Carbon stock in European Forests: State of the Art, Uncertainties and Political Challenges

Marian Drăgoi
”Ştefan cel Mare” University of Suceava, Forestry Faculty, Universităţii Street, 13, Suceava, Romania
Corresponding author e-mail address: dragoi@usv.ro

Abstract: The article summaries the most important papers published in the last decade on three issues dealing with carbon sink: methodological issues on assessing the carbon stored by the forest vegetation, life-cycle analyses and bio-energy. The first section presents the progress made in evaluating the carbon contents in different components of the forest ecosystem, ethenone one is being focused on the complexity of life-cycle analyses with the bio-energy section mostly deals with the dilemmas concerning the use of use pellets, bio-ethanol and bio-diesel.

Keywords: carbon sink, forest management, climate change

1. Introduction

Most of the processes triggered by climate change alter the forests on short time (Schlyter et al. 2006; Frank et al. 2015; Hanewinkel et al. 2012) while the forests have a tremendous potential to offset the emissions of greenhouse gases released into the atmosphere by burning the fossil fuels. Forest management, on the one hand, and land use change, on the other hand link the forests and climate for good either at global and regional scale (Cienciala et al., 2008). Forests may produce carbon-neutral fuel, if the trees are being harvested when the average growth reaches a peak (substitution effect), or may store the carbon sink as standing biomass (offset effect). Between these two extreme solutions there are a myriad of mixed managerial options unless other objectives are pursued, the most important being the biodiversity conservation. Shifting the goals from timber production to bio-energy or conservation brings about serious changes throughout all carbon pools and also modifies the amount of fossil fuel substituted by biomass (Böttcher et al. 2012).

In Europe, the forest growth accelerated in the last century as Pretzsch et al., (2014) showed for the Norway spruce, and European beech respectively. Based on long term measurements carried out in permanent plots installed in 1870 (36 for Norway spruce and 22 for beech) collecting climatic data from four meteorological stations and using a growth simulator fed with field and climatic data the research team concluded that the growing season is 22 days longer now than 110 year ago; noteworthy, the main increase occurred in the last 50 years and triggered faster growths for the two species: 32% for Norway spruce and up to 77% for beech. The additional amount of 34 million tons of carbon per year estimated by simple extrapolation across the area covered by the two species in Central Europe yet deserves more precaution.

Due to the high intrinsic complexity of any forest policy, most of the forest management scenarios and prognoses have tried to account for this variety of goals; however, things are more complicated because these `end-use` or 'management' scenarios must be enveloped by three types of scenarios, as Moss et al. (2010) suggested: emission scenarios, climate scenarios and environmental scenarios.

2. Which are the most important terrestrial sinks

Assessing the content of soil organic carbon (SOC) under the forests provides a better understating the dynamics of carbon stock under different scenarios of land use change (Strand et al., 2016), while the distribution of carbon across different components of the living plants has too large variations. In Turkey for example, an extensive assessment based in the 2004 National Forest Inventory data showed that about 75% of the total stock is in the soil, 21% in living biomass and 4% in deadwood and litter (Tolunay, 2011). In Italy, a similar study carried under the second NFI cycle concluded that 58% of the carbon stock is to be found underground, 38% above ground, 2.3% in litter and 2% in deadwood (Gasparini and Di Cosmo, 2015).

According to a very extensive study carried out in Southern Spain by Muñoz-Rojas et al. (2012,) SOC varies between 33.2 Mg C/ha corresponding to Arenosol to 96.9 Mg C/ha, corresponding to Calcisol; worth-noting, the highest value across all types of soils were reported under shrubs vegetation, not under forests.

Because the photosynthesis is the paramount ecosystem service provided by forests (Hodas 2013), and the old-growth forest is best able to mitigate the CO2 concentration of the atmosphere, any scenario shall consider this option, opened by the unmanaged forest category. The next equally important condition for developing whatever scenario is an initial reference level, whatever it be.

In Germany, Wutzler et al., (2011) assess the tree biomass carbon stock through basal area measurements carried out on stand level, or cohorts of trees within each stand (for un-even aged structures). The carbon accumulation was appraised at 1.8 t C/ha/annum. Across the 550000 hectares of the study area, the carbon stock varies between 0.4 t C/ha/year in the northwest and 3.0 t C/ha/yr in the south. At regional level, in North Rhine Westphalia, Knauf et al. (2015) developed two scenarios regarding the wood usage and concluded that on middle and long term (2050 and 2100, respectively) and concluded the net climate protection function of forest management is better with changing levels of wood usage than the base-line scenario, without wood mobilization in long-term wooden-based products.

Estimating the total biomass is a challenging issue because it implies inevitable extrapolations of volumes per hectare across much larger areas within the forest is considered homogeneous although it is not. Hence, whoever wants to make such evaluations shall firstly contemplate how many and how representative are the types of forest worth working with (Mason et al. 2011; Allen et al. 2010; Verkerk et al. 2015; De Wit et al. 2006).

Any assessment on the total carbon stock depends on a large extent to the methodology used to evaluate the total biomass, on the one hand, and the carbon stored in the forest soils, on the other hand. Either ways the forest area is the first requisite for having a proxy of the carbon stock and the main source of data is the national forest inventories (Herrero & Bravo, 2012; Cienciala et al. 2008; Romijn et al. 2015; Pilli et al. 2013; Wit et al. 2006; Muukkonen & Heiskanen 2007). Yet these baseline references are further used to foresee the forest areas after a couple of decades, most prognoses being made up to the end of this century.

Inevitably all studies aiming at foreseeing the forest structure after a couple of decades are based on models, and a series of assumptions depending on the goals and the scope put forward by the academic community. hence the first issue addressed is the overruling approach: bottom-up (or inductive reasoning), top-down (deductive reasoning) or a mixture of the two (Mantau 2015; Smeets & Faaij 2007; Nidumolu et al. 2009).

In addition to the growth models, different additional sources of data are being used to cope with aggregating the data over long period of time, different forest types and areas encompassing many countries, with different forest management peculiarities. Van Breugel et al. (2011) came to the conclusion that allometric models fail to predict with accuracy the carbon stock over large areas and developing new regional or local models is justified if the sampling is reliable at landscape level.

Pilli et al. (2017) parametrized the Canadian Carbon Budget Model (CBM) to the European conditions and concluded that between 2000 and 2012 the net primary productivity (NPP) of the forest pools at the EU22 level averaged 639 $Tg\,C\,yr^{-1}$. The analysis spans over all 26 countries and took into account the land-use changes, natural disturbances (storms and ice damages, insects attack) and the forest management. Forecasts to 2030 were carried out considering two scenarios and to assess the impact of specific harvest and afforestation scenarios after 2012 on the mitigation potential of the EU forest sector. Substitution effects and the possible impacts of climate were not included in this analysis.

For instance, d'Annunzio et al. (2015) based on GEOMOD model (a spatial model that predicts forest areas likely to be lost for other land-uses, concluded that over 95% of primary forest loss is projected to occur at Tropics.

Due to higher productivities in agriculture, the marginal farmlands are abandoned in Europe and turned into forest, but the whole process is not determined by the EU climate change mitigation policies (Burrascano et al. 2016).

The dynamics of forest cover and forest growth span over long periods of time and the carbon sink depends on forest management practices and forest policies. The annual rate of afforestation is about 2% globally, since 1990 (Payn et al. 2015). The mean volume per hectare increased in East Asia, Caribbean, Western and Central Asia, North America, Europe, and Oceania, while the carbon sink declined by 13.5 Pg C in the same period of time (Kohl et al. 2015). Discrepancies between continents are obvious and the most deforested continent remain Africa and South America (Keenan et al. 2015). At EU level the carbon sink seems to approach a maximum level, thus challenging the forest management (Nabuurs et al. 2013; Pilli et al. 2015).

One important challenge is to figure out the differences in carbon per hectare between managed and unmanaged forests. Allen et al., (2016) used the LPJ-GUESS model to gauge the influence of relative CO_2 increase, temperature growth and management on carbon storage in the biomass of unmanaged temperate deciduous forests. LPJ-GUESS model is dynamic vegetation model based on gap modeling approach. The author used the concept of plant functional type (PFT) to classify the vegetation and as many as 22 PFT were modeled. Climatic data from the first three decades of the XX century were used to calibrate the model. The authors simulated the relative effects of increasing temperature, increasing CO_2 concentration in atmosphere and forest management measures in a pilot semi-natural forest located in UK. Forest management has had the greatest effect on carbon stocks throughout most of the study period but, towards the end of the study period, the CO_2 concentration turns into a bigger driver. Main results regarding the carbon sinks under different scenarios are presented in Table 1.

Tab.1 Main reference figures referring to the Carbon sinks

Reference area	Method	Reference period	Carbon storage	Authors
UK, Lady Park Wood 35.2 ha	LPJ-GUESS Dynamic vegetation model	1900-2005 calibration 2005-2100 forecast	Two scenarios: IPCC 4.5 and 8.5 tC/ha stock in old growth forest Up to 30 tC/ha stock in 2100 181.1 tC/ha in old-growth stands	(Allen et al. 2016)
Global, living biomass	Aggregated data from literature	2013	300 Pg C (300 Gt)	(Mackey et al. 2013)
Northern hemisphere	Satellite observations 1981-1999	Late 1990s	61 ± 20 Gt pool 0.684 Gt C/yr. sink	(Myneni et al. 2001)
Eurasia		Late 1990s	37.68 Gt C pool 0.46 Gt C/yr. sink	
Bohemian forest	Ground measurements	2015	Average 41 tC/ha range between 14 and 112 tC/ha	(Seedre et al. 2015)
Meta-analysis on 432 studies	Soil response ratio at clearcutting	2010	On average, 8% reduction in soil carbon	(Nave et al., 2010)

Collecting the wood residues left after harvesting operations is an attractive managerial option but its impact on the long-term site productivity could be quite problematic. Based on an extensive literature and case studies (Achat et al. 2015) estimated that tree growth diminishes with 3-7% on medium term as a consequence of reduced site fertility.

3. Relevance and magnitude of carbon in forest products

Life Cycle Assessment (LCA) became in the last decades the most important method involved in evaluating the environmentally-related side effects of different products and also an important means of eco-designing (Linkosalmi et al. 2016; Peuportier et al. 2013).

Cherubini & Strømman (2011) summarized 104 LCA studies and found as many as four types of functional units the LCA studies referred to as in order to estimate the GHG and GWP of wood-base products or bioenergy: input oriented (helps finding the best use of whatever input), output oriented (the best provision of given a service from different sources), unit of agricultural land, and a given reference year. Most of the studies (73 in total) were output-oriented. Another clear delineation highlighted in this study is the difference between attributional LCA and consequential LCA: the former ones describe the flows that enter and leave the reference system, while the latter explains how the input and output flows are changed by a given production process. Attributional methods are the most used ones but when it comes to bioenergy systems the consequential LCA are preferred, because the reference system is the fossil fuel. Attributional LCA are preferred by policy makers, while consequential LCA are preferred by decision makers.

An important driver of the forest policy is the wood-base products capacity to store carbon on longer period as well as the two substitution effects: fuel substitution and material ubstitution respectively (Marcus Knauf et al. 2015). When it comes to material substitution the key issue of storing the carbon in wood products is the service period and, inevitably, the longest service period is being assigned to wooden buildings. (Sartori & Hestnes 2007) summarized 60 case studies of LCA on houses revealed that the since periods of wooden houses vary between 30 to 100 years, depending on how many houses are gathered into a block; however, most of the case studies assumed 50 years of service.

Trying to assess the global warming potential of two alternatives of using the wood residues, Kim & Song (2014) used the LCA methodology on a functional unit of one ton of wood waste. The two alternative scenarios were particle board production, and combined heat and energy production, from the same tone of wood waste. The average life service of particle board was estimated at 14 year by a Weibull function and 16 round of recycling were also considered. The net carbon emission in the first scenario (a series of 16 recycling cycles of particle board followed by combustion) was -428 kg

CO_2 eq. and -154 kg CO_2 in the second one (combined heat and energy directly from wood waste).

A quite similar study was performed by Rivela et al. (2006) who analyzed two different scenarios of using wood residues: recycling wooden waste into particleboard and energy generation from natural gas (Scenario 1) and energy production from wood waste combined with particleboard manufactured from conventional wooden resources (Scenario 2). The authors carried out the whole study on the raw data coming from the Barcelona annual trade fair, where about 8,000 tons of particle boards are used as ephemeral constructions and 70-8% of the wooden waste generated goes eventually to the landfill. The functional unit considered was 1 m^3 of particle board 260 kWh of electricity and 1570 kWh of heat. The study took into consideration most of the detrimental effects on human health, climate change, ozone layer, acidification and water eutrophication. Two conclusions have been drawn: crushing the wood residues on site is more effective in terms of diesel consumption and 2) wood residues recycling, (without producing energy from wood residues) is a more environmental-friendly option.

The cascading effect of using wood firstly in construction then waste from construction as fuelwood, was modeled by Werner and Richter, (2007) in Switzerland, assuming a lifespan of 80 years for the wood mobilized in constructions. In order to better assess the GHG substitution effect the two authors took into account 12 wooden-based products used in a house and their non-wood substitutes, such as: exterior walls, pillars, ceiling, insulation, roofing, flooring, furnishing, furniture and so on. They also hypothesized a 2% growth of the wood products market share every 10 years and a steady flow of non-wood construction materials imported from abroad; moreover, they considered that all the additional wood needed will harvested from Switzerland. The conclusions are quite interesting although the model seems to be too deterministic. So, the GHG effect on material substitution is about -6 M tone CO_2 equivalent, while GHG emissions of the wood residues reach about 3 Mito CO_2; the avoided GHG emissions due to thermal use of wood residues levels out after 2050 and only after 150-200 year the cumulated production and disposal emissions match the additional carbon stored by the whole ecosystem (in a broader sense). This study is important for a series of graphs that describe potential carbon pools of different parts of building worth being replaced by wooden-based equivalent.

A sort of ‘gate to gate’ LCA analysis was carried out by a Croatian team (Vusić et al. 2013) to evaluate the labor productivity and energy consumption under two different silvicultural interventions: thinning, and regeneration fellings respectively. The data were collected from two tracts of fellings located in Croatian mountains. It was fond that thinning operations need two times more energy per cubic meter of harvested wood (the functional unit) that regeneration felling. Such a conclusion is important for drafting different management scenarios, assuming that more energy consumed over a series of rotations means diminishes the carbon stock accumulated into the woods and wooden products.

4. Role of forest management in CO_2 mitigation

Forest management planning has two major effects: on the one hand, it may increase the forests' CO_2 mitigation potential (longer rotations, new forest species), on the other hand, the forest management may also reduce the forests' resilience to the climate change if the higher rates of tree mortality brought about by draughts, heat waves, fires and insects are not compensated by higher growths and newly afforested areas. Allen et al. (2010) summarized as many as 15 studies published between 1980 and 2008 concerning the draughts and heat-induced forest mortality in Africa, 22 articles about tree mortality in Asia and Australia, 36 in Europe, 54 in North America and 10 in South America.

As the concept of forest management envelopes not only silvicultural system but also any type on intended human interventions, the main management practices are those meant to improve the site productivity, disturbances (structural and soil disturbances), nutrition and genetic factors (Noormets et al. 2015).

Tab.2 Main results on assessing the carbon sinks under different management scearios

Reference area	Management scenarios	Estimated values	Author(s)
Northern boreal and temperate forests	Change the composition of species	62.1 ± 20.7 C/ha in coniferous forests 58.0 ± 22.1 tC/ha in broadleaf and mixed forests 40.0±15.4 tC/ha for boreal forests over 3 Asia, Europe and North America	(Thurner et al. 2014)
EU 27	Maximizing standing biomass	From 30 tC/ha to 50 tC/ha in 2100	(Kindermann et al. 2013)
	Maximizing growth	From 30 to 20 tC/ha in 2100	
North Rhine-Westphalia	Conservation and wood use	3.6 tC/ha/year = wood use strategy; 3.42 tC/ha/year biodiversity conservation strategy	(M Knauf et al. 2015)

Climate change projections are based on general world-wide circulation models; hence the pixels with different climatic features are too large to allow for modeling the connections between the forest management measures, species and terrain conditions (Lindner et al., 2010). Therefore a great deal of research was devoted to downscaling the aggregated results provided by official data (Kindermann et al. 2008;(Rupert Seidl et al., 2014); Blanke et al. 2016) and satellite images (Townshend et al. 2012; Srivastava et al. 2012; Muukkonen & Heiskanen 2007; Bayat et al. 2012; Gallaun et al. 2010).

(Kindermann et al. 2013), concluded that maximizing the increment will be more effective than maximizing the standing biomass at the end of the forecast period, in 2100. The estimations were done at EU27 level. The additional amount of carbon compensated by forest growth and wood products is about 1750 million tC compared with the management focused on maximizing the standing biomass. Because maximizing growth implies lower rotations, by the end of the forecast period the authors estimated that the average amount of carbon stored by a hectare of forest will decrease from 30t C/ha to 20 tC/ha. Although the credibility of management scenarios stretching over a couple of decades is questionable, on much larger areas their results are sensible, as shown in Table 2.

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5. Role of forests in providing fuel for bio-energy

Birdsey & Pan (2015) based on an extensive literature review, concluded that: 1) harvesting for bio-fuel has recently increased, although the timber production has been relatively stable since 1990, globally; 2) the terrestrial long-term carbon sink decreased due to a higher intensity of management, regardless the land use or the land cover.

Global Biosphere Management Model (GLOBIOM) is a global partial equilibrium model designed for forestry and agriculture, based on spatial optimization. The supply is estimated within a square grid of 200 km resolution while the demand is and trade with biomass operate at regional level, the world being divided into 30 regions. The competition between regions is considered to perfect and some by-products from each production flow are also included into the inputs. The model operates with the following six land cover types: cropland, grassland, managed forests, unmanaged forests, plantations and other natural vegetation land. This model was utilized by (Lauri et al. 2014) to examine the effects of setting aside all primary forests for protection against the baseline scenario, from the biomass energy perspective in 2050. Energy wood supply curves were outlined at various hypothetical energy wood prices. The authors concluded that by the year of 2050, as much as 18% of the energy demand could be satisfied through the baseline scenario, or 14% under the primary forest conservation scenario.

A more detailed study was carried by Smeets & Faaij (2007) who foreseen the demand and supply of wood up to 2050, using the database, scenarios and provisional studies available. The core concept of the study is the forest surplus growth, defined as the forest growth not needed for wood industry and fuelwood; explicitly, the authors have split the demand for bio-energy into two components: the existing demand of fuelwood and the wood surplus that may feed modern bioenergy production. The study concluded that the economical–ecological potential of the wood supply from natural forests will be insufficient to meet the projected demand for 2050. However, the potential supply of bioenergy from logging and wood processing residues was estimated to be somewhere between 3,6 million and 6,1 million GWh in 2050.

Moiseyev et al. (2011) addressed the effect of higher prices for the wood biomass needed to reach the goal of using more renewable energy sources (RES). The research team used the EFI-GTM (European Forest Institute Global Trade Mode) to simulate the behavior of the European wood industries assuming that all wood and forest products are sold and bought on a global competitive market. At high costs, the available wood resources suitable for energy may provide 24% of EU-RES target; if additional by-products would have been mobilized (black liquor from pulp industry, household waste wood and demolition wood, the contribution would barely reach 32%.

In 2014 EU launched the new climate and energy framework, setting up a new target for 2030, when the share of renewable resources is expected to reach 27% of the total energy consumption. The amount of wood needed to satisfy this target is about 108 Mtoe . If all of this would have to come from round wood, it equals 550 million m3 of round wood; equal to the current total harvesting of round wood in the EU. An important concept of this policy is the carbon parity, which actually refers to the year when the biomass growth will compensate the avoided CO2 emission brought about by fossil fuels. This lag occurs because the effectiveness of burning fossil fuels for energy is much higher for coal and natural gas. Nabuurs et al. (2017) estimated that party of wood against coal will be reached by the year of 2120 and the year 2200 for parity against natural gas. These prognoses are not optimistic at all considering the accumulation rate of biomass and the risk of wild fires that would compromise the whole substitution scheme (Mackey et al. 2013; Seidl et al. 2014).

In Japan, Nishiguchi & Tabata (2016) analyzed the social, economic, and environmental aspects of utilizing woody biomass for energy by direct burning and burning wood pellets. They findings indicated that if 8.58 million tons of annually unutilized woody biomass were collected and utilized for direct burning method would have the advantage of reducing 13.7 million tons of CO2 emissions. Analyzing the two options of direct burning and pellets burning respectively and considering all additional side-effects regarding job creation, as well as the production new stoves tailored for pellets, they concluded that direct burning is the best option in terms of induced CO2 emission.

A very interesting study on pellets durability was carried out by Paukkunen (2014) on eight plots of small diameter pine logs on which different technologies of production were tested. The author concluded that longer press tunnels, proper timing of harvesting, and steamed raw material contribute the most to the durability of pellets. Worth noting, pellets durability is a key issue of LCA because the production of steam-treated pellets requires more energy but, at the same time, their breaking strength is 1.4-3.3 times greater than the breaking strength of untreated ground softwood (Lam et al. 2011). The moisture content is important in producing high quality pellets because water is a binding agent that affects pellets durability (Samuelsson et al. 2012; Ahn et al. 2014).

6. Conclusions

In spite of the common sense arguments that forests store high quantities of CO2 by default, their role in carbon mitigation is still controversial due to the numerous uncertainties pending the forest management, on the one hand, and the wide variety of wood mobilization: fuelwood, furniture, composite materials, and so on. LCA is also a very useful tool that allows consistent and coherent analyses of the carbon food print, under different scenarios. However, when it comes to defining the functional unit and the different alternatives of matching its requirements, non-wood products seem to be more reliable, at least for the fact that all non-wood products used in construction and different industries are characterized by well-defined and precise technological inputs, which is not the case for the wood.

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ISSN 2537 - 3757, ISSN-L 2537 – 3757

Proceedings of the 4th Edition of the International Conference Integrated Management of Environmental Resources - Suceava, November 3-4th, 2017. Editura Universității „Ștefan cel Mare” Suceava, Romania.

Publisher:

Editura Universităţii „Ştefan cel Mare” din Suceava

Editors (eds.):

Sergiu-Andrei Horodnic, Mihai-Leonard Duduman, Ciprian Palaghianu

All papers in this publication were submitted on-line and have been edited to achieve a uniform format. Authors are responsible for the content of their paper.

Order to:

„Ștefan cel Mare” University of Suceava, Forestry Faculty

Universității Street 13

720229 Suceava, Romania

Phone: +40 0230/522978 Fax: +40 0230/521664

E-mail: silvic@usv.ro

Web: http://silvic.usv.ro/imer2017/

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