Modelling forest biomass

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Introduction

Converting from coal to forest biomass for electricity generation attracts billions of euros of subsidies in Europe. These subsidies are granted because it is believed that switching from coal to biomass mitigates climate change. However, when a power station switches from coal to wood pellets, a significant amount of extra CO2 is released at first, because for each kWh of electricity generated, biomass emits some 20% more CO2 than the coal replaced (DNVGL 2019). Even worse, converting from natural gas to biomass causes CO2 emissions to be doubled (DNVGL 2019). Of course, when biomass is harvested, vegetation regrows so that this extra CO2 will be reabsorbed from the atmosphere over time, which is exactly the reason that forest biomass is widely embraced as a method to reach the Paris Agreement targets for limiting global warming. In fact, the main reason for converting to biomass is that emissions from burning forest biomass at the power station are allowed to be accounted as zero under EU legislation (Directive 2009/28/EC). It is therefore essential to know how long it actually takes before that initial pulse of extra emissions from the burning of wood is reabsorbed by the regrowth of wood (the so-called carbon payback period). This could then lead to more science-based rules and regulations for emission accounting and subsidies.

Carbon sequestration model

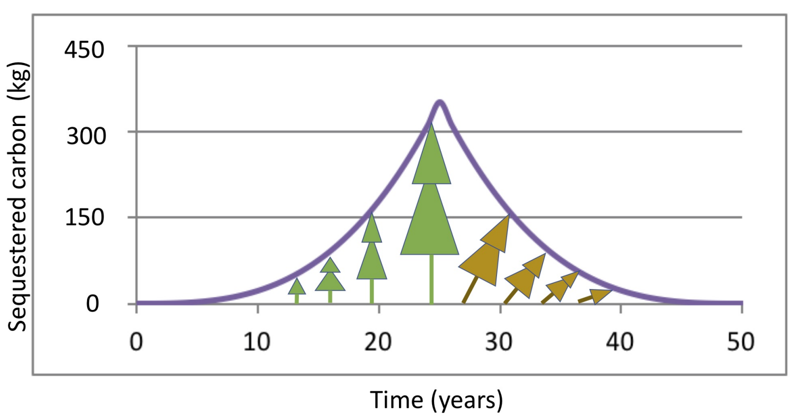

Figure 1: *Sequestered carbon in a poplar tree. After a lifespan of 25 years, the tree decomposes and the carbon is released again*

We model a tree as a cylinder without branches and leaves. We assume linear growth in time for both the tree diameter and the height. This means that the volume of the tree is given as

$$V = Gt^3, \tag{1}$$

with G the growth factor [m^3y^{-3}]. The volume partly consists of carbon. Denoting the carbon mass per unit tree volume by ρ_c [kg/m^3], the carbon mass sequestered in the tree is given by

$$m_c = \rho_c G t^3. \tag{2}$$

We note that 1 kg of sequestered carbon corresponds to 3.67 kg CO2. We assume that the tree has a natural lifespan t_{max}. After reaching t_{max}, we assume that the tree will decompose over the same period t_{max}. During this period the total carbon mass will gradually shrink over time ($t \geq t_{max}$):

$$m_C = \rho_c G \left(2t_{max} - t\right)^3, \tag{3}$$

so that at $t = 2t_{max}$ the carbon mass is zero again. A graphical representation for a poplar tree is given in Fig. 1 for t_{max} = 25 years and $\rho_c = 200$ kg/m^3 (Cannell 1999). We take the diameter growth rate 12.5 mm/year and the height growth rate 0.85 m/year. This means that $G = 1.043 \cdot 10^{-4}$ m^3y^{-3}. After 25 years, the tree has reached a height of 21.3 m, a diameter of 31.3 cm and sequestered 326 kg of carbon (see Fig. 1). After another 25 years, all sequestered carbon is released into the atmosphere again.

Clear-cut model

We will now consider the case where the tree is cut $t = t_c$ and used as biomass fuel. This means that at $t = t_c$, a carbon mass of $\rho_c G t_c^3$ is emitted into the atmosphere and there is no sequestered carbon anymore. We also assume that at t_c a new tree of the same species is planted, which is cut down again at $t = 2t_c$, and so on. This scenario thus addresses natural forests being clear-cut and replaced by production forests and is illustrated in Fig. 2 (brown line), where we take t_c = 20 years. At that time, 167 kg carbon is emitted into the atmosphere by cutting and burning the tree for biomass fuel. The blue dashed line represents the sequestered carbon if the tree would not have been cut. The difference between both lines is the so-called carbon debt, i.e., the carbon that is emitted into the atmosphere in comparison with non-intervention. At $t = t_p = 35$ years, the brown and blue lines intersect (carbon parity), which means that the carbon debt is paid off. The payback period τ is now defined as $t_p - t_c$ = 15 years. This means that carbon parity is reached 15 years after cutting the tree.

Payback period

We now consider the general case that a tree described by growth factor G^A and carbon density ρ_c^A is cut and replaced by a tree with growth factor G^B and carbon density ρ_c^B. The carbon debt will be zero at time t_p defined by

$$G^A \rho_c^A \left(2t_{max} - t_p\right)^3 = G^B \rho_c^B (t_p - t_c)^3, \tag{4}$$

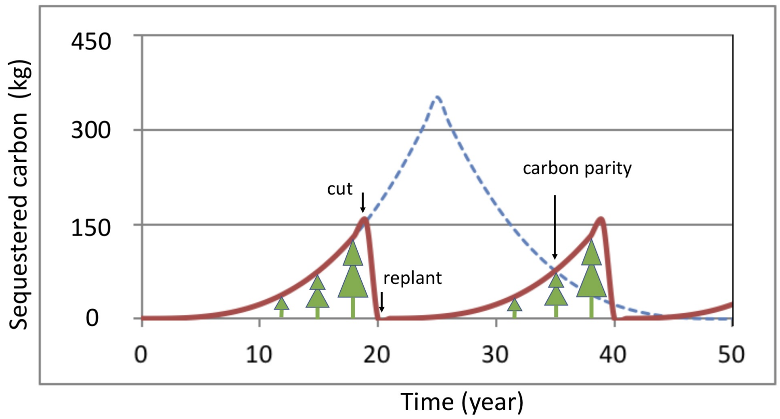

Figure 2: *Sequestered carbon scenario comparison for clear-cut and replant (brown curve) at $t = t_c = 20$ years, and natural forests (blue dashed curve). The difference between both curves is the so-called carbon debt. At $t = t_p =$ 35 years, carbon parity is reached, meaning that the debt is paid off*

which leads to

$$t_p = \frac{2t_{max} + Rt_c}{1 + R}, \tag{5}$$

where $R = \sqrt[3]{G^B \rho^B / (G^A \rho^A)}$ is the replacement coefficient. In Fig. 2, $R = 1$ (we replace poplars by poplars). Also the payback period can now be computed:

$$\tau = \frac{2t_{max} - t_c}{1 + R} \tag{6}$$

Substituting the values $t_{max} = 25$ years and t_c = 20 years from Fig. 2, we find back that $\tau = 15$ years indeed. If, however, oaks that have a lifespan of 100 years are replaced by poplars we find that the carbon payback period is 154 years.
[For oak, we compute from Cannell (1999) that $G^A = 7.1 \cdot 10^{-6}$ m^{3}y^{-3} and $\rho_c^A = 400$ kgm^{-3}. For poplar, we already had that $G^B = 1.0 \cdot 10^{-4}$ m^{3}y^{-3}, and $\rho_c^B = 200$ kgm^{-3}. This leads to $R = 1.92$. Note that (6) has to be adapted for more generations of poplars].

References

[1] Gevolgen van de inzet van biomassa voor de elektriciteit en warmteproductie op emissies naar de lucht. DNVGL report (in Dutch), 2019

[2] Cannell, M.G.R. Growing trees to sequester carbon in the UK: answers to some common questions. Forestry 72, 237-247, 1999