Forest Carbon Sequestration as a
A summary of the results of a study that compared the effects of climate change on the forest ecosystem, mitigation costs, and timber production under several climate change scenarios.

Forest carbon sequestration is an important technique for the capture of carbon dioxide (CO₂) from the atmosphere. A large number of studies have determined the cost of carbon sequestration in the forest ecosystem (in below- and above-ground biomass and soil). The obtained results allow the costs of forest carbon sequestration, called mitigation costs, to be compared with the costs of other policy options that aim to offset or avoid carbon emissions.

Background
The current paradigm adopted by most researchers is that the forest growth (and as a result, carbon sequestration) is stimulated by increasing CO₂ (fertilization effect) and also, in boreal and temperate
forests, by rising temperatures. Processes underlying respiration are found to respond to the temperature in an exponential way, but are not influenced by the CO$_2$ concentration. However, the analysis of below-ground biomass shows a completely different picture to that of the above-ground biomass, namely, a decline in soil carbon as the temperature increases and a marked decline in sequestration of root-derived carbon in the soil as the CO$_2$ concentration increases. These findings are important for the overall evolution of sequestered carbon in temperate and boreal forests because the amount of carbon stored in the soil may be about four times higher than that stored in the vegetation.

Forests are a valuable natural resource and, hence, finding the optimal trade-off between timber production and carbon sequestration is important for forest managers and forest policies. Different approaches for sustainable forest management are suggested. One of them states that the joint use of carbon sequestration and timber production will produce the lowest mitigation cost; in particular, when land is scarce and forests compete with many other land uses. However, the objective of the maximization of timber production net benefits does not align well with the objective of the maximization of carbon sequestration net benefits.

Furthermore, hardly any work has been presented so far, which analyzes the effect of climate change on the mitigation costs for forest carbon sequestration. Consequently, previously obtained estimates of these costs may need to be revised and the optimal portfolio of climate policies redefined.

**Simulation Model and Data**

To incorporate climate change impact on mitigation costs, this study extended a size-distributed biogeochemical-economic model, which describes the biological processes of the forest ecosystem and the dynamics of carbon in soil and below- and above-ground biomass. The corresponding optimization problem determines the optimal forest management regime, maximizing the joint benefits from timber production and carbon sequestration. Since partial harvesting achieves the highest combination of wood yield ($m^3$) and carbon storage ($kg C/m^2$) in terms of physical units, the formulation of the model has to allow for solutions that range from no harvesting, selective harvesting to complete harvesting of the stand. Qualitative analysis of the problem shows that selective logging is the optimal harvesting regime for the chosen specifications.

**Climate Change**

This study compared the effects of climate change on the forest ecosystem, mitigation costs, and timber production under climate change scenarios A2 (2100: CO$_2$ concentration 870 parts per million (ppm), Δ temperature 5 °C, Δ precipitation – 250 mm) and B2 (2100: CO$_2$ concentration 621 ppm, Δ temperature 4 °C, Δ precipitation – 200 mm) defined by the IPCC Third Assessment Report of Climate Change and the general circulation model ECHAM4, using the baseline scenario with no climate change (NoCC).

With respect to possibilities of adapting the forest ecosystem to climatic changes, the model allows for a variation in the rotation age, stand density, and repopulation, since these options are open to most stands. Other adaptation strategies for stands, such as the change in the tree species, region, or produced mix of timber products, are not analyzed. The mathematical complexity of the model makes it challenging for a qualitative investigation and quantitative techniques are to be employed.

**Computation**

This study used the biogeochemical process model Growth Of Trees Is Limited by Water (GOTILWA) to simulate the evolution of a forest ecosystem. The data generated allow the parameters of the model to be estimated, which, in turn, are solved numerically with GAMS (General Algebraic Modeling System). The study also applied the Escalator Boxcar Train method commonly used for the description of the evolution of size-structured populations and solving distributed optimal control problems.

**Time Horizon**

Most forest carbon sequestration studies consider
Planning horizons from 50 to 150 years; by then, climate change will take place and affect processes in forest, such as the soil carbon dynamics, reproduction, growth, and mortality of the trees. This study considered a time horizon of 150 years.

Data
To reevaluate mitigation costs under climate change, the study determined the optimal logging regime, which maximizes the discounted net benefits from timber production and carbon sequestration of an existing stand of Pinus sylvestris (Scots pine) located in Northeast Spain over a time horizon of 150 years. In other words, the results refer to a change in the management regime, but cannot be transferred directly to afforested or reforested land.

Simulation Results
Figure 1 illustrates the evolution of carbon in the forest ecosystem for the baseline scenario (NoCC) and Scenario A2. For brevity, the results of Scenario B2 are not presented, since they are qualitatively similar to the results of Scenario A2.

In the absence of climate change, an increase in the CO2 price within the historically experienced price range from 0 to 40€ leads to an increase in the amount of sequestered carbon in the forest ecosystem, averaged over time, by approximately 15%; whereas a CO2 price of 0€ (only timber production) leads to a decrease in carbon by approximately 20%. However, in the presence of climate change, even a CO2 price of 40€ is not sufficient to maintain the initial amount of sequestered carbon. The higher net productivity of the forest leads, at the beginning of the planning horizon, to an increase in the retained carbon in the forest ecosystem.

Even after a decade, the decrease in soil carbon offsets the increase in the sequestered carbon in the biomass and the forest ecosystems can become a source of carbon emissions for any of the evaluated carbon prices. If the initial amount of soil carbon is reduced by 50% (50 tons instead of 100 tons), the ranking of the evolutions of the different climate scenarios is maintained (not shown in Figure 1). In this case, Scenario A2 with a carbon price of 0€ leads to a decrease in the amount of sequestered carbon in the forest ecosystem, while all other scenarios and price constellations lead to an increase at the end of the planning horizon.

Although an increase in the CO2 price favors management regimes that augment the sequestered carbon in the forest ecosystem, it comes at the cost of a decrease in the net benefits of timber production. The study calculated the corresponding mitigation costs in terms of sequestered carbon per ton, using the average storage method.21 These costs are presented in Figure 2 for the three different scenarios.

Without climate change, the sequestration of 15 (35, 55) tons of carbon leads to a mitigation cost of 18.79 (39.93, 60.06) €, while the same amount of sequestered carbon leads to a mitigation cost per ton of carbon of 35.53 (66.86, 83.78) € in scenario A2, and to a mitigation cost of 27.43 (47.64, 69.19) € in scenario B2. Figure 2 shows that, when the amount of sequestered carbon per hectare is low (< 5 tons), the mitigation costs per ton of carbon are similar for each scenario. However, once the average tonnage of sequestered carbon reaches 20–50 tons, the mitigation costs increase with climate change by approximately by 20–100%. Finally, when the amount of sequestered carbon is approximately 80 tons per hectare, the mitigation costs again tend to be closer. However, the latter
situation is not very interesting, because then mitigation costs per ton of carbon are not competitive compared to other policy options.

**Conclusion**

In the presence of climate change, forest carbon sequestration remains a viable policy option to offset or avoid human induced carbon emissions. However, forest carbon sequestration is losing its competitiveness compared to other policy options if the amount of sequestered carbon per hectare exceeds 5–10 tons per ha. (due to rising CO$_2$ prices and limited availability of land). This effect will be even more essential if other policy options become cheaper, for instance, due to technological and scientific innovations.

This study demonstrated that the consideration of climate change effects significantly alters the magnitude of mitigation costs, so that the role of forest carbon sequestration as part of a general climate policy needs to be revised. Further research is necessary to determine the overall balance of the opposing effects of CO$_2$ fertilization and soil carbon release for different locations and different forest types, for instance tropical or boreal forest. Moreover, the analysis needs to be complemented by considering the feedback effects of biophysical factors in order to evaluate the entire effects of changes in forest management on local and global warming. em

**References**


20. Goetz, R.; Hrtonenko, N.; Xabadia, A.; Yatsenko, Y. Using the Escalator Boxcar Train to determine the optimal management of a size-distributed forest when carbon sequestration is taken into account; *Large-Scale Scientific Computing* **2008**, 4818, 334-341.