Estimation of Net Primary and Net Ecosystem Productivity of European terrestrial ecosystems by means of the C-Fix model and NOAA/AVHRR data

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ABSTRACT

Assimilation of atmospheric carbon by terrestrial ecosystems is driven by photosynthesis. However, respiratory processes re-emit part of this gross CO₂ uptake. Depending on the balance between uptake and release, vegetation can act as carbon sink or source. The monitoring of carbon dynamics at the ecosystem level thus is a crucial issue in studies of global change – nowadays a lively environmental and political issue. The C-Fix model, presented in this paper, is based on an elementary Monteith-based formulation of Gross Primary Productivity, remotely sensed fAPAR and standard meteorological inputs. This allows to estimate the temporal evolution and geographical distribution of carbon fluxes relevant to the carbon balance. The possibilities offered by the C-Fix model are demonstrated with its application for the European continent, using a one-year series of NOAA/AVHRR images (January 1997 - December 1997). Validation is performed by comparing the model outputs with field measurements for two Euroflux test sites.

KEYWORDS: Carbon fluxes, Net Ecosystem Productivity, fAPAR, Remote Sensing, NOAA / AVHRR

1. INTRODUCTION

The net balance of assimilation and respiration of atmospheric carbon dioxide, is measured in detail at specific forest sites in Europe by means of eddy covariance techniques. However, such point measurements are costly and difficult to extrapolate in space and time. To obtain spatially explicit information on carbon exchange or to estimate a continental scale carbon budget, models can be used. Quite often these models rapidly become very complex and require lots of input parameters, which are hardly available on a regional or continental basis. The gap between both strategies (point measurements and regional modelling) can partially be bridged by the use remote sensing imagery, registered by earth observation platforms.

The C-Fix procedure, presented by Veroustraete et al. (1994), quantifies carbon fluxes on a regional and continental basis, by combining a simplified carbon exchange model with satellite observations. The key element in this approach is that the evolution of the biophysical state of the vegetation is directly inferred from space born observations, and hence no longer has to be estimated by model applications.

C-Fix was applied with reasonable success on the Belgian territory using NOAA/AVHRR images of 1990 (Veroustraete et al., 1996). The model was also applied on the European continent, using a one-year series of NOAA/AVHRR images (April 1992 - March 1993) (Sabbe et al, 1999).

2. DESCRIPTION OF THE C-FIX MODEL

This paragraph briefly summarises the C-Fix model. For a more detailed description we refer to Veroustraete et al. (1994, 1996). For a given image pixel location, the model uses the following equations to estimate three types of fluxes of the carbon balance (all in [g C/m²/d]) on a daily basis:
Gross Primary Productivity: \( \text{GPP}_d = S_{g,d} \cdot f_{\text{APAR},d} \cdot F_d \cdot C \) \hspace{1cm} (1)

Net Primary Productivity: \( \text{NPP}_d = \text{GPP}_d \cdot (1 - A_d) \) \hspace{1cm} (2)

Net Ecosystem Productivity: \( \text{NEP}_d = \text{NPP}_d - R_d \) \hspace{1cm} (3)

\( \text{GPP}_d \) represents gross uptake of carbon (expressed as carbon) by photosynthesis. \( \text{NPP}_d \) accounts for the autotrophic respiratory losses, which are mainly related to the conversion of glucose into more complex photosynthates and the maintenance of standing phytomass. Finally, \( \text{NEP}_d \) includes soil respiration losses \( R_d \), by heterotrophic decomposition of soil organic matter. Average values are then derived by numeric integration over the days in the considered period (one year typically).

In equation (1), the approach of Kumar and Monteith (1981) to estimate \( \text{GPP} \) is formalised. \( S_{g,d} \) is the daily incoming global solar radiation, \( f_{\text{APAR}} \) is the fraction of incoming PAR (Photosynthetically Active Radiation: 400 – 700 nm) which is absorbed by the vegetation. \( F_d \) expresses the (non-linear) dependency of GPP on the daily mean air temperature formalised according to Wang (1996). The factor \( C \) takes into account, dry matter conversion efficiency, the proportion of PAR to global radiation and a \( \text{CO}_2 \) fertilisation factor.

The autotrophic respiratory fraction \( A_d \) in equation (2), is modelled as a simple linear function of daily mean air temperature \( T_d \), according to the parameterisation of Goward & Dye (1987). For the sake of simplicity, other effects such as the dependency of maintenance respiration on the amount of living phytomass, is neglected. \( C\text{-Fix} \) accounts for the impact of temperature on the soil respiratory flux \( R_d \), induced by heterotrophic decomposition of soil organic matter. \( R_d \) is determined by a parameterisation based on the \( \text{CO}_2 \) flux measurements as performed in the Euroflux network for different sites in Europe for 1997.

The model has the merit of simplicity, and for its application only requires the input of the daily values of three parameters: \( f_{\text{APAR},d} \), global incoming solar radiation \( S_{g,d} \), and mean air temperature \( T_d \).

\( f_{\text{APAR}} \) data are derived from remote sensing imagery, registered by optical sensors with high temporal frequency, such as NOAA / AVHRR or SPOT4 / VEGETATION. The pixel size of these images, about 1 km², also determines the spatial resolution of the \( C\text{-Fix} \) outputs. For each registration date, an image with NDVI-values (Normalised Difference Vegetation Index) can be computed from the reflectances in the red and near infrared (NIR) wavelength bands: \( \text{NDVI} = (\text{NIR}-\text{RED})/(\text{NIR}+\text{RED}) \). As suggested Myneni and Williams (1994), NDVI and \( f_{\text{APAR}} \) are strongly linearly correlated. The meteorological input variables are obtained from WMO meteorological stations, distributed over the region of interest (ROI).

3. DATA SETS

The 1997 NOAA / AVHRR imagery used in this paper to demonstrate \( C\text{-Fix} \) application was obtained from the DLR (Deutsches Zentrum für Luft- und Raumfahrt) in raw image level1b format and was pre-processed to European wide multitemporal decadal NDVI composites with the Vito NOAA pre-processing chain (Veroustraete et al., 1999). Out of this huge data set, 12 separate European NDVI-composites covering the period from January 1997 till December 1997 were calculated. These are then converted into as many \( f_{\text{APAR}} \)-raster pixel values with the linear \( f_{\text{APAR}}\text{-NDVI} \) function. Daily \( f_{\text{APAR}} \)-values are subsequently derived by linear interpolation of monthly mean values.

The meteorological inputs (daily incoming global radiation and mean air temperature) are obtained from about 800 weather stations administered by the World Meteorological Organisation. They are distributed homogeneously over the ROI. Since direct physical measurements of incoming global radiation for Europe are sparcely available, a semi-empirical approach was used to estimate this variable, validated with physical measurements (for Belgium only). The Supit or extended Hargreaves formula (Supit et al., 1998), gives incoming daily global radiation [MJ.m².d] as a function of cloud cover and air temperature. The required meteorological data for each pixel is derived from the surrounding stations using a distance-weighted spatial interpolation technique.

4. RESULTS

The \( C\text{-Fix} \) model was applied on the European continent with the data sets above, for the year 1997. As an example of the results obtained, figure 1 shows maps of simulated Net Ecosystem Productivity (NEP) during four periods.
Figure 1: Decadal (10 daily) means of Net Ecosystem Productivity (NEP), estimated with the C-Fix model, for four periods in 1997: A. Winter (10/02 – 19/02 1997); B. Spring (11/05 – 20/05 1997); C. Summer (10/08 – 19/08 1997); D. Autumn (09/10 – 18/10 1997). White colour corresponds with water bodies, snow and missing values.

The temporal evolutions, regional distributions and absolute NEP-levels, portrayed in this figure, all agree with normal expectations. Throughout Europe, NEP logically culminates in spring and summer, and productivity clearly decreases with latitude towards the north. In autumn and winter, primary exchange is positive (uptake) in the Mediterranean belt with its typical regime of winter rains and relatively higher temperatures. Persistently negative (release) NEP-values can be observed in mountainous and boreal areas.

Figure 2 shows NEP simulated with C-Fix, for 1997 for two forest sites, compared with eddy covariance measured NEP. The first forest is a 90-year-old mixed deciduous forest located in the montane-mediterranean climate of Collelongo, Italy. The second forest is a 30 years old Pinus sylvestris stand growing in a boreal climate of Hyytiälä in Finland.
Figure 2: Evolution of Net Ecosystem Productivity for two forest carbon exchange experiment sites of the Euroflux-network. Results of eddy covariance field measurements (January 1997-December 1997, data partly missing) versus C-Fix estimates (January 1997 – December 1997).

Figure 2 illustrates that NEP calculated with C-Fix ranges the same as the measured values. Hence we suggest that C-Fix results in realistic estimates of NEP at site level. The difference in NEP behaviour between both sites appears strikingly as well. In summer, the Collelongo mixed deciduous forest shows a higher carbon uptake than the Hyytiälä pine stand. In winter, both forests act as carbon dioxide sources due to low irradiation levels. This phenomenon is however less pronounced for the evergreen pine forest, which releases less carbon in the cold season than the more southern Collelongo site.

5. CONCLUSIONS

The C-Fix model presented in this paper, provides a means to assess the evolution and geographical distribution of the main constituents of the carbon budget of terrestrial ecosystems. Disregarding the simplified approach, we suggest that remote sensing is a valuable tool for estimating radiation absorption at the forest level, which can then be incorporated in an ecosystem model like C-Fix.
The role of soil respiration and hence NEP is a complex issue. We estimated the soil flux by parameterisation of yearly NEP measurements hence singling out the soil heterotrophic respiration rate constant. Methodologically it is improbable that phytomass retrieval from optical remote sensing imagery is feasible on the short term. Therefore a parametric relationship independent of standing phytomass was used to calculate autotrophic respiration. Despite these boundary conditions, NEP simulations with \textit{C-Fix} show a good agreement with Euroflux site flux measurements.

Further applications will mainly concentrate on the use of high quality and recent imagery of the SPOT-4 / VEGETATION sensor. Respiratory fluxes, as well as the incorporation of land cover information in \textit{C-Fix}, are fields for further research and modelling efforts.

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