Using Remote Sensing to Model Carbon Source/Sink Dynamics in the Sahel

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Abstract - Recent research has identified the grasslands of the Sahel as a potential carbon sink, but regional carbon stock accounting in such biomes is undermined by the poorly recognized role they play in the carbon cycle as well as lack of data. In this paper, we demonstrate the feasibility of coupling the satellite data-driven light use efficiency model (Lund University Light Use Efficiency Model - LULUE) with Roth-C, a dynamic model that estimates the turnover of carbon in non-waterlogged soils for a 10560 km^2 test area in the Sahel. LULUE is used to estimate the rate and amount of carbon drawdown into the vegetative carbon pool while Roth-C is used to estimate soil respiration from a number of well-defined pools, ranging from labile to inert. Running the ensemble requires the parameterisation of Roth-C using NPP from LULUE, with the aid of a land cover/use map. The result is an estimate of NEP (Net Ecosystem Production). Our results show that total annual area-averaged NPP ranges from 1.8 tCha^{-1} in 1987, to 4.1 tCha^{-1} in 1992, and increases steadily throughout the period (r^2 = 0.44). Total annual area averaged soil respiration ranges from 2.5 tCha^{-1} in 1986, to 5.0 tCha^{-1} in 1993, with no appreciable trend observed. Our NEP trend analysis (r^2 = 0.14) suggests that this ecosystem became a carbon sink around 1994 with a total 5.14 tCha^{-1} sequestered throughout the period. This approach holds promise for quantifying carbon sink/source dynamics in a spatially explicit manner for grasslands, though a full sensitivity analysis should be implemented before geographically extending the method.

Keywords: remote sensing, carbon stocks, Sahel, carbon dynamics, light-use efficiency, Roth-C

1. INTRODUCTION

Recent research suggests that the grasslands of the Sahel may be a sink for carbon. For the period 1982-1999, Eklundh and Olsson (2003) identified geographically extensive positive trends in vegetation greenness for the region using smoothed NDVI (Normalized Difference Vegetation Index) time series (Jönsson and Eklundh, 2004) derived from the NOAA AVHRR Pathfinder Land Data Set (Smith et al., 1997). In 2001, Schimel et al. reported that the large CO_2 source from tropical deforestation cannot be detected using atmospheric inverse model calculations. Rather, their estimates fluctuated around null alluding to the presence of a sink that at least partially counteracts this source. The identification of regional carbon sinks for tropical grasslands is undermined by the poor understanding of the role of grasslands in the global carbon cycle, as well as lack of data available to accurately characterize them (Scurlock and Hall, 1998; Verburg et al., 2004).

To partially address this issue, Seaquist and Olsson (2004) used the Lund University Light Use Efficiency (LULUE) model to provide a map of the increase in net carbon storage for the Sahel biomass pool (net primary production – NPP) for 1982-1999. Their estimate of 0.051Gt C yr^{-1} did not differ substantially between the 1980s and 1990s, and comprises about 3% of the total tropical carbon uptake, and 12.5% of the net tropical carbon sink. But for tropical savannah ecosystems, about 80% of the total organic matter resides in the soil. It is therefore important to estimate soil respiration so that the Sahel's role in the tropical carbon budget can be contextualized with confidence. Ardö and Olsson (2003) also point out that such modelling experiments are in the interests of assessing carbon sequestration potential of grasslands for climate change mitigation. The use of satellite data with point-based soil carbon turnover models will add a large degree of spatial heterogeneity beyond traditional land cover maps.

In this paper, we couple LULUE with Roth-C, a model that estimates the turnover of C in non-waterlogged soils, for a 10560 km^2 test area in the central part of the Sahel for the period 1982-1999. The resulting time series of net ecosystem production (NEP) is analyzed and discussed.

2. METHODS

2.1 LULUE

LULUE is a light use efficiency model especially tailored to grassland biomes. This class of model encapsulates the essence of the plant growth process at an aggregate level; solar radiation is absorbed by plants to provide energy for photosynthesis, while soil moisture controls the efficiency of light usage. The foundations of the approach were established by Monteith (1972);

$$NPP = \left(\sum_{i=1}^{n} \varepsilon p \times \varepsilon \times (a \times NDVI + b) \times PAR \right) \times RESP \qquad (1)$$

where;

NPP = Net Primary Production summed over the growing season (tCha^{-1})
ε_p = maximum biological efficiency of PAR conversion to dry matter (tCMJ^{-1}ha^{-1})
ε = environmental stress scalar (water use efficiency)

$$NDVI = \frac{NIR - RED}{NIR + RED} \text{ (unitless)}$$

PAR = Incoming Photosynthetically Active Radiation ($MJha^{-1}$)
a, b = regression coefficients
RESP = Growth and maintenance respiration ($tCha^{-1}$)

LULUE is implemented on a quasi-daily time step, after which results are summed to monthly or growing season totals. A complete description of LULUE is given in Seaquist et al. (2003). For the current paper, we applied LULUE to estimate the rate and amount of carbon drawdown into the vegetation carbon pool in terms of NPP on a monthly basis. Smoothed NDVI observations from the NASA/NOAA Pathfinder AVHRR Land (PAL) Data Set are used to parameterize the model. Other inputs included monthly rainfall totals (interpolated), mean monthly temperature (interpolated), a cloudiness layer from the Pathfinder data set (CLAVR – Clouds from AVHRR) and water holding capacity from the Soil Map of the World (FAO/UNESCO, 1995).

2.2 Roth-C

Roth-C is a soil carbon turnover model originally developed for temperate crops that has been tested and validated for semi-arid grasslands (Kirschbaum et al., 2001). In Roth-C, plant matter enters the soil via litter fall. Part of this plant material is returned to atmosphere via CO_2 (soil respiration), having previously passed through a number of soil compartments including inert organic matter, easily decomposable plant material, resistant plant material, microbial biomass, and humified organic matter. Carbon balance in the soil is a function of percent clay, crop cover, soil depth, type of plant, evaporation, soil temperature, and the decay rate constant for each compartment. Roth-C requires easily obtainable monthly climate drivers (pan evaporation, mean air temperature, and total rainfall). Management parameters include the timing and amount of litter input, manure input, and crop rotation. A complete description of Roth-C is given in Jenkinson (1990) and Coleman and Jenkinson (1995).

2.3 Coupling LULUE to Roth-C

Linking the two models was carried out in a FORTRAN 90 environment. Due to computational demands, we chose a small test area bounded by 12.06°N and 12.86°N and 7.83°E and 9.00°E. For the 8 km pixels in the PAL Data Set, this corresponds to an area of 10560 km^2 (15 x 11 pixels). Before Roth-C could simulate conditions for 1982-1999, it was run to equilibrium using long term climate means. For the period 1982-1999, running the ensemble required the parameterization of Roth-C with the following surfaces from LULUE; NPP, Priestley-Taylor-derived potential evapotranspiration (in lieu of pan evaporation), mean monthly temperature, total monthly rainfall, and fraction of vegetation cover (computed from the NDVI). A land cover map with the IGBP legend derived from the Africa Land Cover Characteristics Data Base, v. 2.0 (USGS, 2003) enabled simple management information to be passed to Roth-C on a per pixel basis. Using the IGBP land cover legend as a guide, 79% of the area was indicated as cropland, 19% grassland or savannah, 1.2% woody savannah, while the rest was urban. Due to lack of detailed knowledge about the area, a simple scheme was used to guide the amount of carbon partitioned between vegetative pools, as well as their transfer to residue (Table 1) (Huggett, 1993). For all classes, the transfer of NPP to litter was assumed to occur in November of each year. The savannah and grassland classes were assumed to consist of 20% and 5% tropical forest, respectively. Net ecosystem production for every cell was then computed as follows;

$$NEP = NPP - RESP_s \tag{2}$$

where;

NEP = Net Ecosystem Production ($tCha^{-1}$)
NPP = Net Primary Production ($tCha^{-1}$)
$RESP_s$ = Soil respiration ($tCha^{-1}$)

Table 1. Scheme for partitioning carbon between compartment, and transfer to litter (based on Huggett, 1993).

NPP C Partitioning	Trop For.	Grass-land	Crop-land
Leaves	0.3	0.6	0.8
Branches	0.2	0.0	0.0
Stems	0.3	0.0	0.0
Roots	0.2	0.4	0.2
Transfer of C to Litter			
Leaves	1	1.0	1.0
Branches	0.1	0.1	0.1
Stems	0.033	0.02	0.02
Roots	0.1	1	1
NPP to Litter	0.350	1	1

3. RESULTS AND DISCUSSION

Our results show that total annual area-averaged NPP ranges from 1.8 $tCha^{-1}$ in 1987, to 4.1 $tCha^{-1}$ in 1992, and increases steadily throughout the period (r^2 = 0.44) (Figure 1). Total annual area averaged soil respiration ranges from 2.5 $tCha^{-1}$ in 1986, to 5.0 $tCha^{-1}$ in 1993 with no significant trend observed (Figure 2). Our NEP trend analysis (r^2 = 0.14) suggests that this ecosystem became a carbon sink around 1994 with a total 5.14 $tCha^{-1}$ sequestered throughout the period (Figure 3). Total, area-averaged NPP for the period is 58.7 $tCha^{-1}$, while $RESP_s$ yields 63.8 $tCha^{-1}$. All three metrics exhibit considerable inter-annual variability.

We interpret these results with caution. That an increasing trend in NPP exists for the study area is not surprising, since this pattern has already been identified for much of the Sahel (Seaquist and Olsson, 2004). That $RESP_s$ does not change in step (in either direction) with NPP, leads to the observed trend in NEP. Though both LULUE and Roth-C have been validated elsewhere, they have not been validated for this specific region, either separately, or together. Even if trends in these variables were correctly identified, the timing of the switch from carbon source to sink may be an artefact of the way the ensemble has been parameterized. Uncertainties in $RESP_s$, NPP, or both will naturally lead to large uncertainties in NEP. Roth-C was fed with generic and highly simplified land management (according to IGBP land cover class) for both the equilibrium phase of the run, as well as for the 1982-

1999 period. The land cover map (USGS, 2003) is derived from 1992-1993 NOAA AVHRR data and has an overall accuracy of 83% which is only valid for that one year period. A full sensitivity test must be conducted on the ensemble, especially with regard to management information to assess the impact on the results. Janek et al. (2002) found Roth-C to be most sensitive to variations in resistant plant material pool size, decomposition rates, the variables associated with plant inputs, and extreme rainfall events for Australian conditions. Moderate sensitivities could be expected from the humus decomposition rate and the inert organic matter pool. The effects of grazing and fire remain unknown. Seaquist et al. (2003) reported that NDVI and the water stress factor (ratio of actual to potential transpiration) are the variables to which LULUE is most sensitive.

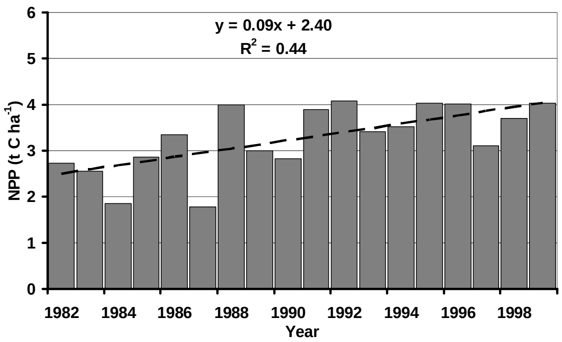

Figure 1. Yearly NPP variations for extent of NOAA AVHRR record with regression line.

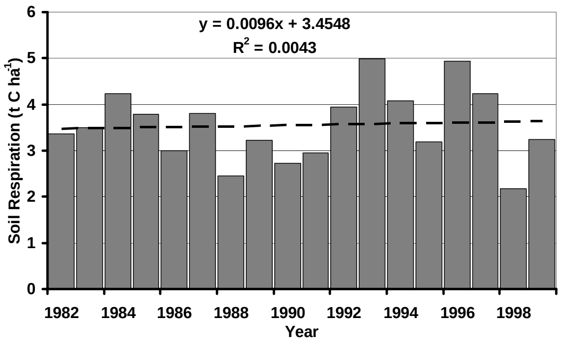

Figure 2. Yearly soil respiration variations for extent of NOAA AVHRR record with regression line.

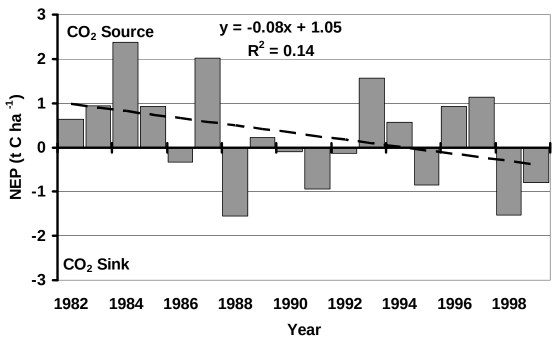

Figure 3. Yearly NEP variation (inverted) for extent of NOAA AVHRR record with regression line.

4. CONCLUSIONS

We have established a framework for coupling a satellite-data driven light use efficiency model (LULUE) to a point-based soil decomposition model (Roth-C) for a grassland biome. We tested the ensemble for a small area in the Sahel, and despite relatively high inter-annual variability in output parameters, our results suggest that this ecosystem may have become a carbon sink during the 1990s. We advocate extreme caution in interpreting this result due to inherent uncertainties and assumptions in model parameterization and lack of a validation exercise. Our approach has merit because it lends a degree of spatial heterogeneity from remote sensing for the computation of NEP that is not possible with conventional land cover or soil maps. Our approach holds promise for quantifying carbon sink/source dynamics in a spatially explicit manner for the Sahel. This will highlight geographical patterns connected to specific mechanisms of carbon exchange. Future work will include expanding the study area to the entire Sahel for the NOAA AVHRR record and undertaking a full sensitivity analysis.

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