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Sustaining the sequestration efficiency of the European forest sector

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ABSTRACT

The optimal forest management strategies for mitigating climate change are hotly debated during political negotiations, because afforestation and forest management can increase atmospheric CO_2 removal, and the wood produced can provide a substitute for fossil fuel. Studies quantifying the carbon balance of the forest sector apply a wide variety of management and wood-use scenarios. Some model studies include future climate change effects on forest growth, but others ignore them. Here, a conceptual empirical model of sequestration efficiency, the fraction of net primary production stored in the biosphere and anthroposhere, simulates European forest carbon pools and fluxes. The sensitivity of the sequestration efficiency of European forests was quantified by varying model parameters along the forest growth and wood transformation chain: environment and climate change, harvest intensity, rotation length, fraction of harvest residues left on site and substitution efficiency. Irrespective of the evolution of the sink, the forest sector as a whole remains a net carbon absorber in 99% of the simulations at a time horizon of 100 years, even if in 25% of the simulations the forests themselves become sources. However, if the goal is to enhance the current sequestration efficiency to mitigate emissions, only in 25% of the simulations the sink efficiency was found to be enhanced. If the current sink were to reverse to a source, no management action or change in wood use would result in an increase in the current forest sequestration efficiency. In all other cases, increasing harvest levels would lead to an increase in forest sector carbon emissions, highlighting the pivotal role of the baseline used to set the emission reduction targets. Our results show that the uncertainty on the response of European forest to climate change undermines the quest for a carbon-optimal management strategy. The uncertainty in whether climate change will maintain the current forest sink or turn it into a carbon source is largely overlooked in the debate over the best forest management strategy to reduce the growth of atmospheric CO_2 concentration, yet it is large enough to change the merit order of different alternatives.

1. Introduction

Expectations of forests and forest management are high, especially in the context of climate change mitigation (UNFCCC, 2015). These expectations are based on the potential of: (a) afforestation, reduction of deforestation emissions and forest management to remove atmospheric CO_2 through photosynthesis, (b) carbon stored in wood products to delay the release of harvested carbon into the atmosphere, and (c) substitution of fossil fuel by wood in energy production or by the replacement of energy-intensive materials. With 64% of the world's forests being managed (FAO, 2010) and an estimated global forest carbon sink of 2 Pg C yr^{-1} (Pan et al., 2011), excluding tropical deforestation (Le Quéré et al., 2009), forests appear to live up to these expectations. As a result, the Paris agreement places forests at the heart of the carbon emissions mitigation initiatives with its articles 4 and 5 respectively stating the need to "reach a balance of anthropogenic emissions and removals in the 2nd half of the century" and to "conserve and enhance the sink" (UNFCCC, 2015).

A large body of research has been published focusing on evaluating and managing the potential of the forest sector to offset CO_2 emission from fossil fuel burning. This work shows that increasing wood removal, while keeping all other parameters constant, whether realized through shorter rotation length (Kaipainen et al., 2004; Liski et al., 2001) or removal of stumps and slash (Strömgren et al., 2013), would increase the carbon emission of the forest sector in the first years following the treatment. Where wood products are used in place of more fossil-intensive energy or materials, wood usage leads to a (relative) reduction in carbon emission quantified through so-called substitution or displacement coefficients (Sathre and O'Connor, 2010). Even though the substitution effect was found to have a large impact on the wood-

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products carbon balance (Fortin et al., 2012; Lundmark et al., 2014), the definition and use of substitution coefficients is subject to large uncertainties due to their dependence on methodological choices to define the characteristics of the industries, and the reference scenario (Hellweg and i Canals, 2014). Consequently, increased wood removals were reported either to reduce, at least in the long term (Lundmark et al., 2014; Marland and Schlamadinger, 1997; Perez-Garcia et al., 2007; Vanhala et al., 2013), or not reduce (Fortin et al., 2012; Hudiburg et al., 2011; Kallio et al., 2013; Sievänen et al., 2014) atmospheric CO_2 concentration as substitution effects accumulate over time.

Wood removal, product use and energy substitution are all accounted for in recent studies on carbon management in the forest sector, however, the uncertainty surrounding the future evolution of the forest sink under climate change—changes in allocation of carbon to the short- and long-lived soil and biomass pools of the forest—and its interaction with management practices have mostly been ignored. It is often implicitly assumed that the forest sink tends towards zero when forest stands grow older than 100 years leading to carbon-neutral forest (Lippke et al., 2011), even though observational evidence does not lean in that direction (Lewis et al., 2009; Luyssaert et al., 2008). Some other studies assume that the current sink strength is maintained indefinitely, either implemented as a single average sink over the study area or, more refined, as a function of age (Hudiburg et al., 2011; Kallio et al., 2013; Lundmark et al., 2014; Pilli et al., 2017; Smyth et al., 2014) .

The recent forest sink has been attributed to changes in environmental conditions, with CO_2 concentration, temperature patterns and nitrogen deposition all contributing to the observed acceleration in tree growth (Lewis et al., 2009; Magnani et al., 2007; McMahon et al., 2010; Solberg et al., 2009). For the European forests, changes in age structure and management practice (Nabuurs et al., 2003) were also found to play a role. Nevertheless, the importance of the drivers of the current sink likely differs for different regions in Europe (Bellassen et al., 2011). While CO_2 fertilization has been projected to overtake nitrogen deposition as the main driver of the forest carbon sink in the future (Milne and Van Oijen, 2005), these projections are controversial because they disregard physiological constraints (de Boer et al., 2011), overlook the indirect effect of decreased tree longevity (Bugmann and Bigler, 2011) and do not account for the saturation of the CO_2 effect due to nitrogen (Hungate et al., 2003; Norby et al., 2010) or phosphorus limitation.

Much of the controversy stems from the knowledge gap in how the different components of heterotrophic respiration will respond to climate change (Cox et al., 2000; Cramer et al., 2001; Subke and Bahn, 2010). Also, it is currently suspected that interannual variability and the role of disturbance will become major future players in driving the sink strength of temperate and boreal forest (Anderegg et al., 2013; Beck et al., 2011; Kurz et al., 2008; Lindroth et al., 2009; Zeng et al., 2009). As a result of this inadequate process understanding, an ensemble of state-of-the-art process-based models disagrees on the magnitude of the terrestrial carbon sink by 2100, and even on its sign (Friedlingstein et al., 2014). Under the same emission scenarios some models predict the European forest will absorb up to 0.5 Pg C yr^{-1}, while others conclude it will become a source of 0.5 Pg C yr^{-1} (Friedlingstein et al., 2014). Despite being the most advanced tools to integrate ecological and physical knowledge into a consistent numerical framework, the capability of process-based models is still limited in tackling the aforementioned issues because these models are rarely designed to explicitly simulate forest management, nitrogen dynamics, pest and disease hazards and extreme events all at the same time (Naudts et al., 2015). Regional-scale empirical models, for their part, include all the complexity of management strategies and forest types and structures but are constrained to short time horizons and often limited in their capacity to simulate the effects and feedbacks of climate change on forest growth and dynamics (Pilli et al., 2017).

Although all of the controls listed above have been extensively studied separately in almost two decades of carbon management research, it remains difficult to integrate the results of this research into a consistent framework (Bellassen and Luyssaert, 2014). The problem is that different studies make different assumptions and this hampers the comparison and generalization of the results. In this study, the main uncertainties in European forestry carbon management are analysed with the goal of quantifying their contributions to the overall carbon balance of the sector and of delimiting a “safe operational space” for carbon management. This safe operational space is defined as a combination of forest management and wood-use measures that should result in maintaining or increasing the overall forest sector carbon sequestration potential compared to today.

2. Methods

2.1. Carbon sequestration efficiency

The net carbon budget of the forest sector consists of the carbon sequestered in both the forest ecosystems and in wood-use chains either through storage or substitution. In ecosystems, the net carbon input is referred to as net primary production (NPP); here we assume NPP is equal to biomass production and focus on sequestration efficiency, which is defined as the ability of the ecosystem and wood use chain together to retain part of the incoming NPP. In Europe, temperate and boreal forests lose carbon through two major pathways: timber harvesting, and heterotrophic respiration (R_h) (Luyssaert et al., 2010). The balance between carbon inputs and outputs is called the net biome production (NBP; (Chapin et al., 2006)). A positive NBP indicates the forest is a sink and thus accumulates carbon in the soil, litter and/or biomass, whereas a negative NBP indicates the ecosystem is a carbon source. Contrary to R_h, the carbon contained in the harvested wood is not immediately released back into the atmosphere—it can be stored in wood products. If it is stored in wood products, carbon is released at a decay rate that depends on the products’ longevity. Furthermore, if the harvested wood is used to replace a more fossil fuel-intensive material or energy source, the substitution effect may come into play. Substitution may result in avoided emissions, which, for bookkeeping purposes, can be considered as a sink that should be included in the carbon budget of the forest sector. The carbon balance of the forest sector ($\Delta C_{forest\ sector}$) can thus be formalized as:

$$\Delta C_{forest\ sector} = NBP_t + HWP_t + S_t \tag{1}$$

where NBP_t, HWP_t, and S_t are the carbon input at time t, into the ecosystem, into the wood-product pool, and the avoided emissions through substitution respectively, all expressed in g C m^{-2} yr^{-1}. Likewise $\Delta C_{forest\ sector}$ can be written as a function of the overall NPP at time t:

$$\Delta C_{forest\ sector} = NPP_t . \left(\frac{NBP_t + HWP_t + S_t}{NPP_t}\right)$$
$$\Delta C_{forest\ sector} = NPP_t .\ SE_t \tag{2}$$

where SE_t is the unitless sequestration efficiency of the forest sector and is calculated as:

$$SE_t = \frac{NBP_t + HWP_t + S_t}{NPP_t} \tag{3}$$

As shown in Eq. (2), the carbon balance of the total European forest sector can be calculated as the product of the total forest NPP over Europe and the sequestration efficiency for European forests. The sequestration efficiency of the forest sector represents the share of carbon sequestered in the forest sector per unit of NPP. In other words, if the sequestration efficiency equals 0.23 this implies that for each gram of carbon that has been used for biomass production in the forest ecosystem, 0.23 g C will be sequestered in the forest sector and thus did not end up in the atmosphere. This study focuses on quantifying the main drivers of the sequestration efficiency.

The advantage of this approach is that it separates the production, i.e., net primary production, from the efficiency of the production, i.e., sequestration efficiency. Such an approach stresses the fundamentally