REMOTELY SENSED SOIL MOISTURE EFFECTS ON CARBON SEQUESTRATION SPATIAL PATTERNS

W. W. Verstraeten [a,b,] *, F. Veroustraete [a], P. R. Coppin[c], J Feyen[b],

[a] Remote Sensing and Earth Observation Processes, VITO, Boeretang 200, BE-2400, Mol, Flanders - willem.verstraeten@vito.be, frank.veroustraete@vito.be

[b] Division of Soil and Water Management, Katholieke Universiteit Leuven (K.U.Leuven), Celestijnenlaan 200E BE-3001 Heverlee, Flanders – jan.feyen@biw.kuleuven.be

[c] M3-BIORES, Katholieke Universiteit Leuven (K.U.Leuven), Celestijnenlaan 200E BE-3001 Heverlee, Flanders – pol.coppin@biw.kuleuven.be

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ABSTRACT:

Carbon emission and fixation fluxes are key variables to guide climate change stakeholders on the use of remediation techniques. To develop Kyoto Protocol support tools, a sound application perspective is offered by expert systems based on earth observation (EO). This allows estimates of vegetation carbon fixation using a minimum of meteorological data. The core module of this type of expert systems is a production efficiency based model (C-Fix). C-Fix estimates the carbon mass fluxes, gross primary productivity (GPP), net primary productivity (NPP) and net ecosystem productivity (NEP) for various spatial scales.
Global carbon budget studies are still dominated by temperature driven approaches only. Nevertheless, a strong coupling between the carbon and the hydrological cycles exists. To take water limitation in carbon studies into account, water availability for vegetation must be estimated, preferably with Earth Observation (EO). However, the strong coupling between the carbon and hydrological cycles is a longstanding acquisition of ecophysiology. When taking account of soil moisture as water limiting factor of ecosystem carbon models or not, ecosystems can revert from a net carbon source to a net sink and vice versa. The main ecosystem compartment responsible for these source sink shifts is identified as the soil compartment. Hence soil moisture singles out as a quite important determinant for carbon sequestration and proves to have a strong impact on carbon sequestration spatial patterns.

1. INTRODUCTION

Knowledge on the spatial and temporal behaviour of net ecosystem carbon uptake is crucial in the framework of environmental conservation, the struggle for limiting greenhouse gasses, understanding global climate change and predicting crop production to anticipate on food security issues.
The carbon balance of a terrestrial ecosystem is profoundly determined by the difference between carbon sequestration in plants and soils and carbon released through ecosystem respiration, i.e. the combination of soil and plant respiration. The processes of carbon fixation and release by plants are mainly driven by solar radiation and ambient temperature as well as by plant water availability. When modelling carbon dioxide it is important to make distinction between carbon pools and carbon dynamics. Some examples of terrestrial carbon pools are soils, litter, peat lands, vegetation such as forests. Leaves can store carbon for one to several seasons, wood stores carbon for years to centuries, soil for years to millennia. Forests may dominate the terrestrial carbon storage capacity, but not the dynamics of the carbon cycle. Agricultural crops have a higher carbon dynamics than woodland, but its storage capacity is very small. Moreover, the distribution of carbon in the vegetation-soil system is very heterogeneous. For example, Vande Walle et al. (2001) studied the carbon storage at the local stand scale in both an oak-beech and an ash stand of the 80-year-old Aelmoeseneie experimental forest (Gontrode, Flanders). They have reported that the total carbon stock amounted to 324.8 and 321.4 tons C ha^{-1} in the oak-beech and the ash stand respectively. In the oak-beech (ash) stand 41.5% (53.0%) of the total C was found in the soil organic matter, 11% (1.0%) in the litter layer and 47.5% (46.0%) in the vegetation. Most vegetation carbon was found in the stems of the trees (51.1% in the oak-beech and 58.7% in the ash stand).

CO_2 sources	
Emissions from fossil fuel combustion and cement production	5.5 ± 0.5
Net emissions from changes in tropical land use	1.6 ± 1.0
Total anthropogenic emissions	7.1 ± 1.1
Partitioning amongst reservoirs	
Storage in the atmosphere	3.3 ± 0.2
Ocean uptake	2.0 ± 0.8
Uptake by northern hemisphere forest regrowth	0.5 ± 0.5
Other terrestrial sinks (CO_2 fertilization, nitrogen fertilization, climate effects)	1.3 ± 1.5

Tables 1. IPCC average annual budget of CO_2 perturbations for 1980–89 (Gt Cy^1) (Source: Canadell et al., 2000).

* Corresponding author.

At the global scale, it is estimated that about 50% of global ecosystem respiration is determined by microbial decomposition of soil organic matter littered by plants (Grace and Rayment, 2000). In a cold and wet climate at high latitudes or heights a.s.l., soil organic matter decomposition proceeds slowly, and carbon accumulates in thick layers of organic matter on top of mineral soils. Hence, it is plausible to rationalise why approximately one-third of the global soil-carbon pool is located in tundra and boreal forest ecosystems (Post et al., 1982). As mentioned in Verstraeten et al. (2006c), Valentini et al. (2000) demonstrated that ecosystem respiration is the most important determinant of the net carbon balance of Europe even with relatively low mean temperatures occurring in large parts of the continent. Valentini et al. (2000) demonstrated that it is ecosystem respiration and not photosynthesis, that varies with latitude in Europe. To situate the framework of carbon modelling and its impacts Table 1 is given wherein the IPCC average annual budget of CO_2 perturbations for the period 1980–89 is summarized.

In this paper, using earth observation techniques to estimate the ecosystem carbon fluxes, we show the spatial impact of water limitation on NEP. Furthermore, we demonstrate the effect of including water limitation on the recapture potential of anthropogenic CO_2 emissions at the country level for Scandinavia and the Baltic countries. All the analyses are conducted with the C-Fix model which has been recently implemented and evaluated both on the fully as partially water limited NEP mode (Verstraeten et al., 2006b).

2. DESCRIPTION OF THE PEM C-FIX

C-Fix can estimate the vegetation-soil carbon mass fluxes at the local (Veroustraete et al. 2004; Verstraeten et al., 2006b), over a regional (Veroustraete et al., 2002; Chabbra and Dhadwal, 2004; Lu et al., 2005) to a global scale. The fully water limited C-Fix model is validated for European forests by Verstraeten et al. (2006b).

In C-Fix the evolution of the radiation absorption efficiency in the photosynthetic active radiation band (or *f*APAR) of vegetation is directly inferred from space observations using the NDVI (Normalized Difference Vegetation Index) and radiation use efficiency (RUE), or the integrated efficiency of photosynthetic metabolism. *f*APAR is estimated using a linear relationship according to Myneni and Williams (1994). Also more novel approaches based on Radiative Transfer Model (RTF) inversion techniques could be used (Veroustraete and Verstraeten, 2005). Stratification of RUE is obtained using the GLC2000 land cover map (Bartholomé and Belward, 2005). Daily Net Ecosystem Productivity (NEP_d) is the balance of daily gross carbon uptake by photosynthesis (GPP_d) reduced by autotrophic (vegetation) respiration (AR) ($GPP_d.A_d$, based on the adapted Q_{10} relation of Goward and Dye (1987)) and reduced by a soil dependent respiratory flux (SR_d, based on the Q_{10} relation of Maisongrande et al., 1995) originating from the decomposition of soil organic matter and root respiration. The limitation of carbon uptake and release of ecosystems by soil moisture can be associated with two process levels: (i) at the GPP level: water availability for photosynthesis and evapotranspiration is crucial. Hence, in the PEM approach RUE, an integrated efficiency of all the photosynthetic metabolic reactions represented by one value, depends on the water availability for plants; (ii) at the soil respiration level: soil moisture affects the soil ecology and hence the biological soil life. A detailed description of the C-Fix model is found in Verstraeten et al. (2006b).

The daily net ecosystem carbon flux is estimated as (gC m^{-2} d^{-1}):

$$NEP_d = (1 - allo \cdot A_d(T_c)) \cdot GPP_d - [SRF.R_h(T_s) + ((1 - allo) \cdot A_d(T_c)) \cdot GPP_d] \quad (1)$$

Wherein

$$GPP_d = p(T_c) \cdot CO_{2,fert} \cdot RUE_{wl} \cdot fAPAR \cdot c \cdot S_{g,d} \quad (2)$$

$$fAPAR = a \cdot NDVI_{toc} + b \quad (3)$$

$$RUE_{wl} = RUE_{\min} + (c_6 \cdot F_s + c_5 \cdot F_a) \cdot (RUE_{\max} - RUE_{\min}) \quad (4)$$

$$SRF = SR_{\min} + (1 - SAS) \cdot (SSS) \cdot (SR_{\max} - SR_{\min}) \quad (5)$$

In Eqs 1 to 5
- NEP_d = daily net ecosystem productivity [g C m^{-2} d^{-1}];
- GPP_d = daily gross primary productivity [g C m^{-2} d^{-1}];
- allo = allometric factor dividing the autotrophic carbon release in an above (leaves) and underground part (roots) [-];
- A_d = autotrophic respiratory fraction (computed according to Goward and Dye, 1987) [-];
- T_c, T_s = canopy and soil temperature respectively [°C];
- $p(T_c)$ = normalised temperature dependency factor {0:1} [-] (defined accordingly to Veroustraete et al., 1994);
- CO_{2fert} = normalised CO_2 fertilisation factor (defined accordingly to Veroustraete et al., 1994);
- RUE_{WL} = RUE taking into account water limitation (Verstraeten et al., 2006b) [gC MJ(APAR)-1];
- RUE_{min}, RUE_{max} = minimum and maximum RUE [gC MJ(APAR)$^{-1}$];
- *f*APAR = fraction of absorbed PAR (Photosynthetic Active Radiation) {0:1} [-];
- $NDVI_{toc}$ = NDVI at the top of canopy [-];
- $S_{g,d}$ = daily incoming Global Solar Radiation [MJ m^{-2} d^{-1}];
- c = climatic efficiency (=0.48) (McCree, 1972) [-];
- R_h = heterotrophic respiration (compute accordingly to Veroustraete et al., 2004) [g C m^{-2} d^{-1}];
- F_s = stomatal regulating factor controlled by the soil moisture availability [-];
- F_a = stomatal regulation factor for atmospheric changes [-];

SRF = soil stress respiration factor [-];
SAS = soil aeration stress depending on the soil moisture [-];
SSS = soil strength stress depending on the soil moisture [-];
SR_{max}, SR_{min} = minimum and maximum soil respiration factors (between 0 and 1) [-];
c_5, c_6 = empirical coefficients [-] reflecting the relative importance of the water factor in soil and atmosphere for photosynthesis.

3. DATASETS

To analyze the effect of taking water limitation into account to estimate spatially distributed NEP over Scandinavia and the Baltic countries in the C-Fix model data for Europe of 1997 are used. C-Fix was run locally and validated on the EUROFLUX sites. EUROFLUX which became operational in 1997 are all located in European forested areas as can be verified in Valentini et al. (2000), the website http://www.fluxnet.ornl.gov/fluxnet/EUROFLUX/index.htm.
For the retrieval of the difference between GPP and anthropogenic carbon emissions, *f*APAR was derived from NOAA/AVHRR data for 1997 for Europe. World Meteorological Organization (WMO) data were used as described in Veroustraete et al. (2002). Anthropogenic emission data for 1997 are taken from the UNFCC Report of 2005 (UNFCC Report, 2005).
Soil moisture data from the ERS Scatterometer have been used in this study. The data can be obtained from http://www.ipf.tuwien.ac.at/radar/. The ERS Scatterometer is an active microwave sensor working at a frequency of 5.3 GHz (C-band). A method to retrieve soil moisture content from this sensor was developed by Wagner et al. (1999). Another possibility could be using soil moisture content (SMC) derived from optical and thermal spaceborne imagery (Verstraeten et al., 2006a) and the coupling with the evaporative fraction also derived from optical and thermal spaceborne remote sensing (Verstraeten et al., 2005).

4. RESULTS AND DISCUSSION

Since C-Fix ingests NDVI, long term water limitation is implicitly taken into account by drops in chlorophyll content or leaf shedding. In that mode, C-Fix simulates partially water limited (PWL) conditions since they do not include short term water limitation (SWL) by SMC. When SWL is included, the model runs in fully water limited (FWL) mode taking into account soil moisture constrains.
From Verstraeten et al. (2006b) we know that in the FWL mode as opposed to the PWL mode, model NEP estimates fit (EUROFLUX) observations more optimally, with slopes and intercepts close to one and zero respectively. In Verstraeten et al. (2006c) the impact of including SWI in the model performance of C-Fix to produce better NEP estimations was studied using measurements from EUROFLUX sites. Including full water limitation into the C-Fix model generally improves the model estimation compared with the EUROFLUX measurements. In most of the considered EUROFLUX sites the peaks in NEP measurements are better simulated in the FWL mode. Differences between the spatial scales must be kept in mind when using remotely-sensed and field measurements of NEP. For instance the spatial scale of the SWI time series is much larger than the process scale level.

We present the impacts of FWL (including the Soil Water Index) and PWL scenario runs with C-Fix on the temporal and spatial patterns of carbon sequestration as well as the carbon balance of the Scandinavian and Baltic countries.
Figure 1 illustrates spatially explicit NEP results by applying C-Fix for the Scandinavian and Baltic part of Europe. Average daily NEP_{PWL} (Figure 1a) and NEP_{FWL} (Figure 1b) for 1997 and for Scandinavia and the Baltic countries, as well as the difference between NEP_{FWL} and NEP_{PWL} (Figure 1c) are assessed with C-Fix. We can observe that by taking into account short term water limitation (SWL), NEP is reduced in large parts of Sweden, Eastern Finland, and large parts of Estonia and Latvia. On the other hand, including SWL, increases NEP for Eastern Finland and southern parts of Norway and Sweden. The spatial patterns elicited in Figure 1b are related to high or low SMC relative to soil texture properties. Very low SMC values reduce and ultimately, completely inhibit soil micro-organism activity so that soil respiration is decreased or respectively brought to a standstill.

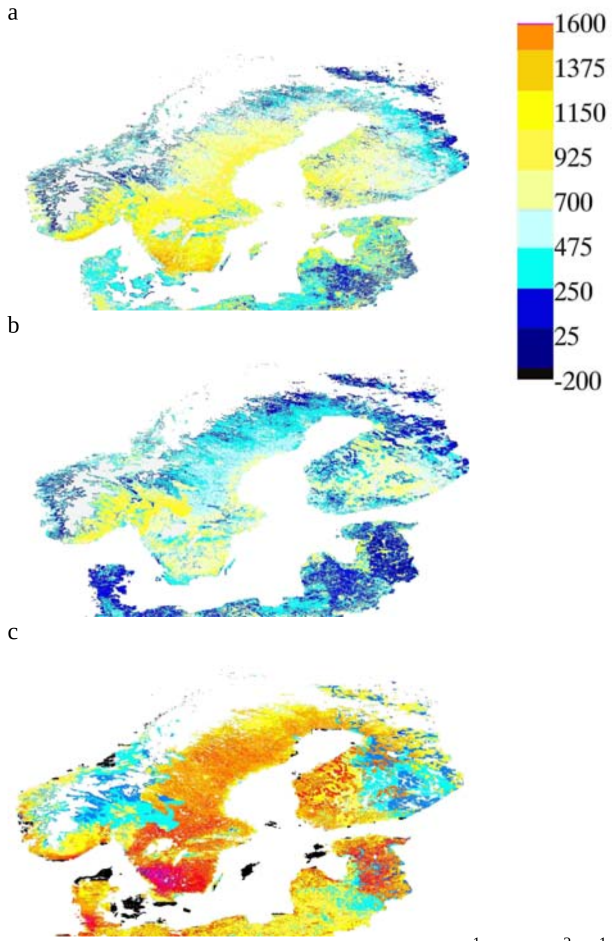

Figure 1. Estimated average daily NEP (in 10^1 g C m^{-2} d^{-1}; divide by 10) for 1997 for Northern Europe using the C-Fix PEM. Panel a, excluding SWL (NEP_{PWL}) and Panel b, including SWL (NEP_{FWL}). Panel c illustrates the difference between the NEP of Panel a en b (NEP_{FWL} - NEP_{PWL})

On the other hand in dry water depleted soils, the decrease of GPP can be sharper than that of soil respiration. In that case a decrease in NEP will be the result. Oppositely to very low SMC soils, high SMC values can lead to soil anaerobiosis and as a result a significant inhibition of soil micro-organism activity as well. Hence, very high SMC's can also inhibit photosynthesis. Moreover, some types of high SMC soils e.g. those with a high organic content can become very acidic so that heterotrophic respiration activity is strongly inhibited. Hence, also decomposition of soil organic material (SOM) is strongly inhibited or brought to a standstill. Figure 2 illustrates whether NEP remains negative, when NEP is estimated in FWL mode compared to the PWL mode, or whether NEP remains positive, or whether NEP switches from positive to negative values and finally, or whether NEP switches from negative to positive values. Clearly, NEP for most parts of Scandinavia remains positive. This is elicited for parts of Latvia. The NEP of large parts of Estonia, northern parts of Norway, Sweden and Finland, the NEP of large parts of Denmark switches from positive to negative values. Oppositely, NEP changes from negative to positive values in some parts of Scandinavia.

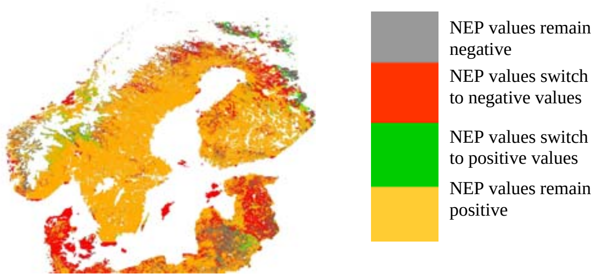

Figure 2. Sign switch of NEP (positive or negative) when estimating NEP from C-Fix in the FWL mode instead of the PWL mode (Northern Europe, 1997). The orange colour indicates parts where NEP remains positive, the grey colour indicates parts where the NEP remains negative. The red colour indicates parts where NEP switches from positive to negative values and the green colour show parts where the NEP switches from negative to positive values

As illustrated in Table 2, the selection of NEP_{PWL} or NEP_{FWL} estimated with C-Fix, leads to fundamentally different estimates of carbon recapturing magnitudes at the country level in Northern Europe. In Table 2 the differences between NEP and anthropogenic carbon emissions (ACE) for the northern European countries are shown for both the PWL as the FWL case. ACE values have been obtained from the UNFCC Report of 2005.

Country	ACE [Tg C a^{-1}]	NEP_{PWL}-ACE [Tg C a^{-1}]	NEP_{FWL}-ACE [Tg C a^{-1}]
Denmark	65.7	-49.3	-43.6
Estonia	20.2	11.6	-14.7
Finland	62.3	125.7	56.7
Latvia	8.7	30.5	1.4
Lithuania	16.2	1.1	-6.9
Norway	40.6	219.5	199.7
Sweden	56.8	390.1	152.0

Tables 2. Difference between NEP and anthropogenic carbon emissions (ACE) for Scandinavia and the Baltic countries. Country level for 1997 (Tg C a^{-1}).

From Table 2 it is clear that the inclusion of water limitation turns Estonia and Lithuania from net carbon dioxide sinks to net carbon dioxide sources. The CO_2-emitter Denmark gets a better scenario when NEP_{FWL} is used in stead of NEP_{PWL}. Finland, Latvia, Norway and Sweden remain net CO_2 sinks even with the inclusion of short term water limitation. Is the difference between the NEP_{PWL}-ACE and NEP_{FWL}-ACE for Norway only minor, oppositely the difference gets larger for Sweden and Latvia.

5. CONCLUSIONS

The impact of water relations is assessed at the level of carbon sequestration by NEP and anthropogenic emissions (ACE). In that respect we suggest that a crucial factor in soil organic matter decomposition is not only soil moisture but also dissolved oxygen. We included these restraints in soil organic matter decomposition and root respiration in the C-Fix model for optimal estimation of soil (micro-) biological activity at the continental scale. With the use of the remotely-sensed production efficiency model C-Fix and the Soil Water Index of the ERS Scatterometer, we have indicated that water limitation in ecosystems may affect the net ecosystem productivity in both a positive as negative way. Water stress might decrease the carbon uptake by vegetation. On the other hand, in very dry soils the heterotrophic respiration will be reduced such that a decrease in carbon uptake by photosynthesis is (over-)compensated (Verstraeten et al., 2006c). Another extreme situation are saturated soils which reduce the fauna and flora activity (thus the respiration) due to oxygen depletion. Hence, the water status of the soil affects the carbon dioxide recapture potential of the soil-vegetation systems and thus some northern European counties turn from net carbon sinks to net carbon sources.

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