Study of two forested watersheds in Les Landes region: monitoring of carbon stock and water cycle over the last decades.

Guillot Marie (1) ; Dayau Sylvia ; Spannraft Katharina ; Guyon Dominique ; Wigneron Jean-Pierre ; Loustau Denis.

(1) INRA, UR1263 EPHYSE, F-33140, Villenave d'Ornon, marie.guillot@bordeaux.inra.fr

Abstract:

Linking water and carbon cycles and their interactions will be a key issue in the future to understand the ecological processes. Very few studies quantify the feedback effects of the two cycles based on long time series measurements, in order to understand the effect of climatic change and the impact of extreme climatic events such as storms.
Our project aims to implement and calibrate a coupled eco-hydrological approach over two watersheds to estimate the effects of land cover changes, extreme climatic events, climatic changes and forest management on the water and carbon budgets for the last decades.
The study is carried out over two watersheds (Tagon and Bouron) of Les Landes forest located in the South Western region of France. These two watersheds are comparable in terms of land cover: close to 90% of planted and managed coniferous forest. They have been alternatively damaged by the two successive Martin (Dec. 1999) and Klaus (Jan. 2009) winter storms, Tagon being more damaged by the former and Bouron by the latter. The water runoff, water table depth and climate of the two watersheds have been monitored since 1967 at the earliest. For each watershed, land cover maps, including detailed information of the pine forest's age structure, was obtained from 1984 to 2008 using satellite information, ground truth and statistics of the national inventory.

In 1999, 36 % of the stands of the Tagon watershed where affected by the storm at levels of more than 20% of fallen trees, having for consequences to drastically change the age distribution of pine forest stands within the watershed. In 2007, 70 % of its surface is still occupied by stands younger than 21 years, which can be linked with the increase in runoff after 1999 (decreased rainfall interception and tree canopy transpiration. These higher peak flows decrease with time (progressive recovery of the vegetation) but are still visible after four years.

Keywords: water cycle, carbon stock, monitoring, long-time series, watershed hydrology, Landes forest.

Introduction

Water availability influences strongly carbon stock as it is a determinant factor for forest distribution (Spurr, 1980) and a limiting factor for tree productivity. The effects of water table variation on tree performance have been investigated in several studies (Fraser, 1962, Polacek et al., 2005). Water and carbon cycles and their interactions have been also monitored from large scale to point scale (Habets, 1998; Nemani, 2003; Rivalland, 2005; Govind, 2009) but very few studies quantify the feedback effects of the two cycles by a spatially explicit coupling between a hydrological and an ecological model. The assessment of such interactions in the case of forest ecosystems requires embracing the whole life cycle. Long time series are therefore required because delayed effects of climate and management may impact the forest functioning for decades.

The ongoing greenhouse-gas induced climate forcing must be accounted for in such an approach. Climate change includes both a climatic shift, soft and progressive, which will change mean temperature and precipitation patterns, and the extreme climatic events (ECE), such as storms, droughts, and heat waves. ECE may change drastically the age structure of forest stands and create large patches within forests. Hurricane-associated winds and rains have indirect consequences on carbon and water flux and budgets (Cook, 2008). The recent storms' impact in Florida and Europe on carbon sink has been documented (Chambers, 2007; IPCC, 2007). Their effects on runoff and evapotranspiration on forested watersheds and thus on the regional water cycle are also important (Badoux, 2006).

The effect of management may not be neglected. Forest clearing generally leads to an increase in runoff (Badoux, 2006; Tremblay, 2008). In young forest plantations, the drainage flux can be doubled and evapotranspiration reduced by 50% as compared with older stands (Stella et al., 2009). Moreover, intensification changes rotation length of managed stands and thus, the evapotranspiration partitioning between the tree and understory vegetation: the latter offsetting the reduction of evapotranspiration by pine trees as trees are getting older (Delzon, 2005).

The maritime pine stands covering the coastal area of Southwestern France are an interesting case to study the coupling of carbon and water cycles in forests. In this region, managed Pine forests cover nearly 1 million of hectares (IFN, 2009). The productivity of the forest is related to the mean water-table level (Loustau, 1999). Stands are usually classified among "dry" stands (ground-water table deeper than 2 meters in winter) to "humid" ones (mean ground-water table depth close to 0.3 meter in winter) (Augusto, 2006), and the optimum for productivity are mesic stands. Reciprocally, the regime of fluctuations of the water table is closely linked to the land use and forest and agricultural management practices. This forest ecosystem has been studied for a long time in the framework of European, national and regional research projects. Models describing maritime pine forest functioning were developed in the past at the stand level (Porté, 1999; Ogée 2003; Cucchi, 2005) and applied for the prediction of climate effects on the tree growth and carbon and water cycles.

Our project aims to implement and calibrate a coupled eco-hydrological approach to estimate the effects of land cover changes, ECE, climatic changes and forest management on the water and carbon budgets for the last decades over two forest watersheds. In this study, we present first experimental results that illustrate the impact of the 1999's storm in terms of damages to the forest structure and of runoff processes.

1. Material & Methods

1.1. Description of the watersheds

The two watersheds are located in the South Western region of France. They are small tributaries to the Leyre River, which flows to the Arcachon Bay (Figure 1). The Bouron (W 00°80'02", N 49°42'31") and the Tagon (W 1°03'02", N 49° 63'18") watersheds cover, respectively, an area of 48 km² and 22 km². Elevation ranges from 16 m to 80 m a.s.l. (above sea level) for the Bouron watershed, and from 1 m to 60 m a.s.l. for the Tagon watershed. Slopes are very low: 1% mean for each watershed. The steeper slopes can be found in the riparian zone which is less than 16 % of the total watershed surface for the Bouron and 4% for the Tagon. Soils are mainly sandy spodosols settled from fluvio-atmogenic deposits, during the Pliocene and the Quaternary with some clay vein and gravel concentration in small areas.

The main land use of the two watersheds is forest (Corine Land Cover (CLC)) which covers 92% (89%) of the total area for the Bouron (Tagon). Within these forested areas, 87% and 86% respectively, are occupied by conifer forest, with maritime pines (*Pinus pinaster*) in large majority. Surfaces occupied by crops or pastures are very small: less than 6% of the total surface for the Bouron and less than 2% in the Tagon. The Tagon watershed is more urbanized with nearly 9% of urban areas versus 2 % for the Bouron.

The Land cover of both watersheds remained unchanged during the 1990-2000 period (CLC 1990 and CLC 2000). The Tagon watershed is close to the Arcachon bay, so changes in land cover are mainly due to urbanization pressure (0.25 %), whereas on the Bouron watershed, changes were caused by deforestation for cropping (0.45%) and conversion from conifer forests into deciduous forests (0.4%).

The climate is mild oceanic with an average annual precipitation of about 900 mm and a mean temperature of 12.7°C.

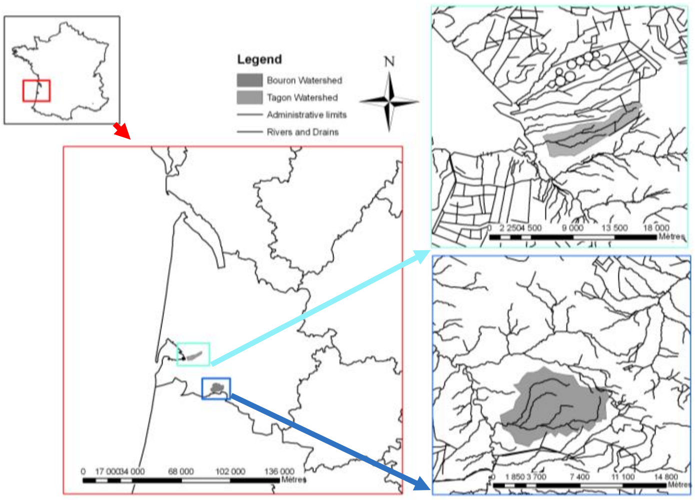

Figure 1. Location of the two studied watersheds.

1.2. Measurements

Groundwater table levels were monitored with 9 and 12 wells for the Bouron and Tagon watersheds, respectively (Figure 2), from 2 to 11 m deep. Runoff at the watershed outlets was measured continuously from 1967 at the earliest to present by the DIREN[1] except for the Tagon where measurements were interrupted between January 2006 and November 2009.

Two simple weather stations were installed in both watersheds to provide measurements of temperature and atmospheric pressure (HOBO U20 Data Logger) and rainfall (SPIEA rain gauge and "Precis Mecanique" automatic rain gauge).

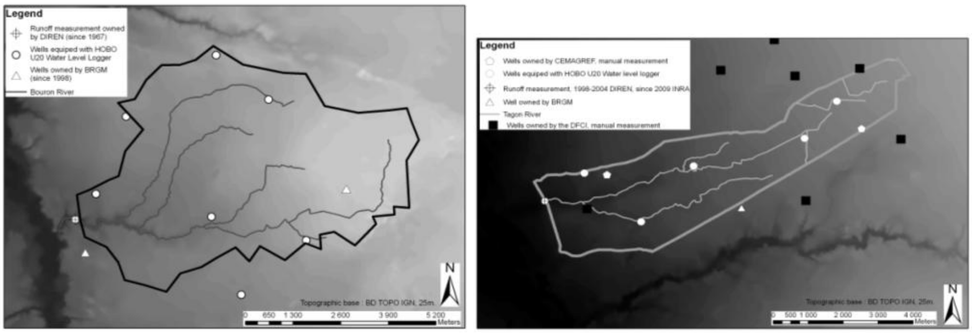

Figure 2. Location of the water table depth and runoff measurements: on the left, within the Bouron watershed and on the right, within the Tagon watershed. Topographic base of the map: Scan 25 IGN.

1.3. Mapping land cover through time

First, multi-seasonal SPOT 2 and 4 images acquired during 2007 in NIR, RED and MIR spectral bands were segmented and classified with an object-oriented image processing approach (Spring software; Camara, 1996) to obtain the current land cover map with 14 classes: 3 classes of agricultural covers, one for deciduous forest, one for urbanized areas, one for water areas and 7 classes concerning maritime Pine forest (one for firebreaks and 6 for coarse age class : recent clear-cuts, older clear-cuts and young plantations, stands from 6 to 10 year old - y.o.-, stand from 11 to 20 y.o., stand from 21 to 39 y. o. and stand older than 40 y.o.). This classification was calibrated and validated using ground survey measurements (102 stands were sampled over the Bouron watershed representing 532.71 hectares or 5.4 % of the classified image, 86 stands were sampled over Tagon representing 754.95 hectares or 4.79 % of the classified image).

Second, in order to refine the previous classification of the age for maritime Pine forest, age of stands replanted after 1984 was deducted from clear-cut map information available from 1984 to 2007 (coming from Landsat TM time series, INRA for period 1984 to 1990, Jolly, 1993; and IFN after 1990, Deshayes, 2006), considering a two year sanitary period between clear-cut and plantation. The accuracy of the improved map was estimated to be about 63.7 % for the Bouron and 68.5 % for the Tagon watershed. The age of the

[1] DIRection de l'Environnement de Bordeaux, local delegation of the Ministère de l'Ecologie, de l'énergie, du développement durable et de la mer.

oldest stands (before 1984) was filled using the statistics from IFN data, resulting of the last ground-based forest inventory in the area.

Third, to go back in time, i.e. reconstitute the spatial distribution of age of pine stands from 2007 to 1984, we simply remove one year to obtain the year n-1 map and, when coming to the clear-cut year, we used the statistical distribution of the age before cutting from IFN data, derived from the 3 last inventories performed at ground level in the region.

2. First Results and discussion

Damages were mapped for the two successive Martin (Dec. 1999) and Klaus (Jan. 2009) winter storms by the IFN and the CEMAGREF (downloadable online on the IFN website: http://www.ifn.fr/spip/, last access: 31/07/2009, Minimum Map Unit = 1 hectare). The two watersheds have been alternatively damaged by the two storms as showed in Table 1. Tagon was more damaged by the Martin storm, with nearly 40% of the surface of the watershed with damaged trees ratio higher than 20%, whereas the Bouron was two times less damaged. Klaus storm damages were more severe on the Bouron watershed compared to the Tagon, as 13% of the surface of the watershed with damaged trees ratio higher than 50%, compared to 7% for the Tagon.

Table 1. Surface of the watershed affected by the Martin and the Klaus storm. P20: Percentage of the total surface of the watershed with damaged trees ratio higher than 20%. P50: Percentage of the total surface of the watershed with damaged trees ratio higher than 50%.

		Tagon	Bouron
Martin (1999)	**P20**	32.9	19.8
	P50	24.2	12.4
Klaus (2009)	**P20**	25.6	33.3
	P50	7.5	13.1

We will only present results for the Martin storm impacts on water cycle and on pine forest age structure as the 2009 data have not been analyzed yet.

Peak flows on the Tagon watershed occurs more frequently after the 1999, and these peak flows are not visible on the Bouron watershed (Figure 3). This is mainly due to an increase of flood flow during the winter. The effect of the storm is clearly visible on Figure 4 : linear regressions fitted on Tagon and Bouron specific runoff relationship before and after storm show a shift in the slope between the two regression curses ($a = -5.45$, $R^2 = 0.70$, and $a = -6.12$, $R^2 = 0.655$ respectively). This difference was highly significant with a t-value of 5.98 for 2522 ddl and p-value of 2.52e-09. Since the Tagon watershed was more affected by the Martin storm, higher runoffs can be explained by an increase in drainage fluxes due to a combined decrease in rainfall interception and tree canopy transpiration. These higher peak flows decrease with time but are still visible after four years (Figure 3). These effects decreased in relation with the progressive recovery of the vegetation, due the combined effect of regeneration of maritime pine stands and understory growth.

The 1999's storm had a deep and long term impact on the vegetation structure as it changed drastically the age distribution of the pine forest stands within the two watersheds.

In 1997, before the ‘Martin’ storm, the two watersheds had comparable distribution of stand ages (Figure 5). After the storm, in 2007, the Tagon watershed had more than 70 % of its surface occupied by stands younger than 21 years, amongst which 50% are younger than 11 years. Comparatively, over the Bouron, stands older than 21 years still represented 47% of the total surface after the storm.

Conclusion

The next step of the study will be to implement a process-based model describing forest functioning (in terms of energy balance, evapotranspiration, carbon balance, tree growth, management etc.) in order to calculate carbon budget for the two watersheds and its evolution over time. Spatially-distributed ground water level will be simulated with MODFLOW (Chiang W-H., 2005). It will allow the understanding and quantification of cumulative effects on watershed functioning over the two last decades; considering land cover heterogeneity, temporal changes in land cover, progressive climatic shifts and abrupt events such as storm events and land use conversion. This coupled eco-hydrological model will be a key tool to investigate these effects.

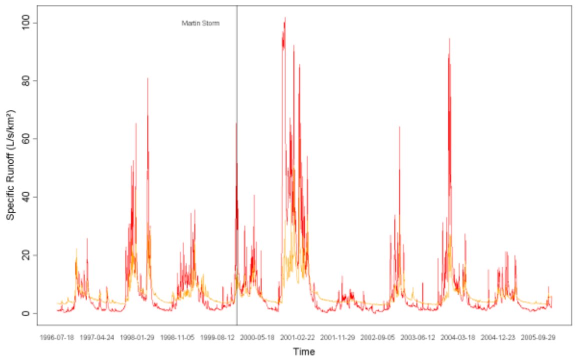

Figure 3. Specific runoff of the Bouron (orange) and Tagon rivers (red): time series from July 1996 to December 2005

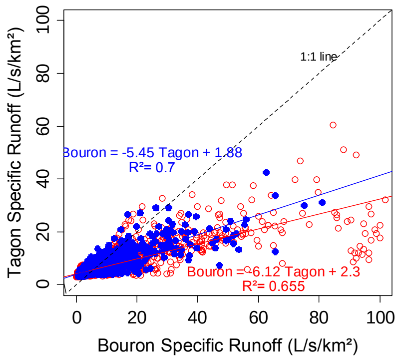

Figure 4. Tagon to Bouron specific runoff before (blue) and after (red) the ’Martin’ storm in 1999.

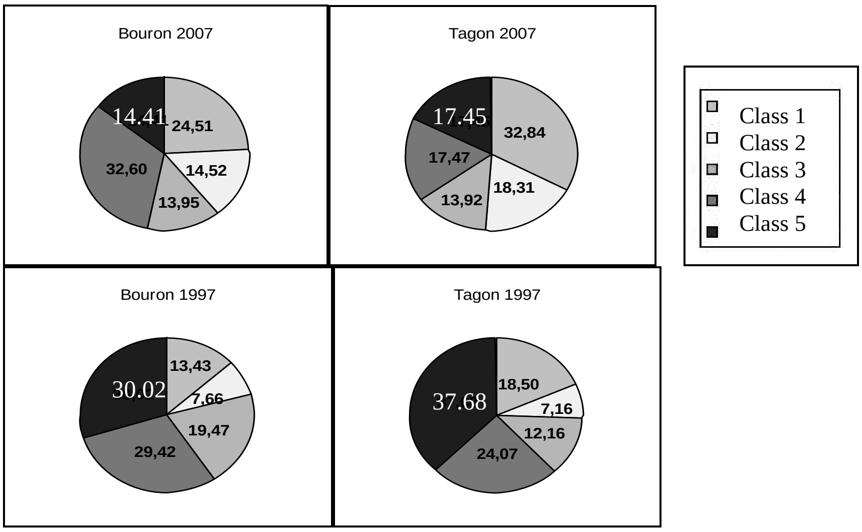

Figure 5. Distribution of the stand age for the two watersheds after the 1999 storm (2007, the 2 top pie-charts) and before the 1999 storm (1997, the 2 bottom pie-charts): Class 1 corresponds to clear cuts or to 0 to 5 years stands; Class 2, 6 to 9 years, Class 3, 10 to 20 years; Class 4, 21 to 40 years; and Class 5, more than 40 years.

References

Augusto, L. and Badeau, V. and Arrouays, D. and Trichet, P. and Flot, J.L. and Jolivet, C. and Merzeau, D. 2006. Caractéristaion physico-chimique des sols à l'échelle d'une région naturelle à partir d'une compilation de données. Exemple des sols du massif forestier landais. *Etude et Gestion des sols*, 13, 7-22.

Badoux, A.; Jeisy, M.; Kienholz, H.; Luscher, P.; Weingartner, R.; Witzig, J. & Hegg, C., 2006. Influence of storm damage on the runoff generation in two sub-catchments of the Sperbelgraben, Swiss Emmental. *European Journal of Forest Research*, 125, 27-41.

Camara G, Souza RCM, Freitas UM, Garrido J, 1996. SPRING: Integrating remote sensing and GIS by object-oriented data modeling. Computers & Graphics, 20, 3, 395-403.

Chambers, J. Q., Fisher, J. I., Zeng, H., Chapman, E. L., Baker, D. B., Hurtt, G. C., 2007. Hurricane Katrina's Carbon Footprint on U.S. Gulf Coast Forests. *Science*, 318, 1107-1107.

Chiang, W-H., 2005. 3D-groundwater modeling with PMWIN a simulation system for modeling. Springer-Verlag Berlin Heidelberg New York, 397 pages.

Cucchi, V., Meredieu, C., Stokes, A., de Coligny, F., Suarez, J., Gardiner, B.A., 2005. Modelling the windthrow risk for simulated forest stands of Maritime pine (Pinus pinaster Ait.). Forest Ecology Management, 21, 184-196.

Cook, G., and Goyens, C., 2008. The impact of wind on trees in Australian tropical savannas: lessons from Cyclone Monica. *Australian Ecology*, 33, 462-470.

Delzon S. et Loustau D., 2005. Age-related decline in stand water use : sap flow and transpiration in a pine forest chronosequence. *Agricultural and Forest Meteorology*, 129, 105-119.

Deshayes, M., Guyon, G., Jeanjean, H., Stach, N., Jolly, A., Hagolle, O., 2006. The contribution of remote sensing to the assessment of drought effects in forest ecosystems. Annals of Forest Science, 63, 6, 579-595.

Fraser, 1962. Tree growth in relation to soil moisture. In: T.T. Kozlowski (Ed.), *Tree growth*. The Ronald Press Co., New York, 442 pp

Govind A., Chen J-M., Margolis H., Ju W., Sonnentag O., Giasson M-C., 2009. A spatially explicit hydro-ecological modeling framework (BEPS-TerrainLab V2.0): Model description and test in a boreal ecosystem in Eastern North America. *Journal of Hydrology*, 367, 200–216.

Habets, F., 1998. Modélisation du cycle continental de l'eau à l'échelle régionale. Application aux bassins versants de l'Adour et du Rhône. Université Paul Sabatier (Toulouse III), 224 p.

Intergovernamental Panel on Climate Change (IPCC), Climate Change 2007 : The Physical Science Basis – Summary for policymakers, 2007. Cambridge Univ. Press, Cambridge, 996 p.

Inventaire Forestier National, 2009. La forêt française - Les résultats issus des campagnes d'inventaire 2005, 2006, 2007 et 2008. 136 p.

Jolly, 1993. Estimation par télédétection satellitaire de la récolte annuelle en bois dans la futaie pure de pin maritime du massif des Landes de Gascogne, Apports pour la prévision de la ressource forestière, Thèse de doctorat de l'Université Paul Sabatier de Toulouse, 315 p.

Loustau, D., Bert, D., Trichet P., 1999. Fonctionnement primaire et productivité de la forêt landaise: implications pour une gestion durable. Revue Forestière Française, LI, 5, 571-591.

Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., Myneni, R.B., Running, S.W., 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science, 300, 1560–1563.

Ogée, J., Brunet, Y., Loustau, D., Berbigier, P., Delzon, S. 2003. MuSICA, a CO2, water and energy multilayer, multileaf pine forest model: evaluation from hourly to yearly time scales and sensitivity analysis. Global Change Biology, 9, 697-717.

Porté, A., 1999. Modélisation des effets du bilan hydrique sur la production primaire et la croissance d'un couvert de Pin maritime (Pinus pinaster Aït) en Lande Humide. Thèse de l'Université de Paris-Sud, U.F..R. Scientifique d'Orsay, 197 p.

Polacek D., Kofler W., Oberhuber W. (2006) Radial growth of *Pinus sylvestris* growing on alluvial terraces is sensitive to water level fluctuations. *New Phytologist*, 169, 299-308.

Rivalland, V.; Calvet, J. C.; Berbigier, P.; Brunet, Y. & Granier, A., 2005. Transpiration and CO2 fluxes of a pine forest: modelling the undergrowth effect. Annales Geophysicae, 23, 291-304.

Stella P., Lamaud E., Brunet Y., Bonnefond, J-M., Loustau D., Irvine M., 2009. Simultaneous measurement of CO2 and water exchanges over three agroecosystems in South-West France. Biogeosciences Discussions, 6, 2489-2522.

Spurr S.H. and Barnes B.V., 1980. Forest Ecology (3rd Edition). *John Wiley & Sons*, New York, 687 p.

Tremblay Y., Rousseau A.N., Plamondon A.P., Lévesque, D., Jutras S., 2008. Rainfall peak flow response to clearcutting 50% of three small watersheds in a boreal forest, Montmorency Forest, Québec. Journal of Hydrology, 352, 67-76.