Climate change affects the Carbon cycle of forest cohorts but not homogeneously.

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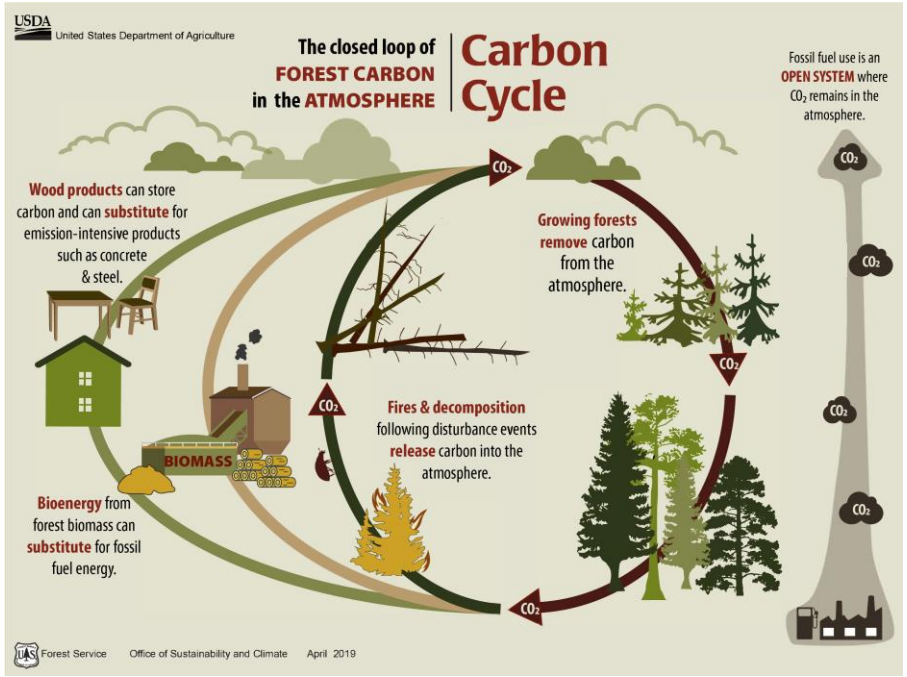
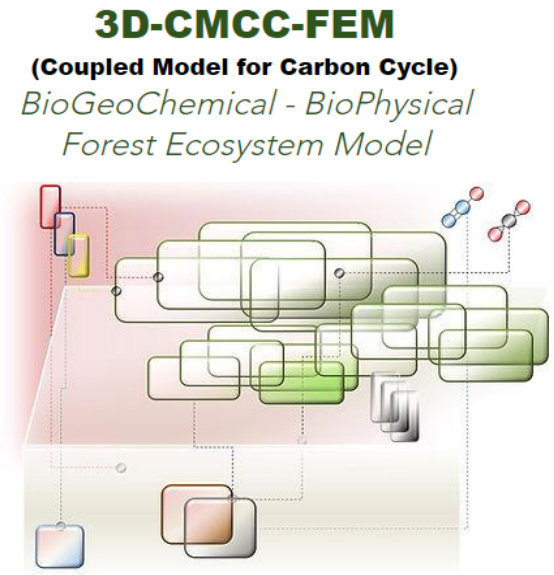
Introduction

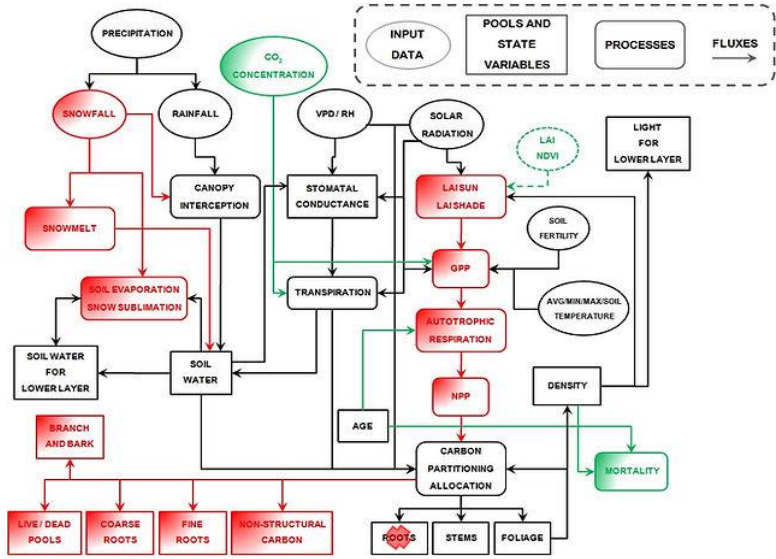
Human intervention shapes the distribution, structure, and age of forests. The dynamic balance between growth (fluxes and stocks) and respiration is climate-dependent but responds differently with stand age.

It is important to quantify carbon storage and flux sensitivity to climate change in different vegetation types and development stages.

A modeling approach allows studying forest dynamics in response to climate change







3D-CMCC-FEM

(*3 Dimensional Coupled Model Carbon Cycle Forest Ecosystem Model*)

Fully bio-geochemical forest model that simulates storage and fluxes of Carbon, Water, and Nitrogen in forest ecosystems. The model reproduces forest dynamics with different species, ages, diameters, and height classes. Considering management practices, the model simulates C and N fluxes in terms of GPP and NPP, partitioning, and allocation in the main plant compartments.

Aims

This study investigates the interactions between future climate conditions and different age classes.

We analyzed:

- How climate change impacts overall forest productivity and C-storage capacity across different species and age cohorts located in different regions of Europe;

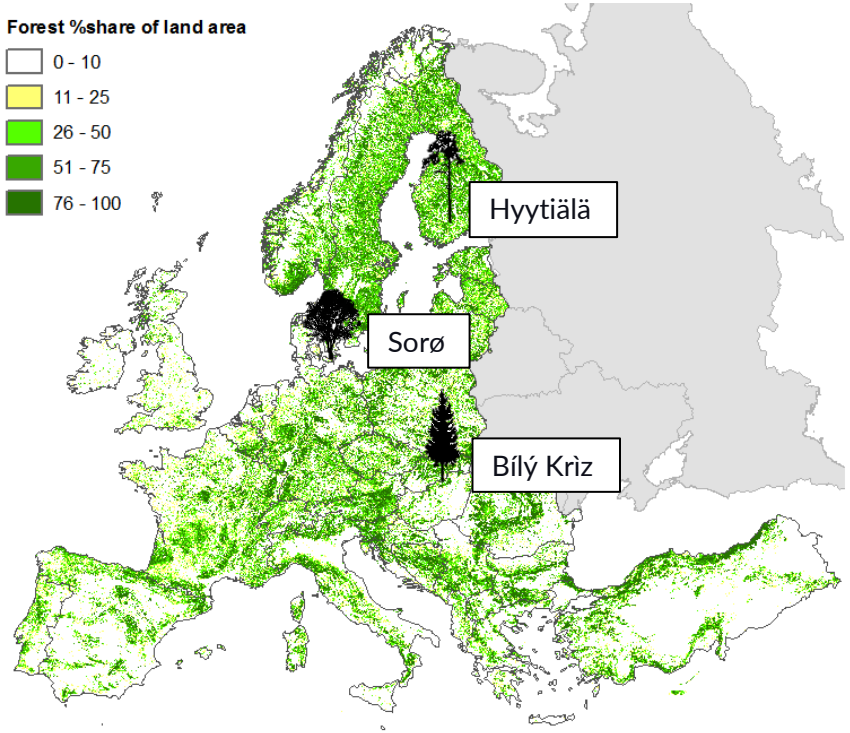
- how and if forest age can modulate stand dynamics in response to climate change.

The chosen species:

1. Covers a wide climatic gradient;

2. They are mono-specific so easy to study the effects of climate change on single species;

3. They have a long monitoring history and the availability of a wide range of data.



- Hyytiälä (FI-Hyy): Scot pine (*Pinus sylvestis* L.) of a boreal forest in Finland.

- Sorø (DK-Sor): European beech (*Fagus sylvatica* L.) of a temperate oceanic forest in Denmark

- Bílý Krìz (CZ-BK1): Norway spruce (*Picea abies* (L.) H. Karst) of a wet continental forest of the Czech Republic

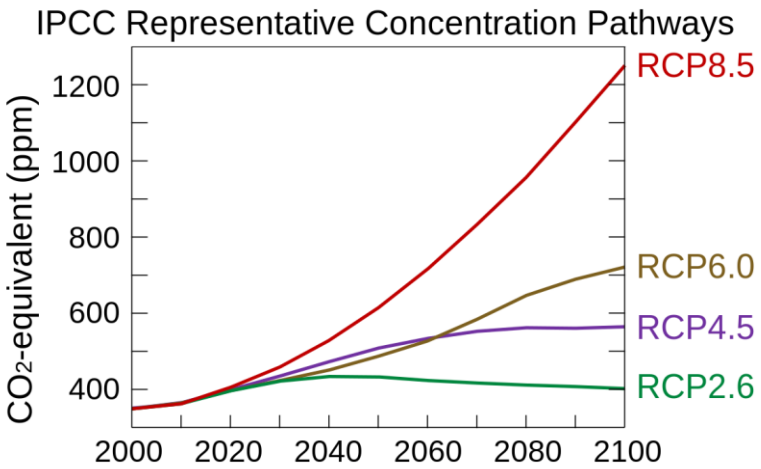
Methods

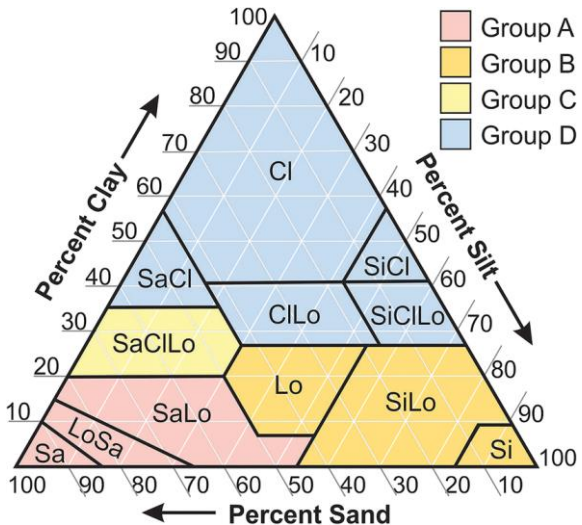
The model was forced with climate outputs under five representative climate scenarios and soil data from the Word Soil Information database

- Current Climate scenario (CCS)
- RCP 2.6
- RCP 4.5
- RCP 6.0
- RCP 8.5

Soil data

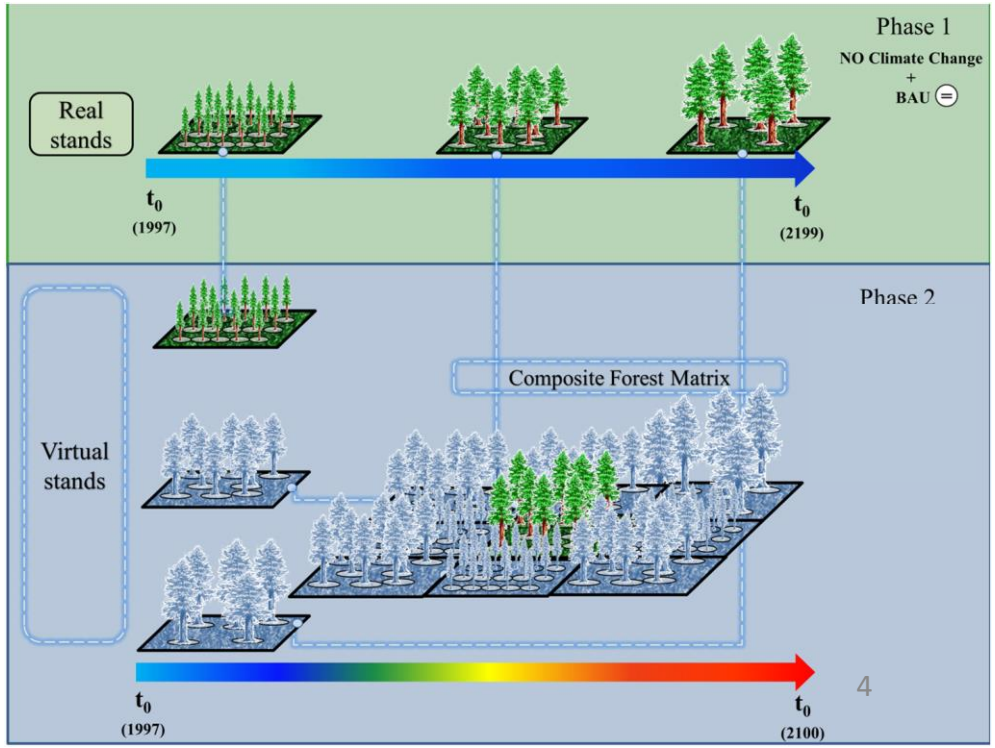
- Soil depth
- Clay content
- Sand content
- Silt content





Over a matrix of 11 age classes for each site, with a Composite forest matrix approach:

- A full rotation period (from 11 to 140 years old)
- Repeated cycles of detrended climate data from 1996 to 2006
- BAU management
- Fixed CO2 concentration (368.8 µmol mol^{-1})

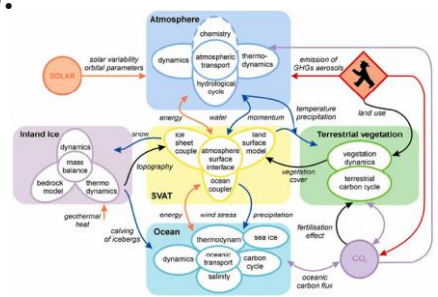


Methods

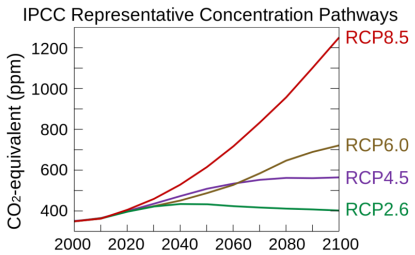
- A factorial ANOVA (p = 0.05) was performed to verify significant differences between age groups, climate scenarios, and their interactions.
- Significance between means was determined using the Tukey *post hoc* multiple comparisons of means test at the 95% confidence level (p = 0.05).

- 825 simulations were performed (5 ESM*5 RCP) * 11 age classes * 3 sites)
- No management (no confounding factors)
- Results are reported for NPP and tCWS for fluxes and stocks

ESMs



RCP scenarios

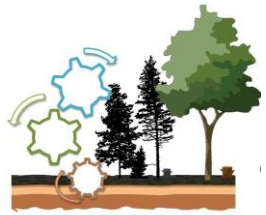


3 Sites
11 Age classes

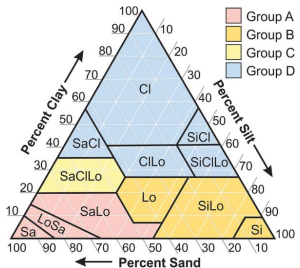
FLUXNET – A Global Network

ISIMIP
Inter-Sectoral Impact Model Intercomparison Project

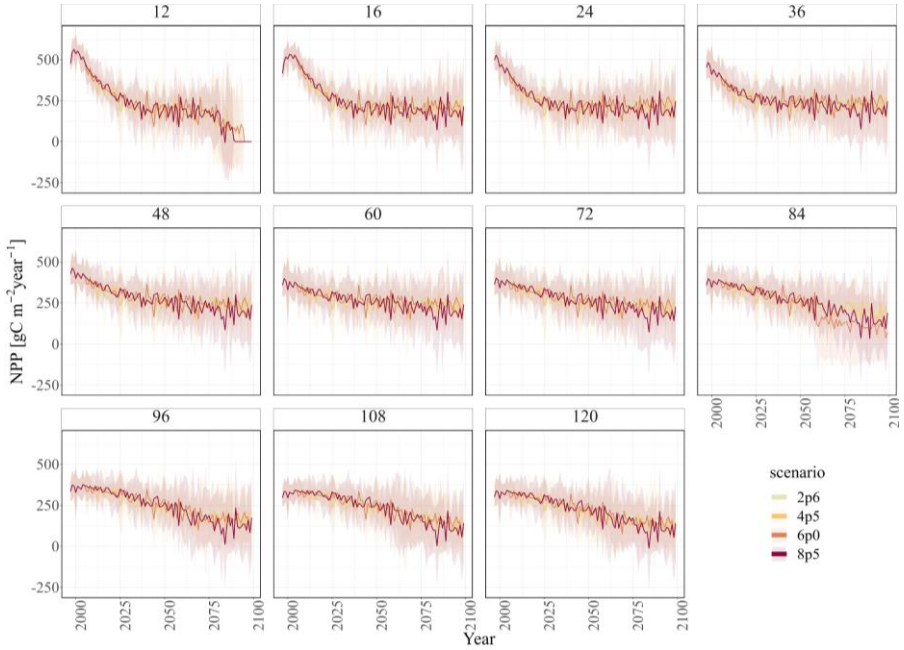
3D-CMCC-FEM



Soil data

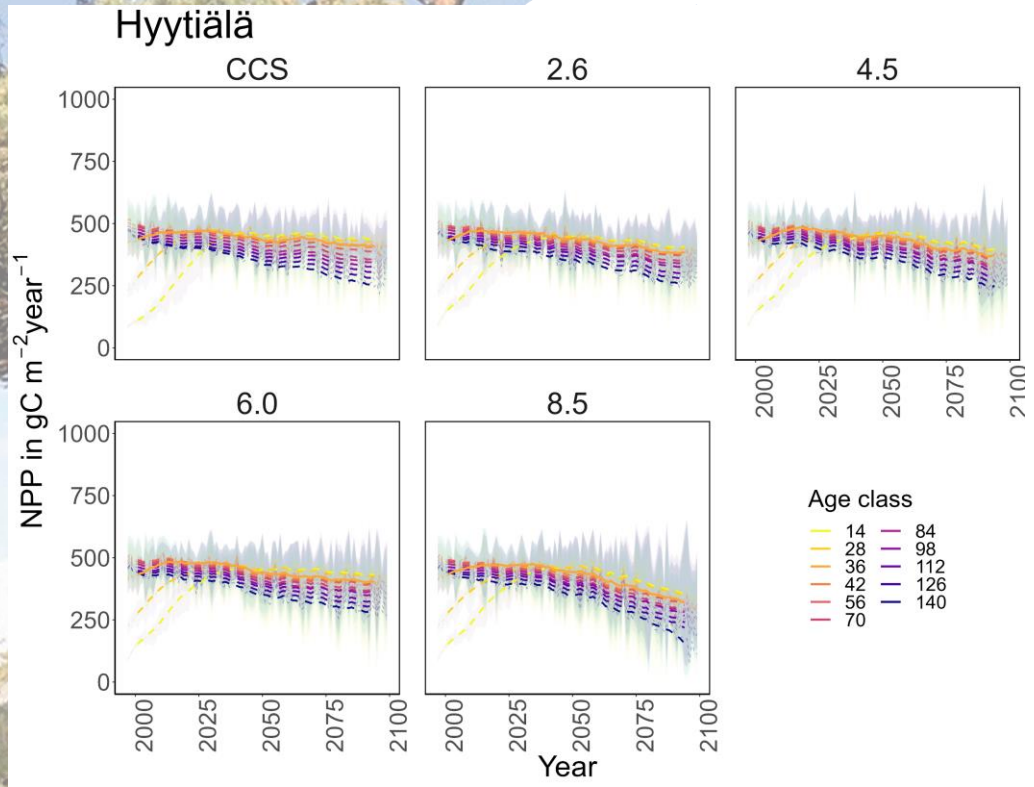


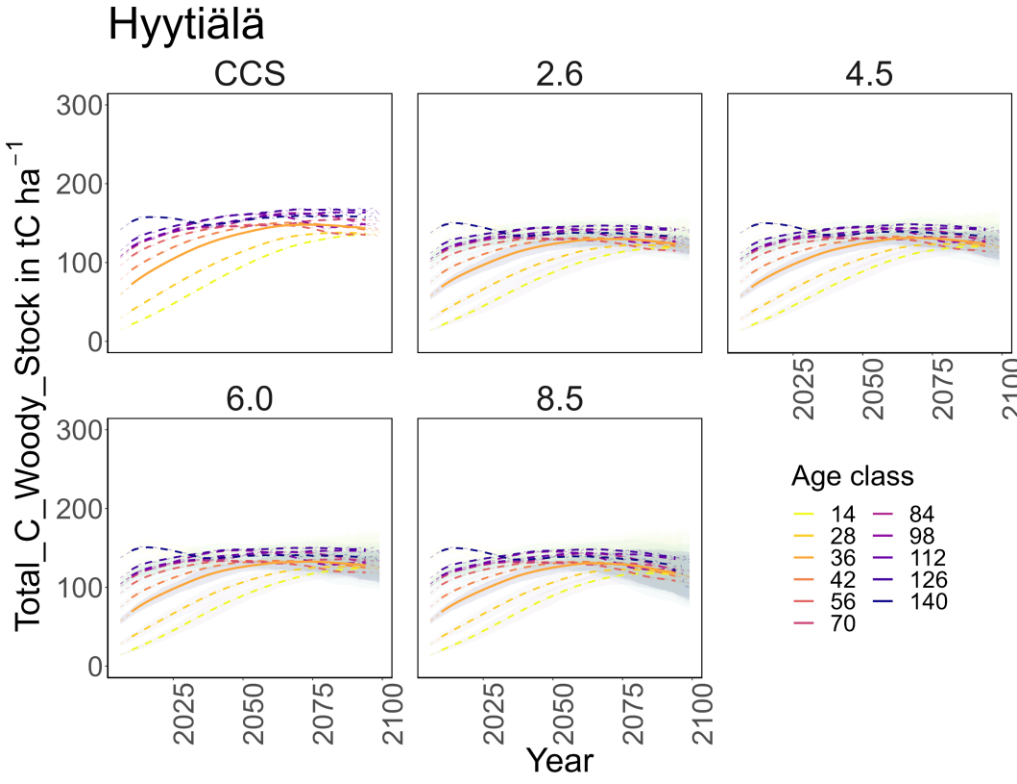
Simulations



Results

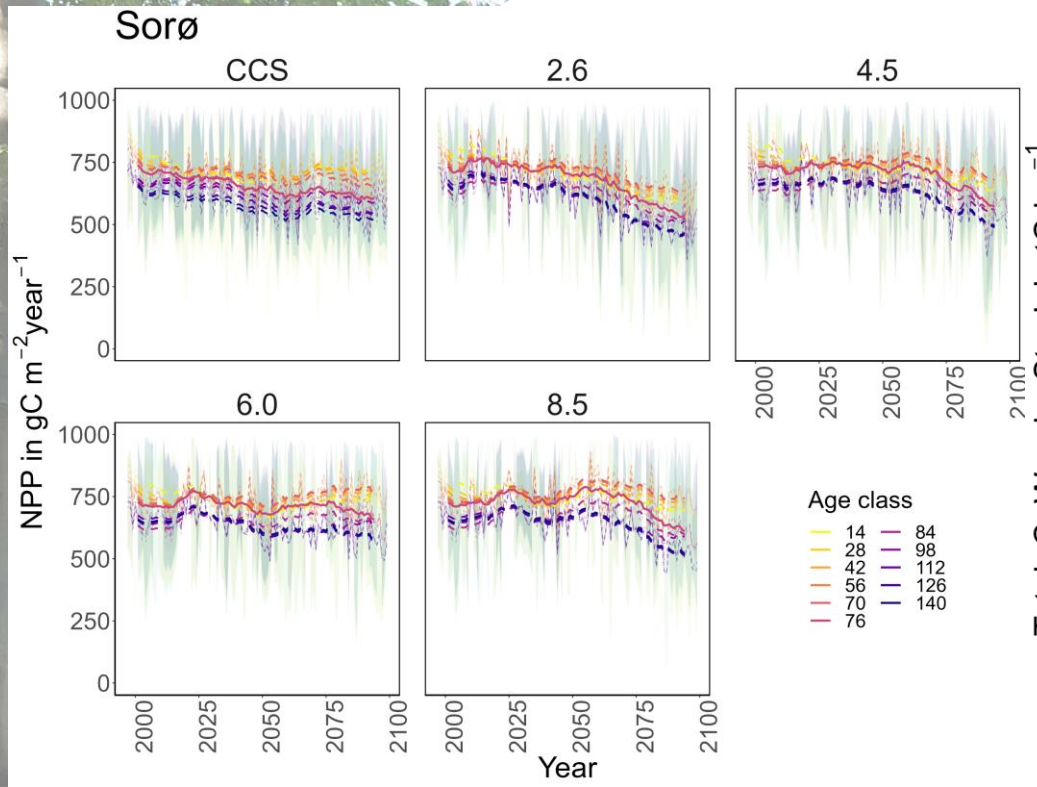
- Scot pine has relatively stable NPP along the century (~450 gC m^{-2} $year^{-1}$) in younger age classes, declining in the oldest ones to ~250 gC m^{-2} $year^{-1}$
- Younger age classes (14- to 56-year-old) showed the fastest increase in tCWS, culminating around 2075 and declining by the end of the century
- The most productive cohorts are 36 to 56 years old
- NPP shows a minor increase under RCPs when compared to CCS, up to RCP6.0.

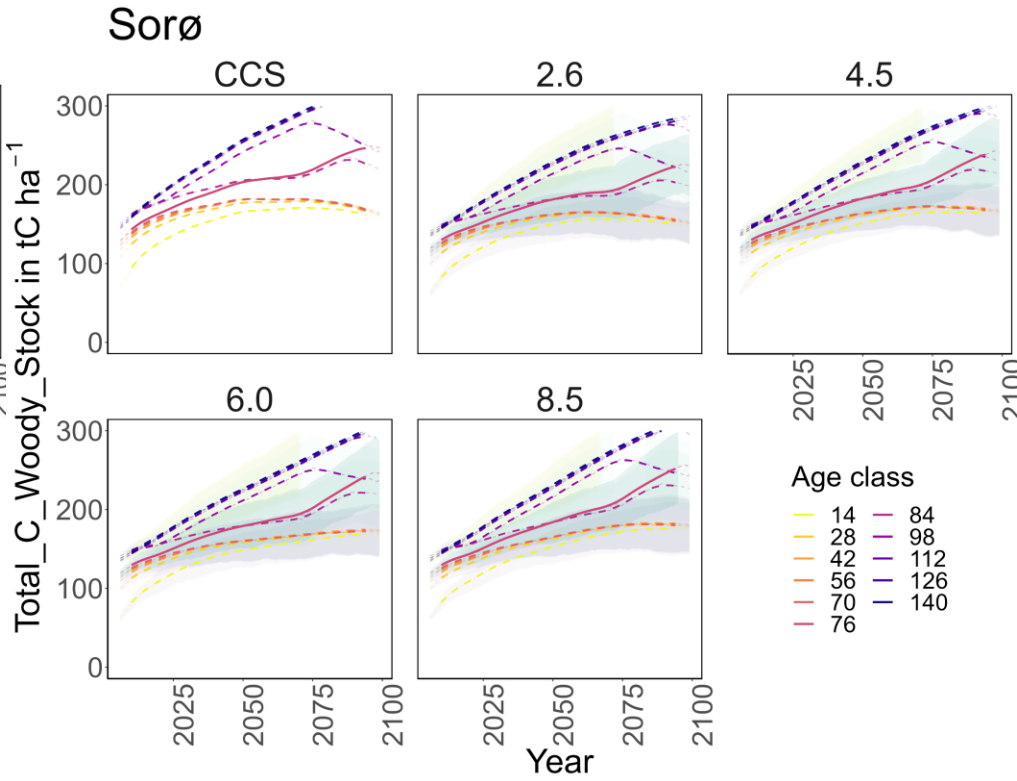




Results

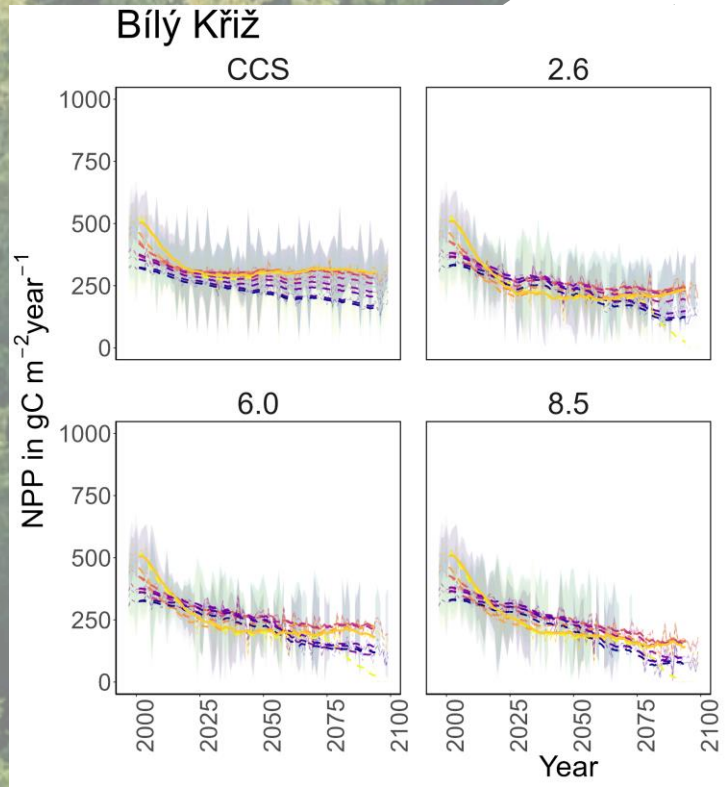
- The beech forest shows an increasing NPP with increasing atmospheric CO_2 and temperature in all age classes
- NPP at the end of the century varying from ~600 gC m^{-2} $year^{-1}$ (under CCS) to ~700 gC m^{-2} $year^{-1}$ (under RCP 6.0)
- Mean annual NPP peak for the 56-year-old class with lowest values for the oldest age classes (112- to 140-year-old)
- tCWS declined in the younger classes at the end of the century while older ones kept growing.
- Mean annual tCWS reached the maximum for the oldest classes (+10% to + 66% of the youngest age class)

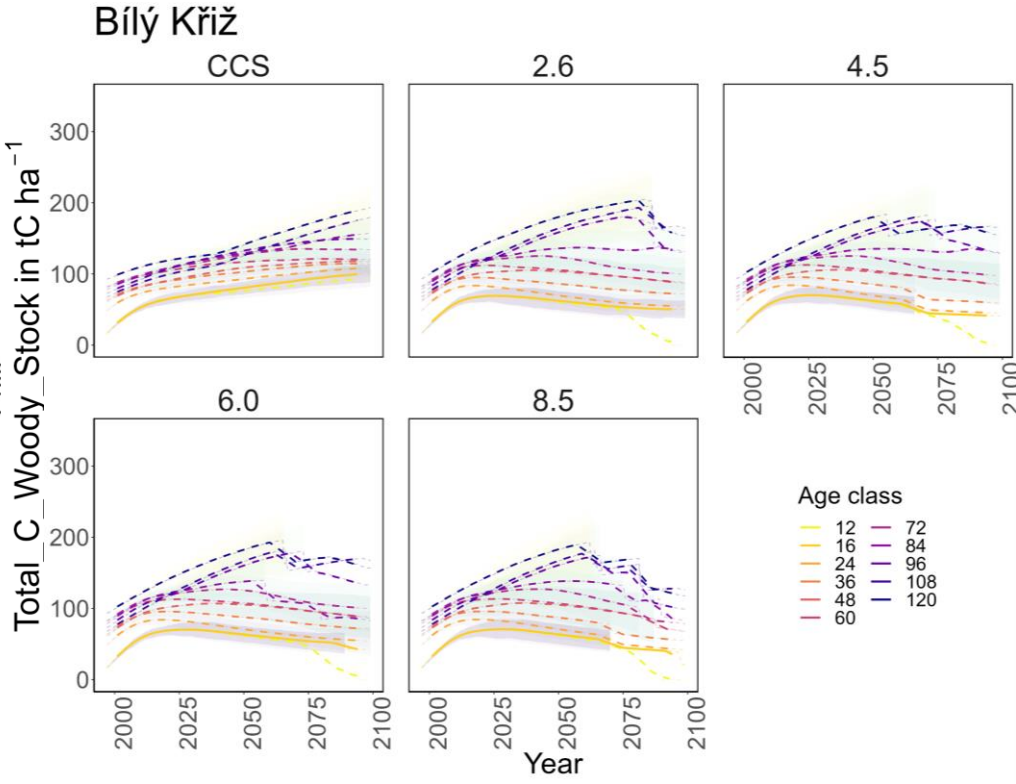




Results

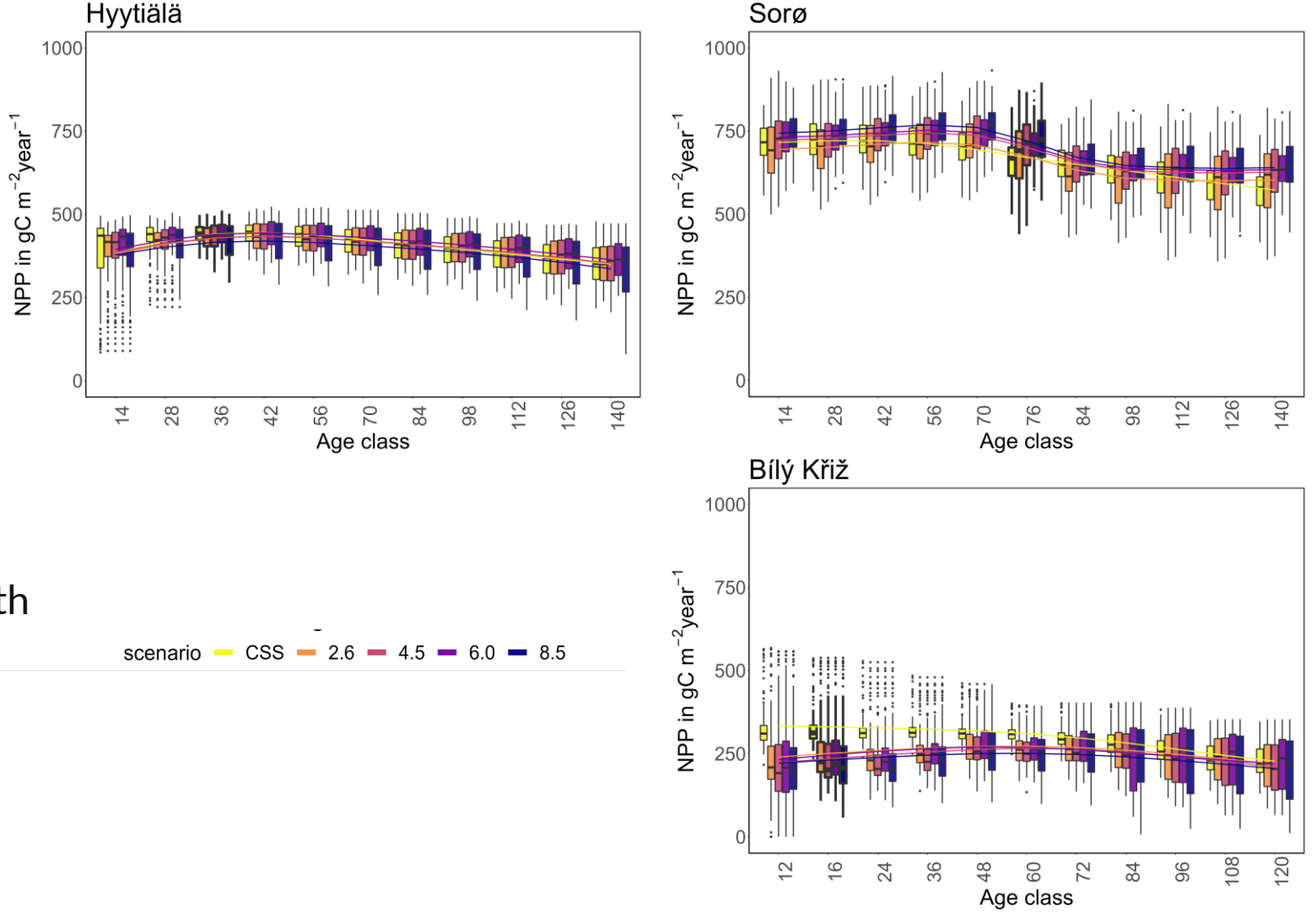
- In Norway spruce, NPP varies from ~500 to ~200 gC m^{-2} $year^{-1}$ in a similar way across all RCPs
- The youngest class under all four RCPs showed mortality at the end of the century (NPP and tCWS decline).
- NPP shows a peak, independently of the climate scenarios considered in the middle age classes (48- to 72-year-old class),
- The oldest classes decay at the end of the century.
- tCWS peaked at 120 years old





Results

- Overall, NPP peaks in the middle-aged class (42- to-56-year-old) regardless of the climate scenario
- The general response to climate change was a slight increase in NPP to CCS, but with different trends across RCP and age classes.
- tCWS increased not linearly with age with different trajectories in the three sites.
- ANOVA: Age and climate scenarios have statistically significant effects on the forest carbon balance when taken individually
- Their interactions are still significant but reduce and, in some cases, cancel their effects altogether.



Site	NPP			tCWS		
	Age class	Scenario	Age class X Scenario	Age class	Scenario	Age class X Scenario
CZ-BK1	0.0001***	0.0001***	0.4442	0.0001***	0.0001***	0.0001***
FI-Hyy	0.0001***	0.0001***	0.9982	0.0001***	0.0001***	0.9993
DK-Sor	0.0001***	0.0001***	1	0.0001***	0.0001***	0.9969

Discussions

- European beech: At DK-Sor, beech seems not yet at its optimum. The fertilization effect can compensate for changes in precipitation regimes and temperature increases up to a certain threshold. After that, the beech is exposed to drought-induced decline. Northern beech forests can be expected to remain productively up to RCP 6.0

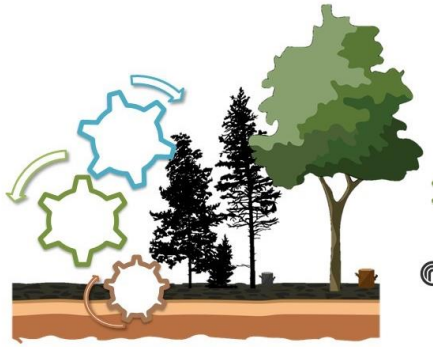
- Scot pine: At FI-Hyy, Scot pine showed a certain level of adaptability to temperature changes, maintaining its productivity at the same level in all scenarios. However, rising temperatures beyond the species' optimal range will lead to reduced growth and increased vulnerability to water stress.

- Norway spruce: Spruce was the most sensitive species, with a strong decline over the century. At CZ-BK1, the species seems already at its optimum, and a slight variation in climate conditions affects its resistance. The youngest and older classes decline, perhaps due to drought damage and C-starvation (too much respiring biomass, too low GPP)

Conclusions and limitations

- Age is not a *per se* effect but the results of factors (biomass accumulation, closing canopies, reduction in stomatal conductance), which are the main drivers of photosynthesis and respiration.
- It seems that age effects could dampen climate effects, especially for the beech and Scot pine, which can be attributed to a diversified structure resulting from natural stand dynamics.
- If the NPP/GPP ratio is not considered fixed, the biomass respiration compensates for the fertilization effect and the lengthening of the growing season, reducing the NPP.
- The study presented here does not consider the indirect effects of climate change, such as altered disturbance regimes and extreme events such as fire, insects, or storms.
- Other drivers such as Nitrogen (N), Phosphorus (P) or Ozone (O3) were not considered
- We did not account for potential new species migrating into the study areas.

Maintaining age diversity through sustainable forest management can help to support the resistance and resilience of forests in the face of climate change, maintaining and promoting biodiversity.



Thank you for your attention

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