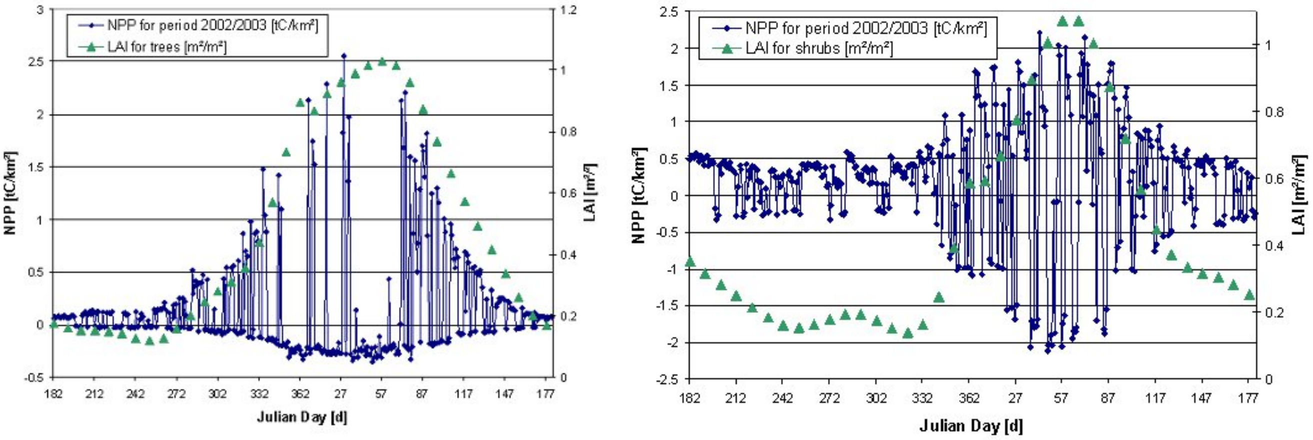

Figure 4: NPP (blue) and LAI (green) distributions for the vegetation period 2002/2003 for two spots representing deciduous broadleaved trees in Swaziland (spot 2, left) and deciduous shrubs in the Limpopo region (spot 1,right).

The amplitude of the LAI for e.g. deciduous broadleaved forest in spot 2 is comparable to the one for deciduous broadleaved shrubs in spot 1 (Figure 4). But the width of the distribution in spot 1 is nearly half the one in spot 2. This means the period of high productivity is much longer for trees than for shrubs in these spots. Figure 4 also shows the close correlation between the LAI input data and the model results for the NPP which can be seen as long as enough water is available to the plants. Water limitation plays a major role, where precipitation events are rare and not equally distributed over the years. This is the case for the drylands in the Northern Cape at the Namibian border.

Looking at a typical scene which is defined as degraded area (spot 3, classified as grassland) by the National Land Cover map for South Africa we see decreased plant activity with lower annual NPP sums, compared to the spots 1 and 3, over several years (see Figure 5).

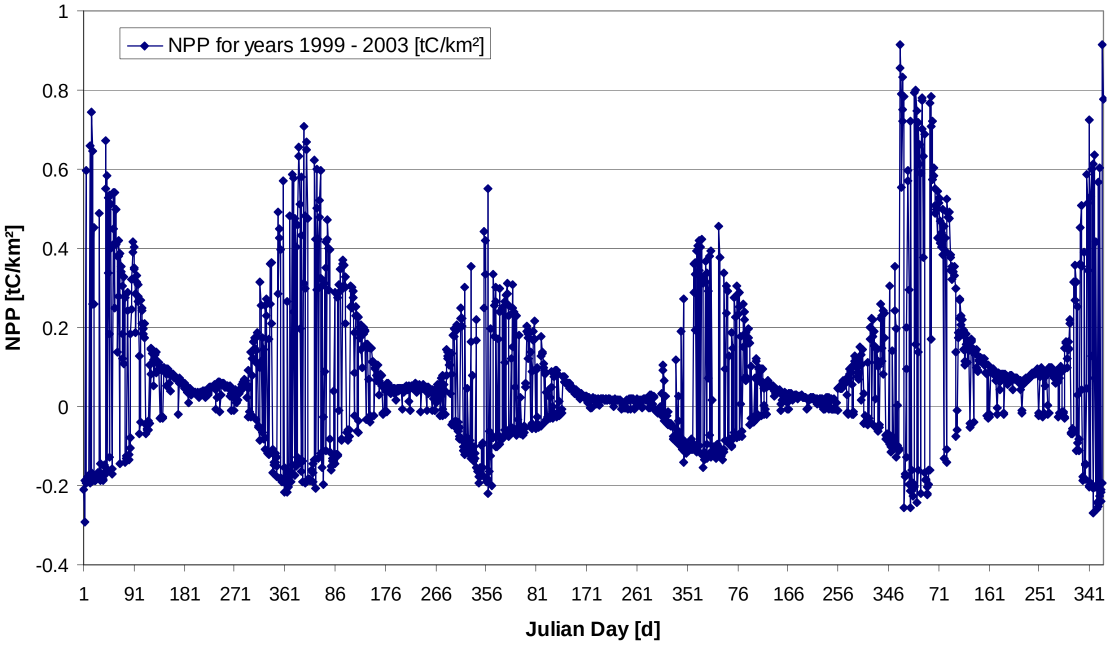

Figure 5: NPP distribution for spot 3, grassland, for the years 1999 – 2003.

These areas can be marked with a high potential for degradation. In the distribution of the NPP over the years 1999 – 2002 there is a significant decline that can also be seen in the sums over the vegetation periods of these years (1999/2000: 28.9 tC/km²/a, 2000/2001: 13.5 tC/km²/a, 2001/2002: 9.8 tC/km²/a). So this can be taken as indicator for ongoing desertification in this region. But looking at the last period 2002/2003 there is a sudden increase of productivity (48.2 tC/km²/a) that can be linked with variable climatic conditions over the years. So it has to be stated that a time span of fife years is obviously not enough to significantly follow a possible process of desertification, but the results can be a starting point for further investigations at those spots.

Since the CYCLOPES data is now available for additionally four years, 2004 – 2007, we will have nearly one whole decade for modelling the biomass change in our next simulation runs and additional simulations will hopefully deliver more advancing insight to this opportunity for a degradation assessment.

4. Discussion

For modelling carbon sinks and sources of vegetation, one needs to consider the important influences of input data on the results of the simulations. For the inhomogeneous conditions found in arid and semi-arid regions there are at first the annual precipitation rates as well as the distribution of rain events over the vegetative phases of the plants. Where enough water is available for the plants the next important variable is the leaf area index for the different vegetation types in the considered area. Further the temperatures in the considered areas are crucial for the plants, whether they are adapted well to those conditions or not.

With our dynamic model, we are able to simulate the vegetative phases of the plants on a national scale, depending on regional climatic and meteorological conditions, for the various plant vegetation types. Using annual NPP sums and the distribution of biomass productivity over several vegetative periods it would be possible to define a scheme for the assessment of land degradation in arid regions. This would make it possible to quantify the further development of the status of the vegetation, whether land degradation is continuing, remaining static or is decreasing.
Next versions of our model will include a phenology scheme for the computation of plant development together with a data assimilation procedure for LAI or FAPAR data. This will allow us to even forecast future changes in vegetation status and health assuming certain scenarios of climatic variations and land use change.

5. Acknowledgement

This research project is funded by the Network EOS – Integrated Earth Observation System PhD program. Thanks are given to ECMWF and MediasFrance for providing their data.

6. Literature

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