Deliverable 2F3
Full Costs of Climate Change
WP 2F: Ecosystems and Forests
Global Report Analysis

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Objectives

Assessment of the global damages from climate change on ecosystems in physical impacts and monetary values, as well as adaptation options in forestry, for the scenarios from WP1.

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1. Summary

This report presents an assessment of the damages from climate change on ecosystems in physical impacts, for the scenarios from WP1. In particular, WP2F has used the Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Land LPJmL simulating the dynamics of natural and managed vegetation grouped into plant functional types for this task. To assess the impacts of climate change on forestry a linkage between the Global Forest Model (G4M) and LPJmL has been established for Europe. This enables to model forestry and alternative land use and to quantify climate change impacts and impacts of responses of forest management of forest management.

The results obtained for this report are largely in line with the existing literature: large biome shifts are detectable, with boreal trees shifting further towards the poles and to higher elevations and shrublands expanding in their area. World-wide a decrease in highly productive evergreen trees can be found which are replaced by summer-green trees (boreal and temperature climate) or rain-green trees (tropical climate).

Concerning the uncertainty between climate models, the standard deviation of simulated vegetation carbon for different climate models for A1B has been found to be rather low in comparison to mean vegetation carbon, but also to be growing over time.

Results for the impact analysis for the forestry sector in Europe and a selection of climate change scenarios are presented. These show a strong climate feedback on forest growth and biomass accumulation that can be mitigated through species change. However, species change needs time to become effective. Moreover, such adaptation strategies might conflict with mitigation measures in the forestry sector such as biomass maximization.

2. Background: Role of ecosystems and forests for the human welfare

Ecosystems directly and indirectly provide various goods and services to humans; these range from regulating services such as climate regulation to food and fresh water provisioning and recreative values. A first attempt to assess the total value of the world's ecosystem services and natural capital was performed by (1997). Based on more than 100 previous studies on single ecosystems or services, they estimated a minimum value of renewable ecosystem services for global biomes. Their estimation included 17 broad goods and services, covering regulating services, supporting services, provisioning services and cultural services (Table 1). Summarising the contribution of each biome to these services leads to a total value of US$ 33 trillion per year (accounting for uncertainties leads to a range of US$ 16-54 trillion per year).

A follow up study by (Balmford et al. 2002) assessed the marginal value of goods and services delivered by a biome when relatively intact and when converted to typical forms of human use. Their clear message is the high net present value of intact ecosystems, and they conclude that the overall benefit: cost ratio of an effective global program for the conservation of remaining wild nature is at least 100:1.

Clearly, these values have to be treated with care. Numerous sources of errors can arise as a result of the great uncertainties in the detection of services, and their valuation methodology. Also, the study of (Costanza et al. 1997) neglected the evaluation of services with uncertain value, and therefore provides only a minimal assessment. Additionally, services undergo tremendous changes in time and space and can feedback on each other. Nevertheless, these highly cited studies show that ecosystem services provide an important total contribution to human welfare, and that it is important to understand the future development of ecosystems.

Table 1: Ecosystem good and services and their values included in the economic assessment of Costanza et al. (1997). Goods and services are classified according to the Millennium Ecosystem Assessment (MA 2005).

	Ecosystem Goods and Services	Example	Global Value (10^9 \$ yr^{-1})
Regulating Services			
1	Gas regulation	CO_2/O_2 balance	1,341
2	Climate regulation	Greenhouse gas regulation,	684
3	Disturbance regulation	Storm protection, flood control	1,779
4	Water regulation	Water for agriculture	1,115
5	Erosion control	Prevention of soil losses by wind or water	576
6	Pollination	Pollinators for the reproduction of plant populations	117
7	Biological control	Reduction of herbivory	417
Supporting Services			
8	Soil formation	Accumulation of organic material	53
9	Nutrient cycling	Nitrogen fixation	17,075
10	Waste treatment	Detoxification	2,277
11	Refugia	Habitat for migratory species	124
Provisioning Services			
12	Water supply	Provision of water	1,692
13	Food production	Production of fish, game, crops	1,386
14	Raw materials	Production of lumber and fuel	721
15	Genetic resources	Medicinal plants, genes for resistance to plant pathogens	79
Cultural Services			
16	Recreation	Outdoor recreational activities	815
17	Other cultural services	Aesthetic or spiritual values	3,015

Bearing in mind the great value of ecosystem services, the question arises how these services are provided and how stable they are. Multiple factors influence the provision of services, for example the area of ecosystems, their species composition, and external factors such as climate and other abiotic conditions.

1.1 Biodiversity

Biodiversity is defined as the diversity among living organisms in terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part (MA 2005). It includes diversity at different levels, ranging from genes and populations over species to communities and ecosystems. Although it is clear that biodiversity is linked to ecosystem stability and ecosystem services, generalising these linkages and quantifying them is not a trivial mission. For example, it has been found that species composition is often more important for ecosystem processes than the number of species (Díaz and Cabido 2001). Also, artificially increasing the species richness in naturally species-poor areas does not necessarily lead to any improvement of ecosystem services (MA 2005). In general, however, high biodiversity seems to enhance the resistance and resilience of desirable ecosystem states (Elmqvist et al. 2003), i.e. the capacity of an ecosystem to remain in the same state, and the recovery rate of ecosystems after perturbations. Here, one important factor can be whether keystone process species can be substituted by others, in case of their local extinction (Folke et al. 1996).

A comprehensive summary showing which of the above-mentioned biodiversity components relates to which ecosystem goods and services provided in Table 1 can be found in the Millennium Ecosystem Assessment (MA 2005).

1.2 Climatic Conditions/Biome

Different climate conditions on Earth have led to various biomes. A biome consists of ecologically similar climatic conditions, and represents broad habitat and vegetation types (MA 2005). Naturally, these biomes not only differ in their primary production (e.g. low productivity in tundras vs. high productivity in tropical rainforests), but also provide different ecosystem services. For example, water regulation functions of forests differ greatly from those of grasslands, and grasslands provide other sources of food than forests. Following the assessment of Costanza et al. (1997), Table 2 provides an overview on the so far known contribution of different biomes to the four classes of services discussed above. It especially shows that little is known about some specific biomes, such as deserts or the tundra.

1.3 Forest ecosystems

Global forests are affected by atmospheric and climate variability and change such as CO2 fertilization, N fertilization by N deposition, plant growth suppression by air pollution and changes in plant production or soil respiration due to decreasing soil water content or elevated soil temperature (Davidson and Janssens 2006). These changes will also have an effect on the forest's role as a provider of timber production, water cycle, evaporative cooling effect and other environmental services. Predicted changes in climate have also raised concerns about potential impacts on the strength and permanence of the observed terrestrial C sink in the Northern Hemisphere (Ciais et al. 1995; Ciais et al. 2005).

Table 2: Known values of ecosystem goods and services according to Costanza et al. (1997). Goods and services are classified according to the Millennium Ecosystem Assessment (MA 2005). Blank spaces indicate that the value is unknown. The given values provide only a minimal assessment, since not all services are fully captured in the study.

	Biome	Area (10^6 ha)	Value per ha in 1994 (\$ ha^{-1} yr^{-1}) Regulating Services	Supporting Services	Provisioning Services	Cultural Services
Marine	Open ocean	33200	43	118	15	76
	Costal					
	Estuaries	180	645	21231	546	410
	Seagrass/ algae beds	200	0	19002	2	0
	Coral reefs	62	2755	65	247	3009
	Shelf	2660	39	1431	70	70
Terrestrial	Forest					
	Tropical	1900	479	1019	396	114
	Temperate/ boreal	2955	92	97	75	38
	Grass/ rangelands	3898	87	88	67	2
	Wetlands					
	Tidal marsh/ mangroves	165	1839	6865	628	658
	Swamps/ floodplains	165	7535	2098	7696	2252
	Lakes/ rivers	200	5445	655	2158	230
	Deserts	1925				
	Tundra	743				
	Ice/ rock	1640				
	Cropland	1400	38		54	
	Urban	332				

2. Methodology

In this report, we will provide a broad first assessment of the impacts of climate change on ecosystems, biodiversity, forestry and selected ecosystem services. For this, we will use the widely tested Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Land LPJmL (Sitch et al. 2003; Gerten et al. 2004; Bondeau et al. 2007), which simulates the dynamics of both natural and managed vegetation grouped into plant functional types.

The potential impacts of climate change on forestry will be assessed by using the G4M model (Kindermann et al. 2006). G4M will be coupled with LPJmL through linking net primary productivity scenarios under climate change conditions (see **Error! Reference source not found.**).An important linkage for the impact analysis is the communication between LPJmL and G4M. LPJmL delivers to G4M the potential Net Primary Production for 100 years for selected different climate scenarios. The spatial resolution is 0.5x0.5 deg. Other data exchanged from LPJmL to G4M includes the development of vegetation zones for the different climate scenarios.

G4M output defines the potential for mitigation and biomass production as well as land use information that informs the models POLES and Metro. Not all linkages are fully implemented (see descriptions in respective reports/sections).

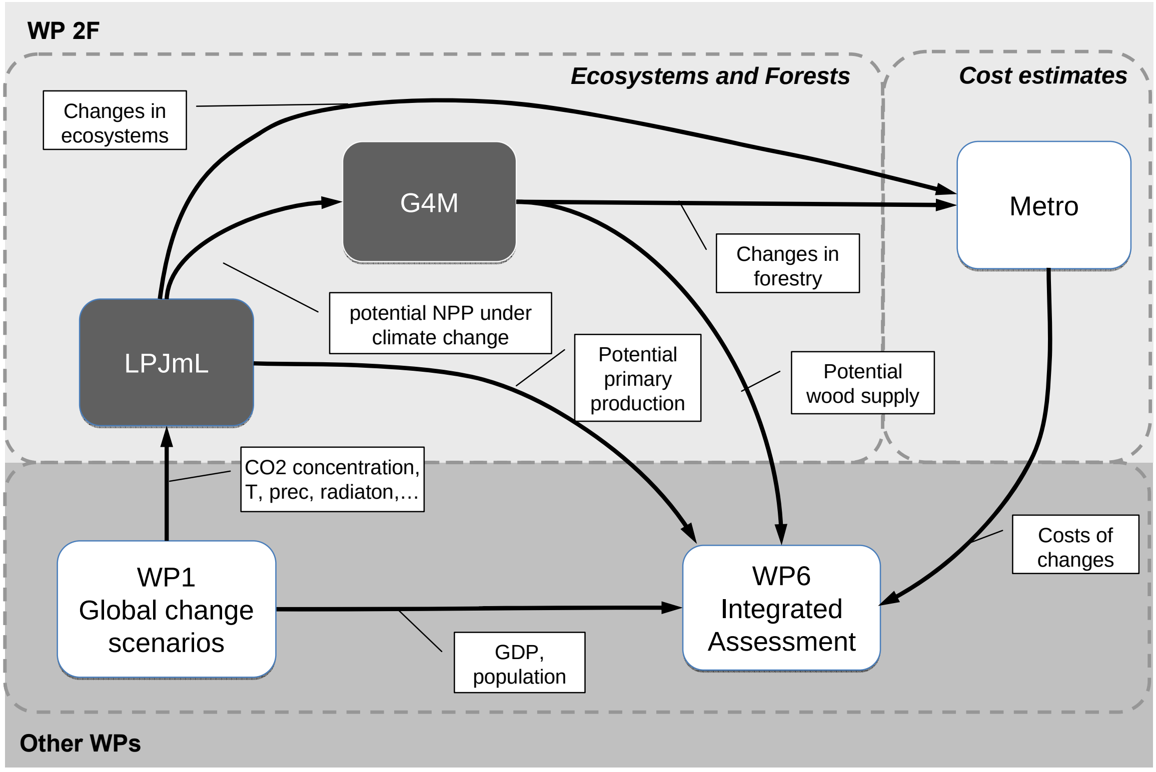


Figure 1: Data flow within WP2F and between other work packages of ClimateCost

2.1 Ecosystems

2.1.1 LPJmL: model description

The Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed land (LPJmL; (Sitch et al. 2003; Gerten et al. 2004; Bondeau et al. 2007) simulates vegetation processes in grid cells with a mesh size of 0.5 degrees in longitude and latitude. The simulation is driven by monthly climate data (air temperature, precipitation, cloud cover, number of wet days), annual atmospheric CO_2 concentration and soil texture. Monthly precipitation is interpolated to daily values according to the number of wet days using a weather generator (Gerten et al. 2004).

LPJmL simulates the dynamics of various plant functional types (PFTs), which share specific attributes controlling their physiology and dynamics (an overview of the PFTs is given in Table 3). Various physiological processes such as photosynthesis, plant respiration, and microbial decomposition, and associated fluxes of carbon and water between soil layers, vegetation, and the atmosphere are simulated on a daily time step. Photosynthesis and thus gross primary productivity (GPP) are calculated according to a modified Farquhar photosynthesis model (Farquhar et al. 1980) generalized for global modelling purposes from Collatz et al. (1991) under the assumption of optimal nitrogen availability. GPP is reduced by the amount of CO_2 released from growth and maintenance respiration, which results in the daily assimilated carbon (NPP). NPP is allocated annually to the different carbon compartments of the plant, namely leaves and fine roots according to specified allometric constraints. LPJmL has been evaluated using observations against many types of observations, on the global (Gerten et al. 2004) and regional scale (Lucht et al. 2002; Cramer et al. 2004; Hickler et al. 2005). A more detailed description of the model can be found in Sitch et al. (2003).

2.1.2 Scenarios and Regions

The impact of climate change on global and European ecosystems was evaluated for the time period of 1961 to 2100. The future state of ecosystems (grid cell-based for spatial evaluations, biome-based for ecosystem evaluations and country-based for monetary assessments) was compared with present conditions.

We evaluated several scenarios to take into account the uncertainty of future conditions. This uncertainty includes the uncertainty of future climatic conditions, of vegetation response to changes and of management options, here in terms of fire prevention. The evaluation of different scenarios allows for "what if" assessments: how will biomes probably change in the future, if the underlying conditions change according to scenario X or Y? For this, we calculated the following scenarios:

i) Variability between climate models

We accounted for the uncertainty in climate predictions by two measures:

First, we approached the uncertainty in economic development and resulting emissions by using the results of climate models following two storylines, namely A1B and E1. The SRES scenario A1B (Special Report on Emissions Scenarios, (Nakicenovic et al. 2000) describes a balanced mix of technologies and supply sources, with technology improvements and resource assumptions such that no single source of energy is overly dominant leading to 703 ppm CO_2 equivalent in 2100. The E1 storyline (van Vuuren et al. 2007) represents a mitigation scenario aimed at stabilising greenhouse gas concentrations at 450 ppm CO_2-equivalent.

Second, we accounted for the uncertainty in the physical processes simulated in climate models by using the results from different climate models (see Section Climate Models).

ii) Uncertainty in the response of vegetation to elevated atmospheric CO_2

Despite intense research during the past years, there is still no understanding that can be generalized on the long-term vegetation response to elevated atmospheric CO_2 conditions. One the one hand, higher future temperatures are likely to intensify water stress through increased evapotranspiration (Hughes 2003). On the other hand, increased atmospheric CO_2 could mitigate these effects directly by higher photosynthetic rates of plants, and indirectly by enhancing the water use efficiency (Bazzaz 1990; Drake et al. 1997). However, plants - even within one functional group - respond differently to elevated atmospheric CO_2 and the long-term response of trees is not clear at this time. LPJmL generally assesses the impact of CO_2 fertilization very high and therefore marks an upper boundary for the response of vegetation to elevated

Table 3: Plant functional types (PFTs) in LPJmL and the corresponding classification into broader groups.

	Classification	PFT type
1	tropical tree	tropical broadleaved evergreen tree
2		tropical broadleaved rain green tree
3	temperate tree	temperate needle leaved evergreen tree
4		temperate broadleaved evergreen tree
5		temperate broadleaved summer green tree
6	boreal tree	boreal needle leaved evergreen tree
7		boreal broadleaved summer green tree
8	grasses	C_3 perennial grass
9		C_4 perennial grass

CO_2. We therefore performed simulations with increasing atmospheric CO_2 levels corresponding to the levels given for the storylines A1B and E1 and simulations, where we keep the CO_2 concentration constant at the level at 2003. With this, we get results for a minimal and a maximal response to CO_2 fertilization, allowing us to narrow down the uncertainty somewhat. It should be noted that the “high fertilization” level is certainly unrealistically positive – however, there is currently no direct evidence indicating the degree of overestimation that this represents.

iii) Impact of fires

Fires impact managed and unmanaged ecosystems. Additional to the release of CO_2 by burned biomass into the atmosphere, fires have the potential to change the whole structure of ecosystems. We therefore performed simulations with and without the occurrence of natural fires, assuming that management strategies could prevent or mitigate fire events in ecosystems.

2.1.3 Climate Models

Uncertainty in future climate was approached by two means: First, we accounted for the uncertainty in economic development and resulting emissions by using the results of climate models following the A1B and the E1 storyline (see previous section). And second, we accounted for the uncertainty in the physical processes simulated in climate models by using the results from different climate models (Table 4). As input, monthly precipitation, mean temperature, mean cloud cover, and atmospheric carbon dioxide were required.

Global

We used eight global SRES A1B runs and eight global SRES E1 runs to simulate the impact of climate change on ecosystems (Table 4). These runs are described more detailed in Deliverable 1.2 (WP1 Report: Climate and Socio-economic Scenarios). Climate data was disaggregated from 1° resolution to 0.5° resolution. Where several run numbers were available, we used for each model the first run given in Deliverable 1.2, Appendix 1.

Europe

We used data from 14 regional climate models, which were driven by a set of different global circulation models. These 14 models include 13 runs of the SRES A1B scenario and one run of an E1 scenario (Table 4, WP1 Report: Climate and Socio-economic Scenarios). A more detailed description on regional runs is given in WP2F Report Ecosystems and Forests - Report Analysis for Europe.

2.2 Forests

To assess climate change effects on forestry and responsive management options in specific locations a combination of two models is used. The forest model (G4M) is a spatially explicit model of forestry and alternative land use, which quantifies the economic impacts of global forest management. In this frame, ecosystem services such as carbon sequestration, biomass for bioenergy, and timber supply will be calculated as 100-year economic forecasts. The economic land use model GLOBIOM uses as macro-economic drivers projections for future bioenergy demand (e.g. derived from POLES) and related assumptions on population growth, economic development, and technical progress rates. Data on potential yields and GHG emissions and removals for diverse agricultural and forest management alternatives can be derived from the more detailed forestry model (G4M).

2.2.1 G4M model description

The Global Forest Model (G4M) is applied and developed by IIASA and estimates the impact of forestry activities (afforestation, deforestation and forest management) on

Table 4: Climate models used for evaluations in ClimateCost. Scenarios A1B and E1 refer to storylines described in the text. Last column indicates, if LPJmL results were used as inputs for forestry assessments.

Global climate models						
	Centre	**Global model**	**Name short**	**First year**	**Last year**	**Used for forestry assessments**
A1B						
1	BCCR	BCM2.0	BCM2	1951	2098	
2	CNRM	CM3	CNCM3	1951	2098	
3	FUB	EGMAM2006	EGMAM	1951	2098	
4	INGV	SXG2005	INGVSX	1951	2098	
5	IPSL	CM4_v1	IPCM4	1951	2098	
6	MPI	ECHAM5	MPEH5	1951	2098	
7	DMI	ECHAM5	DMIEH5	1951	2098	
8	UKMO	HadGEM1	HADGEM	1951	2098	
E1						
9	CNRM	CM3.3	CNCM33	1951	2098	
10	FUB	EGMAM2006	EGMAM2	1951	2098	
11	INGV	C-ESM2007	INGVCE	1951	2098	
12	IPSL	CM4_v2	IPCM4v2	1951	2098	
13	MPI	ECHAM5.4	MPEH5C	1951	2098	
14	DMI	CM3.3	DMICM3	1951	2098	
15	UKMO	HadCM3C	HADCM3C	1951	2098	
16	UKMO	HadGEM2AO	HADGEM2	1951	2098	

Regional climate models (Europe)						
	Regional institution	**Global model**	**Name short**	**First year**	**Last year**	
A1B						
1	METO-HC	METO-HC Standard	METOHCSTD	1951	2099	
2	METO-HC	METO-HC Low sens	METOHCLOW	1951	2099	
3	METO-HC	METO-HC Hi sens	METOHCHI	1951	2099	
4	MPIMET	MPIMET Standard	MPIMET	1951	2100	
5	DMI	MPIMET Standard	DMIMPIMET	1951	2099	
6	DMI	CNRM	DMICNRM	1951	2100	yes, median
7	ETH	METO-HC Standard	ETHMETOHC	1951	2099	yes, minimum
8	KNMI	MPIMET Standard	KNMIMPIMET	1950	2100	
9	ICTP	MPIMET Standard	ICTPMPIMET	1951	2100	
10	SMHI	METO-HC Low sens	SMHIMETOHC-LOW	1951	2099	
11	SMHI	MPIMET Standard	SMHIMPIMET	1951	2100	yes, maximum
12	SMHI	NERSC	SMHINERSC	1961	2099	
13	C4I	METO-HC Hi sens	C4IMETOHCHI	1951	2099	
E1						
14	CNRM		E1CNRM	1950	2100	

biomass and carbon stocks. By comparing the income of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, a decision of afforestation or deforestation is made. As G4M is spatially explicit (currently on a 0.5° x 0.5° resolution) the different deforestation pressure at the forest frontier can also be handled.

Estimating forest biomass development and wood supply in management scenarios is the main application of G4M.. Increment estimates, maximum and optimal stocking degrees, tree diameter and height development are parameterized using yield tables. The yield level can be estimated with temperature, precipitation and soil information but can also be provided by an external input. For an overview of parameters used in G4M see Figure 2.

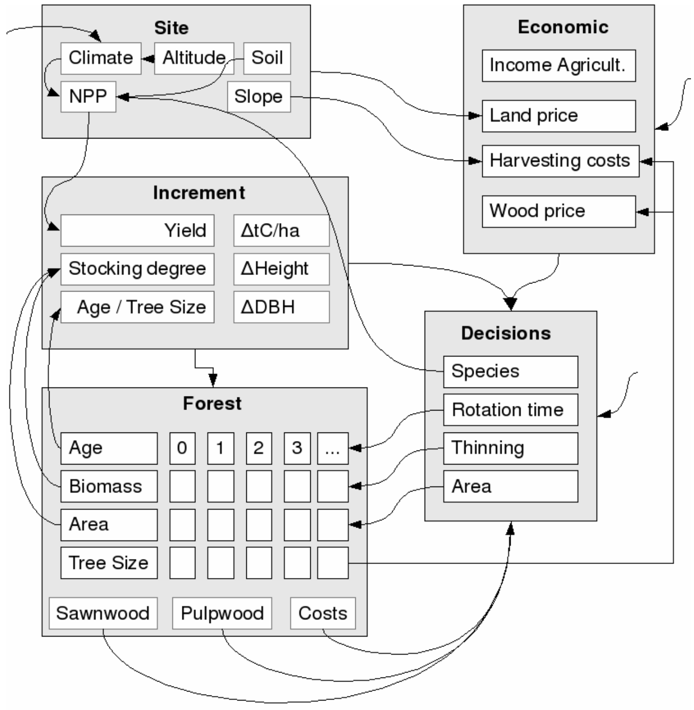


Figure 2: G4M Flowchart.

As outputs, G4M produces estimates forest area change, carbon sequestration and emissions from existing forests, impacts of carbon incentives (e.g. avoided deforestation) and supply of biomass for bio-energy and timber. The main forest management options considered by G4M are species selection, variation of thinning and choice of rotation length. The rotation length can be individually chosen, but the model can estimate optimal rotation lengths to maximize increment, maximize stocking biomass or maximize harvestable biomass. To initialise forest biomass the forest biomass map compiled by Kindermann et al. (2008) was used. Increment is determined by a potential Net Primary Productivity (NPP) map (Cramer et al. 1999) and translated into net annual increment (NAI). By default this increment map is static but in this project it is linked to LPJ output.

An equation system was build which is able to describe the forest increment and mortality per hectare and year depending on yield level, age and stand density. Rotation time and stand density are values which have to be chosen. The increment functions are able to describe the (1) total carbon production of stemwood per hectare (TCP) at increment optimal stocking degree (SDopt) depending only on age, (2) increment optimum stand density, (3) maximum possible stand density, (4) tree size (DBH, height) and (5) influence of stand density on TCP and DBH increment. The used yield table shows values of stemwood in m3/ha. This is transformed into carbon per hectare by applying a total dry weight of 403 kg and carbon density of 0.4417.

By multiplying the given total stemwood volume production with dry weight and carbon density total carbon production (TCP) is estimated. TCP at a certain stand age t can be described with equation (1) where TCPt is the TCP at stand age t, TCPmax is the maximum TCP which will be reached at stand age tmax and k is a factor describing the shape of the increment curve.

$$\mathrm{TCP}_t = \mathrm{TCP}_{max} \cdot e^{k \cdot \ln^2(t/t_{max})} \tag{1}$$

By fitting this curve to growth curves from yield tables, the maximum of the total carbon production and also the forest age, when this point is reached, can be estimated. These values may be different for different yield levels. Also the coefficient k, which describes the form of the curve, has to be estimated. By knowing k and tmax the increment optimal harvesting time topt can be calculated with equation (2).

$$t_{opt} = t_{max} \times e^{0.5/k} \tag{2}$$

By dividing TCP at time topt by topt the optimum mean annual increment (MAI) can be calculated (equation 3). MAI can be used to describe the yield level.

$$\mathrm{MAI} = \frac{\mathrm{TCP}_{t_{opt}}}{t_{opt}} \tag{3}$$

TCPmax, k and tmax are changing for different yield levels. So a relation between these coefficients and the MAI can be described. The relation of the shape factor k and the MAI can be described with equation (4).

$$k = c_0 \times e^{c_1 \times \mathrm{MAI}^{c_2}} \tag{4}$$

$$t_{max} = c_3 + \frac{c_4}{1 + e^{(c_5 + c_6 \times \mathrm{MAI})}} \tag{5}$$

$$\mathrm{TCP}_{max} = \mathrm{MAI} \times t_{max} \times e^{0.25/k} \tag{6}$$

The biomass of unmanaged forests is the TCP subtracted by the biomass of dead trees. The fraction of carbon in the living biomass can be described with equation (7).

$$\frac{\mathrm{CMax}_t}{\mathrm{TCP}_t} = (c_7 + c_8 \times \ln(t/t_{opt})) \times (1 - c_9 \times (t/t_{opt}))^{c_{10}} \tag{7}$$

Yield tables typically describe the stem volume development of managed forests but include the basal area of both, managed and unmanaged forests. By assuming, that the basal area is proportional to the volume, the volume of unmanaged forests can be calculated.

The yield table assumes that there are some trees removed during thinning. This means the living biomass is below the unmanaged biomass. With equation (8) the share of standing tree volume of increment optimal managed forests to the volume of unmanaged forests can be calculated.

$$\frac{\mathrm{CMan}_t}{\mathrm{CMax}_t} = 1 - e^{(c_{11}+c_{12}/e^{\mathrm{MAI}}+c_{13}\times(t/t_{opt})+c_{14}\times(t/t_{opt})^2)} \qquad (8)$$

Tree size has an influence on the harvesting costs and share of wood which can be used as sawn wood. The height development h with age is described in equation (9)

$$HM = c_{15} \cdot mai^{c_{16}} \cdot (1 - exp(c_{17} \cdot Age))^{c_{18} \cdot mai^{c_{19}}} \qquad (9)$$

In each simulation year the age is increased by one year as long as there is some stocking stem volume. The stocking stem volume is updated each year by adding increment and subtracting the losses through thinning and harvest.

The rotation time can be set to an absolute number (e. g. u=100 years) or the model estimates the rotation time internally to optimize either average increment or average stocking biomass. The estimated rotation time depends on the yield level and is adjusted if the yield is changing, e.g. because of environmental change. The rotation time is used to calculate the area harvested per year (area to harvest = total area / rotation time). To prevent harvests of too young forests it's possible to set a minimum relative harvest age (e. g. 75% of rotation time).

The stocking degree managed forests in G4M is determined by the thinning intensity. The stocking degree can be expressed relative to the maximum possible biomass (natural stocking degree) or relative to values of the yield table (yield table stocking degree). If natural stocking degree is set to 1, no thinning is applied and trees die only naturally keeping the stocking degree constant. The stocking degree is calculated by the stocking stem volume in relation to the yield table stem volume or the maximum possible stem volume and those depend on age and yield. By default after harvest the forest is regenerated with the same species but species change can be allowed.

3. Results and Discussion

3.1 Ecosystems

We evaluated the outcomes of all scenarios (different climate models, with and without the effect of increased atmospheric CO_2 level, with and without fire events) until 2100. For this, we calculated mean values for the four time slices of 30 years (1961-1990, 2011-2040, 2041-2070, 2071-2100; data for some climate models only covered a period until 2099, here the last time slice was shortened by one year). Results shown here represent model means for the A1B and for the E1 scenarios (European runs: only means for A1B scenarios). Due to the uncertainty of vegetation response to elevated atmospheric dioxide, we show simulation results (i) with and (ii) without carbon fertilization (i: atmospheric CO_2 concentration according to the A1B/E1 scenario; ii: atmospheric CO_2 concentration kept constant to the level of 1990, the last year of the reference scenario).

Our simulation results describe the impact of climate change on potential natural vegetation, i.e. how ecosystems would change without anthropogenic land use such as agricultural production (WP 2B Agriculture and Water) or forestry (this WP, section 3.2). Changes in ecosystems imply for example the potential distribution of biomes, the structure and composition of ecosystems or the role of fire events, which in turn impact the services provided by ecosystems and thus the value.

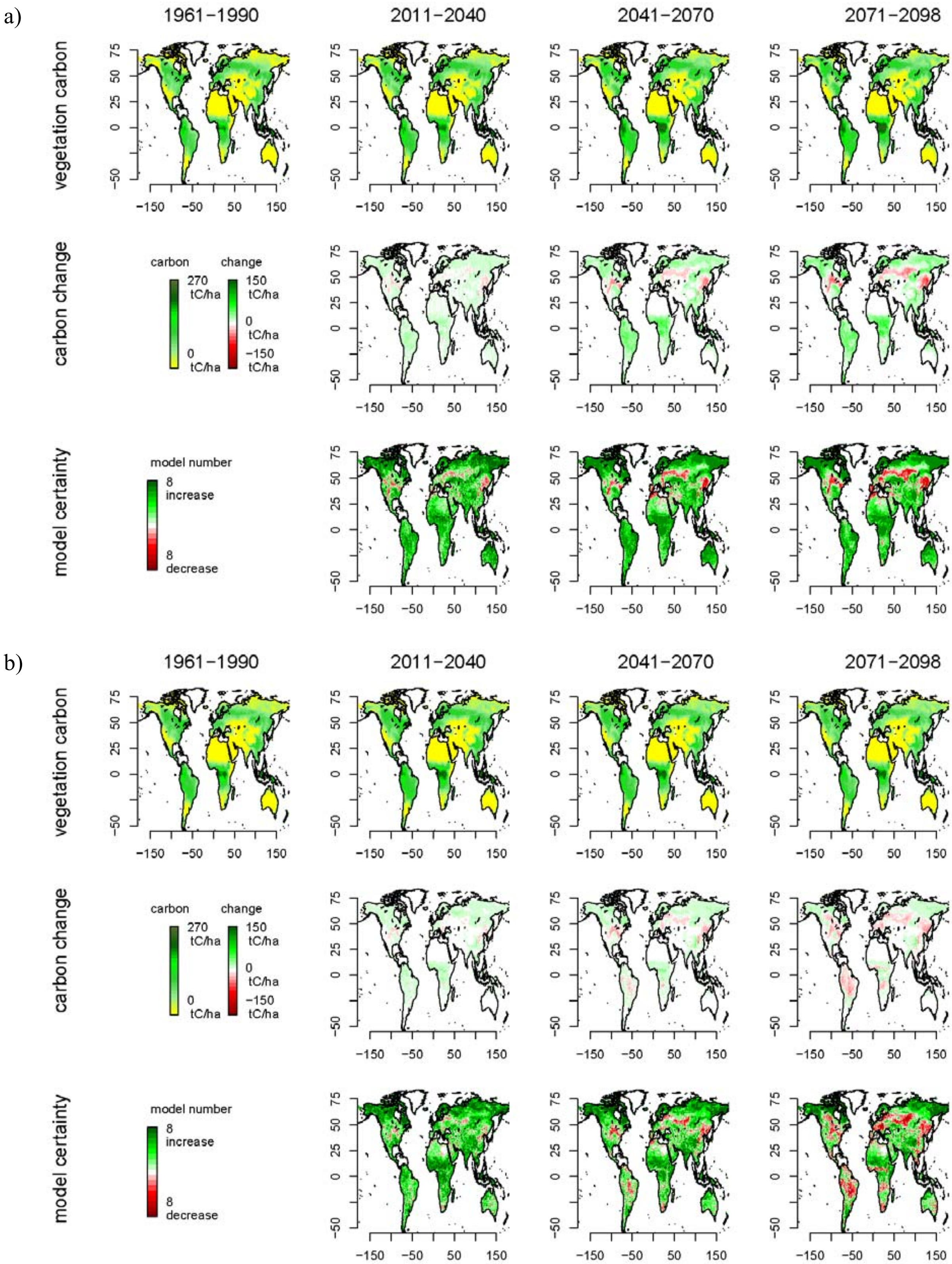
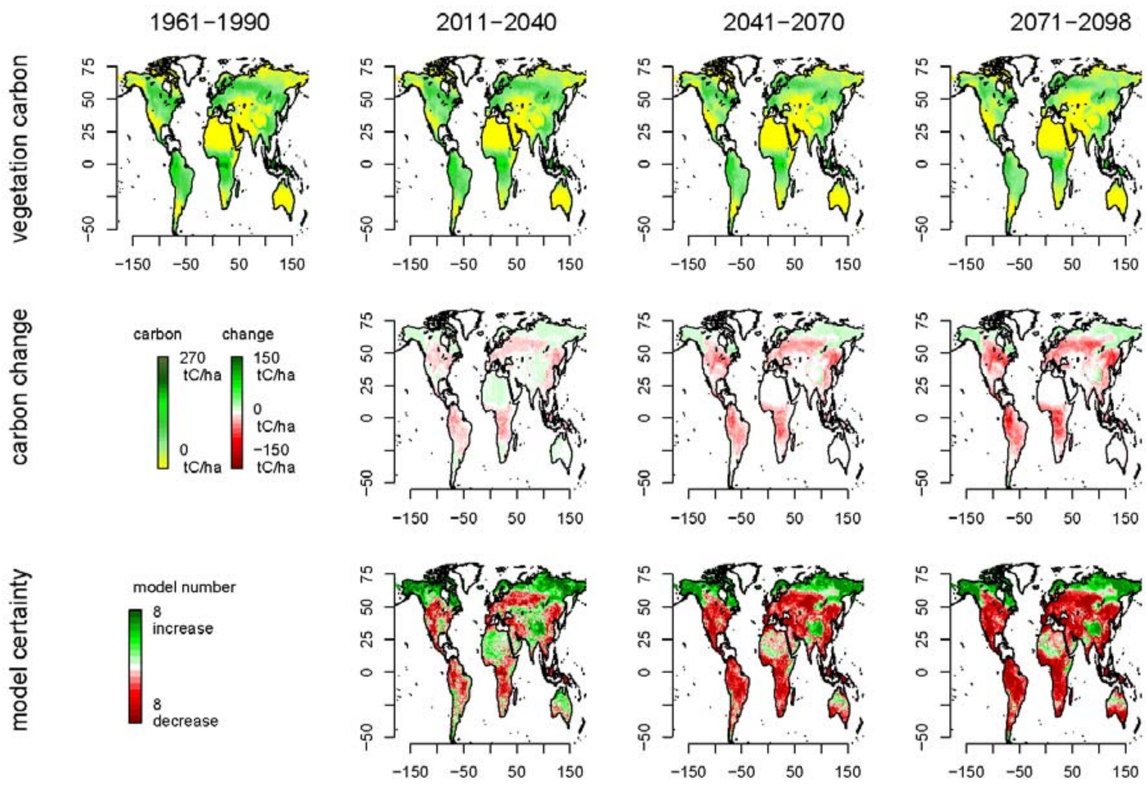


Figure 3: Mean vegetation carbon for the a) A1B and b) E1 scenario with the effects of elevated atmospheric CO_2 at four time slots (upper panels), its change compared to the reference scenario 1961-1990 (middle panels) and the number of models predicting this direction of change, i.e. the

a)



uncertainty between climate models (lower panels).

b)

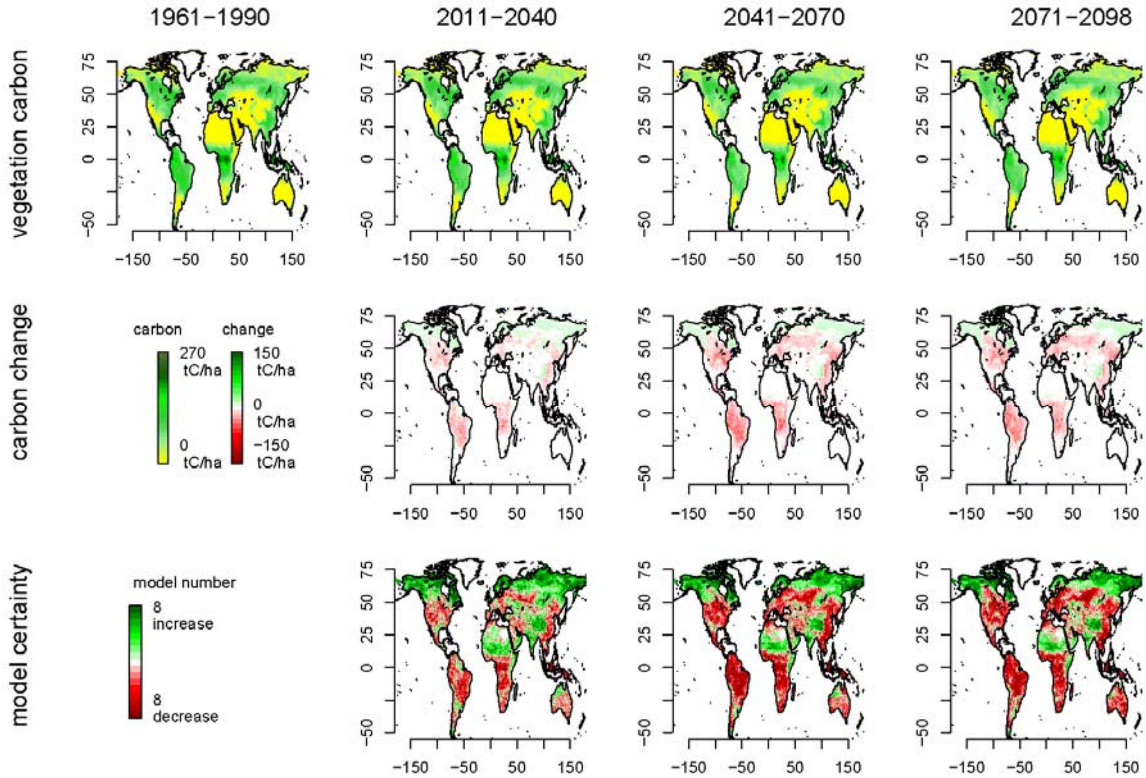


Figure 4: Mean vegetation carbon for the a) A1B and b) E1 scenario without the effects of elevated atmospheric CO_2 at four time slots (upper panels), its change compared to the reference scenario 1961-1990 (middle panels) and the number of models predicting this direction of change, i.e. the uncertainty between climate models (lower panels).

3.1.1 Global Runs

3.1.1.1 Carbon storage

We evaluated vegetation carbon storage for natural ecosystems. The results refer to simulations with natural disturbances by fire. Present vegetation cover storage ranges from values below 30 t carbon per ha (e.g. large parts of Australia, North Africa, Patagonia and Middle East) to more than 200 t carbon per ha (tropical rainforests in Amazonia, West Africa, South East Asia). If high carbon fertilization effects are assumed for the A1B scenario (Figure 3a), vegetation carbon will according to the scenarios generally increase in those regions, where productivity is already high. However, carbon losses are expected in some regions between 30-60 °N. Under the E1 scenario, carbon increases are expected to be lower due to the lower fertilization effect of atmospheric CO_2 (Figure 3b). Here, in addition to regions with expected losses for the A1B scenario on the northern hemisphere, carbon losses until the end of this century are also predicted for the Amazonian region and for parts of central Africa.

If the fertilization effect of carbon dioxide is assumed to be low (Figure 4a,b), which is a conservative assessment, strong decreases in vegetation carbon are expected for most regions of the world (exception: regions further north then 60 °N, lower regions of the Himalaya due to the upward shift of the vegetation boundary).

3.1.1.2 Biomes

We evaluated the distribution of natural biomes according to the potential cover of natural vegetation without anthropogenic impacts. Dependent on the fraction of covered ground by the simulated nine plant functional types (PFTs) and the annual mean temperature, we categorized grid cells into such biomes following Haxeltine and Prentice (1996) (Figure 5). The underlying distribution of four major PFT classes (tropical trees, temperate trees, boreal trees, grasses) can be found in Figure 6. We evaluated the current and future distribution of these biomes, as well as their state.

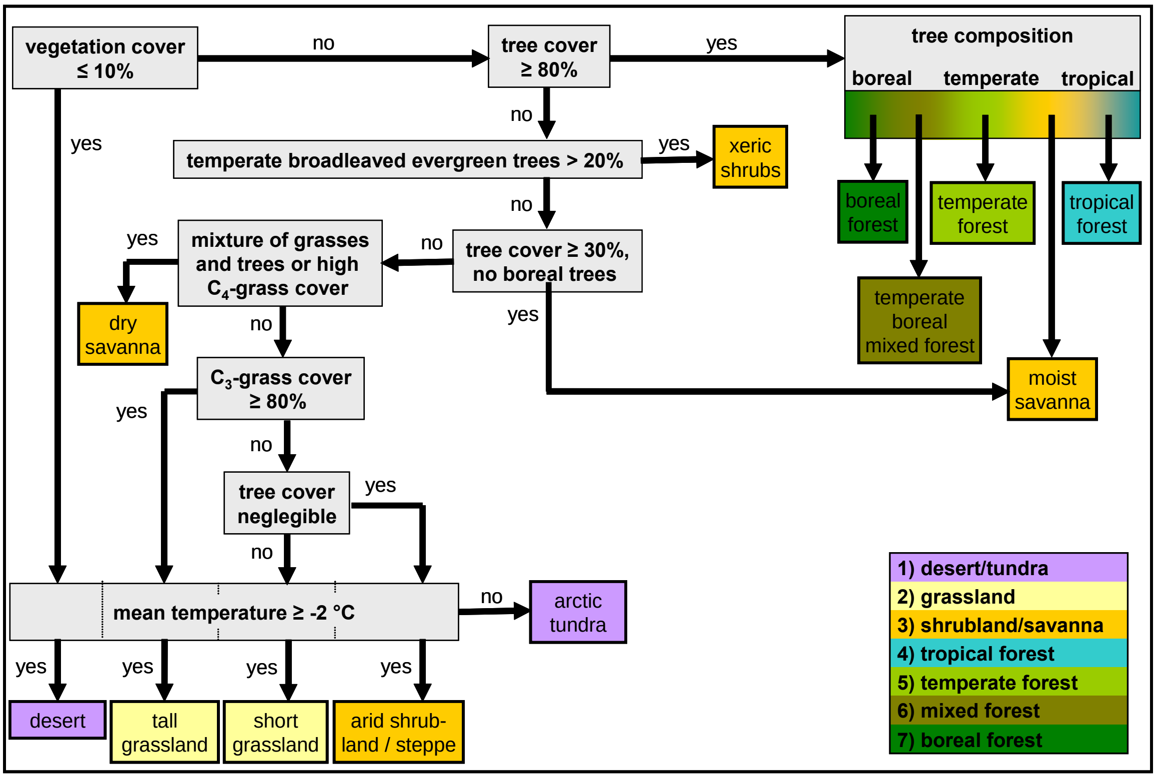


Figure 5: Classification of broad biomes following Haxeltine and Prentice (1996) according to the cover of plant functional types and annual mean temperature.

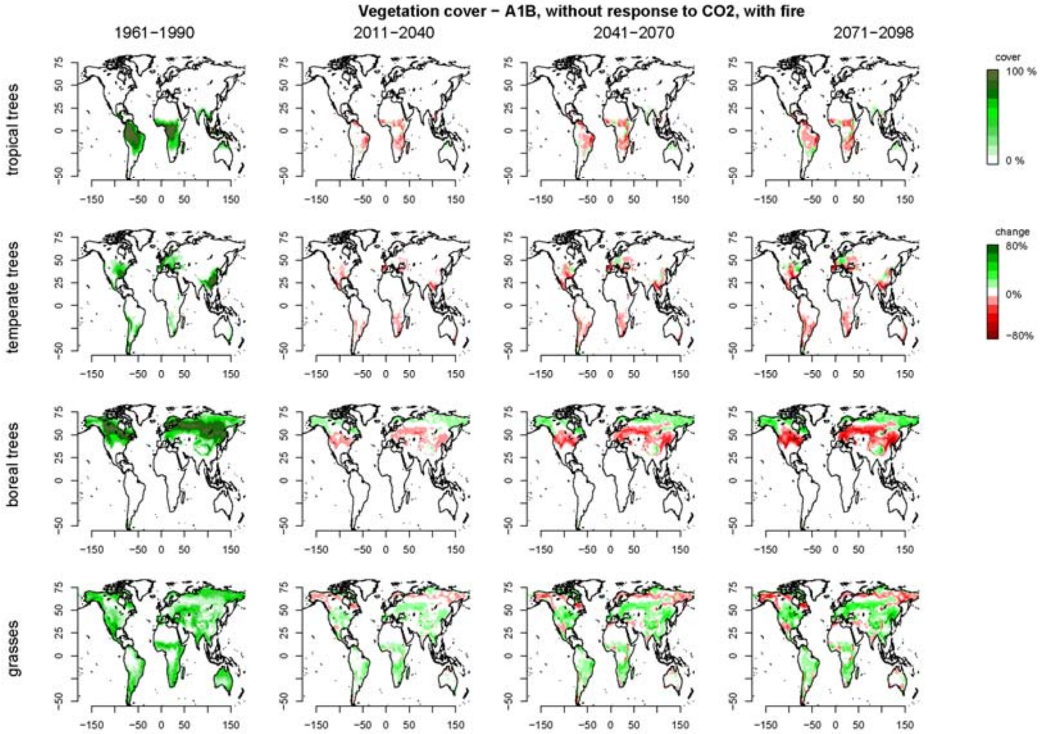


Figure 6: Present vegetation cover (left column) and its change (other columns) of four major PFT classes for the A1B scenario without the effects of CO_2 fertilization.

Boreal forests

Boreal forests can be currently found in the northern hemisphere at latitudes above 50° N or in alpine regions (Figure 8, Figure 8). All SRES-scenarios (with and without the impact of atmospheric CO_2) indicate a northward shift of boreal forests and a shift to higher altitudes as empirical studies have shown already. Boreal forests are likely to replace taiga vegetation, however the overall number of grid cells occupied by the boreal zone will remain relatively stable (dependent on SRES scenario and CO_2 effects). The productivity of boreal forests and carbon storage in vegetation is higher in boreal forests (~ 90 tC/ha) compared to desert/tundra (~ 20 tC/ha).

LPJmL assumes instantaneous migration of plant functional types: If climatic conditions are suitable for the establishment of new types, they can expand their range without any time lag. This will generally overestimate the speed of biome migration, since soil conditions, dispersal limitations or other factors can prevent fast migration, which is not accounted for in LPJmL. The degree of overestimation is however highly species specific and therefore has to be approached with species specific empirical and modelling tools.

Mixed forests

Scenario results suggest that mixed forests will shift northward and replace retreating boreal forests in Europe and North America. Large losses of mixed forests are expected in China. The retreating forests will likely replaced by much lower productive grasslands. Especially if low fertilization effects are assumed, only few mixed forests will persist.

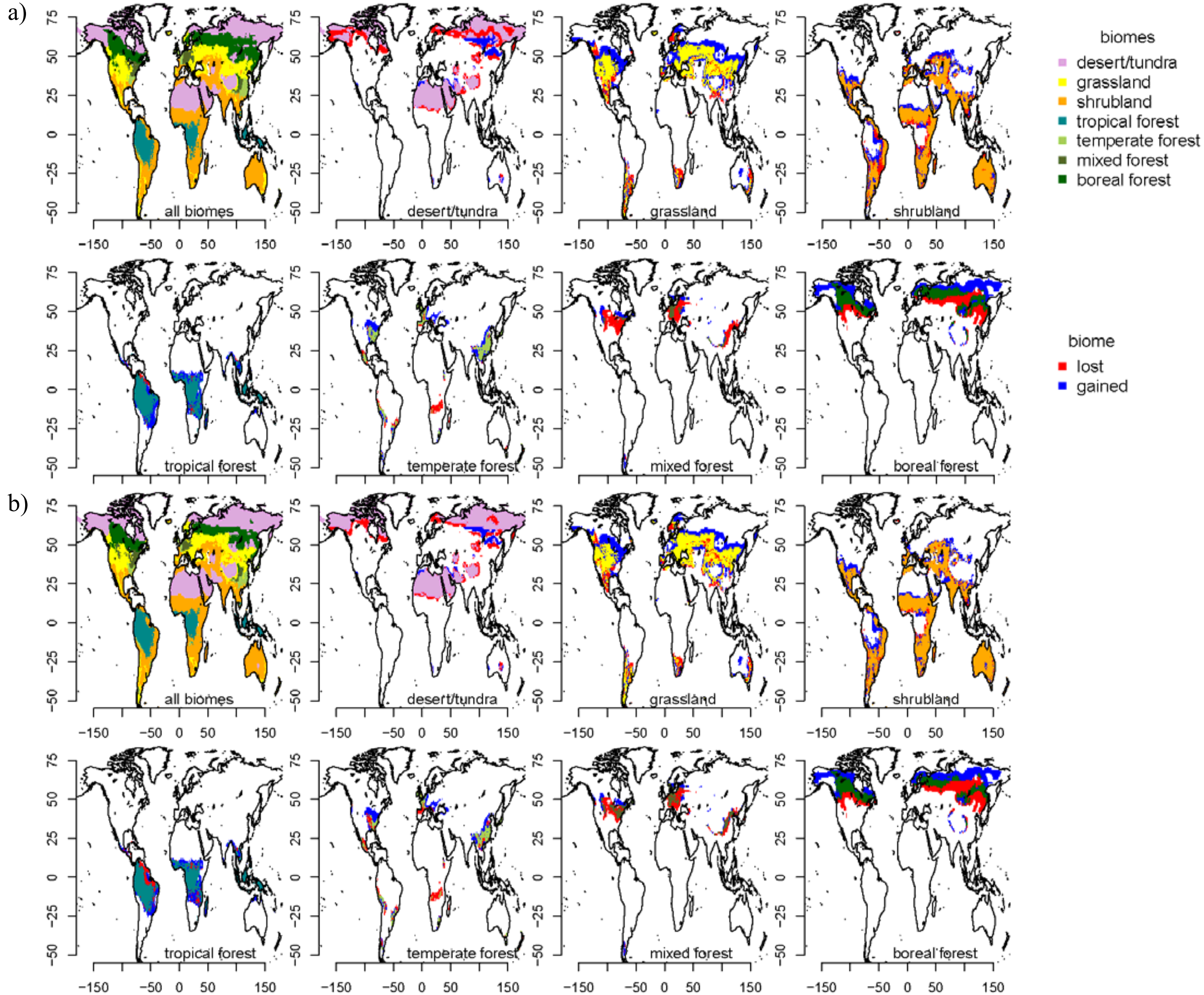
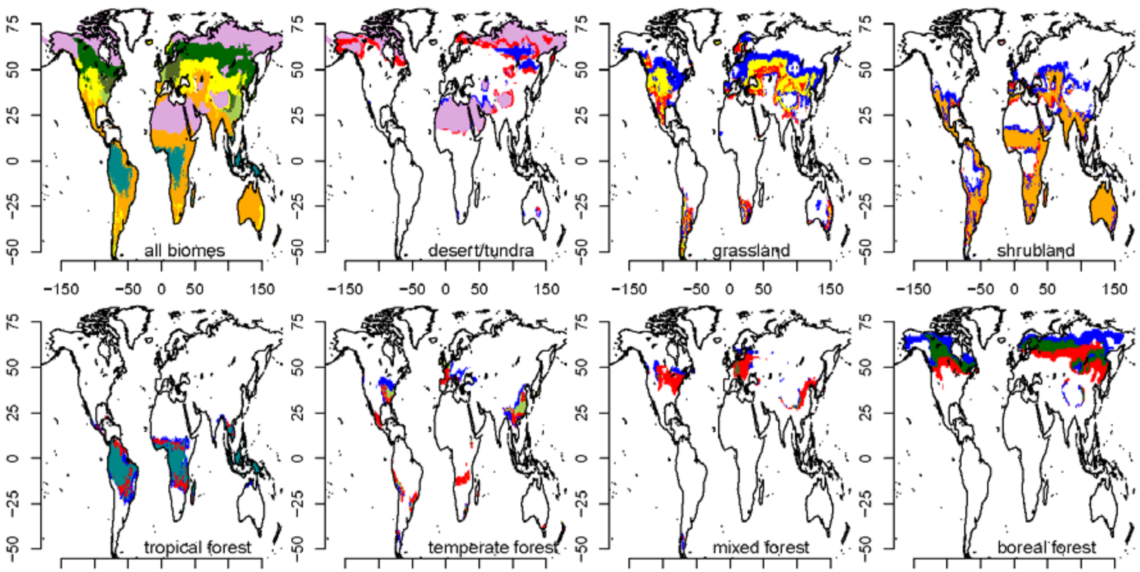
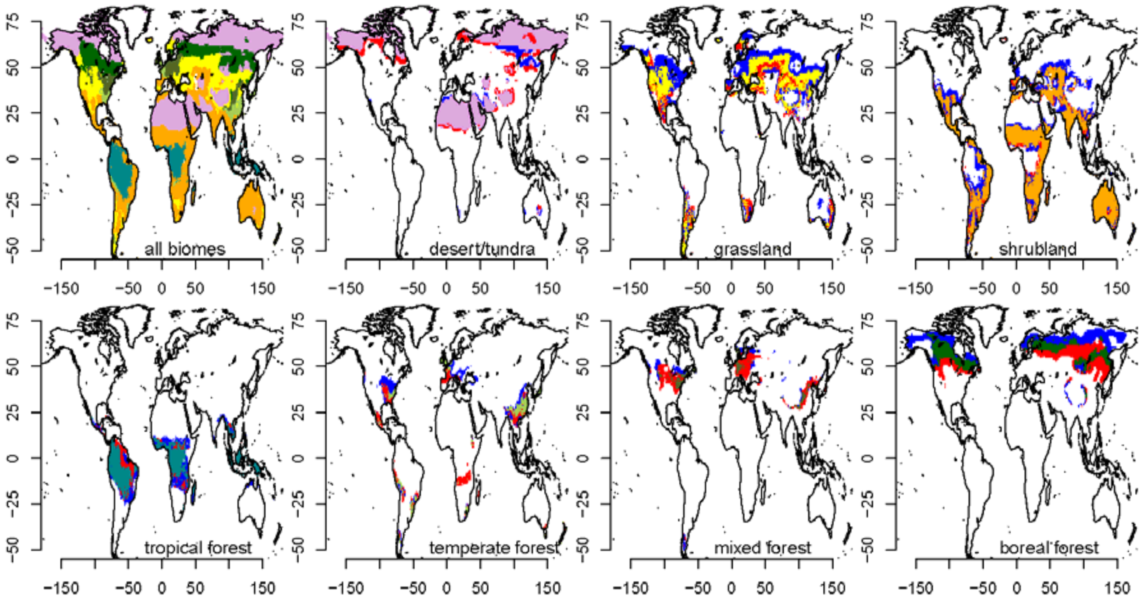


Figure 7: Present biome distribution (first panel) of seven broad biomes for the baseline scenario (1961-1990) and change of biome distribution (other panels) for the last time slot (2071-2098) compared to the baseline with the effect of carbon fertilization for the a) A1B scenario and b) E1 scenario and without the effect of carbon fertilization for the c) A1B and

c)


all biomes
desert/tundra
grassland
shrubland
tropical forest
temperate forest
mixed forest
boreal forest
75 50 25 0 −25 −50
−150 −50 0 50 150

d)


all biomes
desert/tundra
grassland
shrubland
tropical forest
temperate forest
mixed forest
boreal forest
75 50 25 0 −25 −50
−150 −50 0 50 150

Independent on carbon fertilization, vegetation carbon storage capacity of mixed forests will increase for the A1B scenario, since they will likely shift to regions with higher rainfall allowing for higher productivity.

Temperate forests

Temperate forests occupy mid-latitude regions all over the world (on the southern and northern hemisphere). On the northern hemisphere they will slightly expand further north, while replacements by shrublands/savannas are expected for South America. Carbon storage in vegetation is strongly dependent on CO_2-fertilization effects.

In general, temperate forests tend to be more stable for the E1 scenarios than for the A1B scenarios.

Shrublands

Shrublands and savannas highly benefit from the retreat of other biomes. Except for the A1B scenario with high fertilization effects, shrublands will strongly expand, covering large parts of the world. This will lead to a decline in carbon storage, since shrublands are among the least productive systems (~40 tC/ha). Also, a replacement of forests by shrublands will lead to a highly evident shift of the landscape structure: instead of dense forests, only light mixtures of grasses and trees form the landscape, which leads to high losses of refuge sites for many species.

Grasslands

Grasslands cover large parts of both hemispheres further polewards to 25° N/S. As a result of the expected temperature increase, they will shift further polewards and to higher altitudes, leading to an increased productivity in these regions. Their overall extent increases for both SRES-scenarios, independent on CO_2-fertilization effects.

3.1.1.3 Biodiversity

LPJmL is a generic model of potential global natural vegetation based on essential plant functional types, therefore the dynamics of single species or food webs cannot be tracked. Also, the impacts of human actions on biodiversity are not accounted for. However, the above sections indicate that different levels of biodiversity could be affected by climate change and increasing atmospheric CO_2. According to the simulated scenarios biomes will likely shift their range and their size, leading for example to a huge restructuring and displacement of the tundra. The phenology of plants within one biome could change, implicating shifts in plant-animal interactions and therefore in the food web. But also the composition of biomes will likely change, and dominant plant functional types will be replaced by others (Figure 9).

Simulations with LPJmL show an overall decrease of evergreen trees. This applies for boreal needle leaved trees in boreal and mixed forests as well as for temperate needle leaved and broadleaved trees in temperate forests. Evergreen trees will be replaced in these ecosystems by summer green trees. This change is probably caused by the longer growing period levelling of the advantage of evergreen trees, which can respond fast to the first warm days in spring. Resolving this change on the species level would probably even lead to more pronounced changes, where some species can adapt fast to new conditions while others go extinct. This change will have effects on the seasonal cycle of net primary production: Peak production in summer will be higher, while production in winter will decrease.

a)

b)

c)

d)

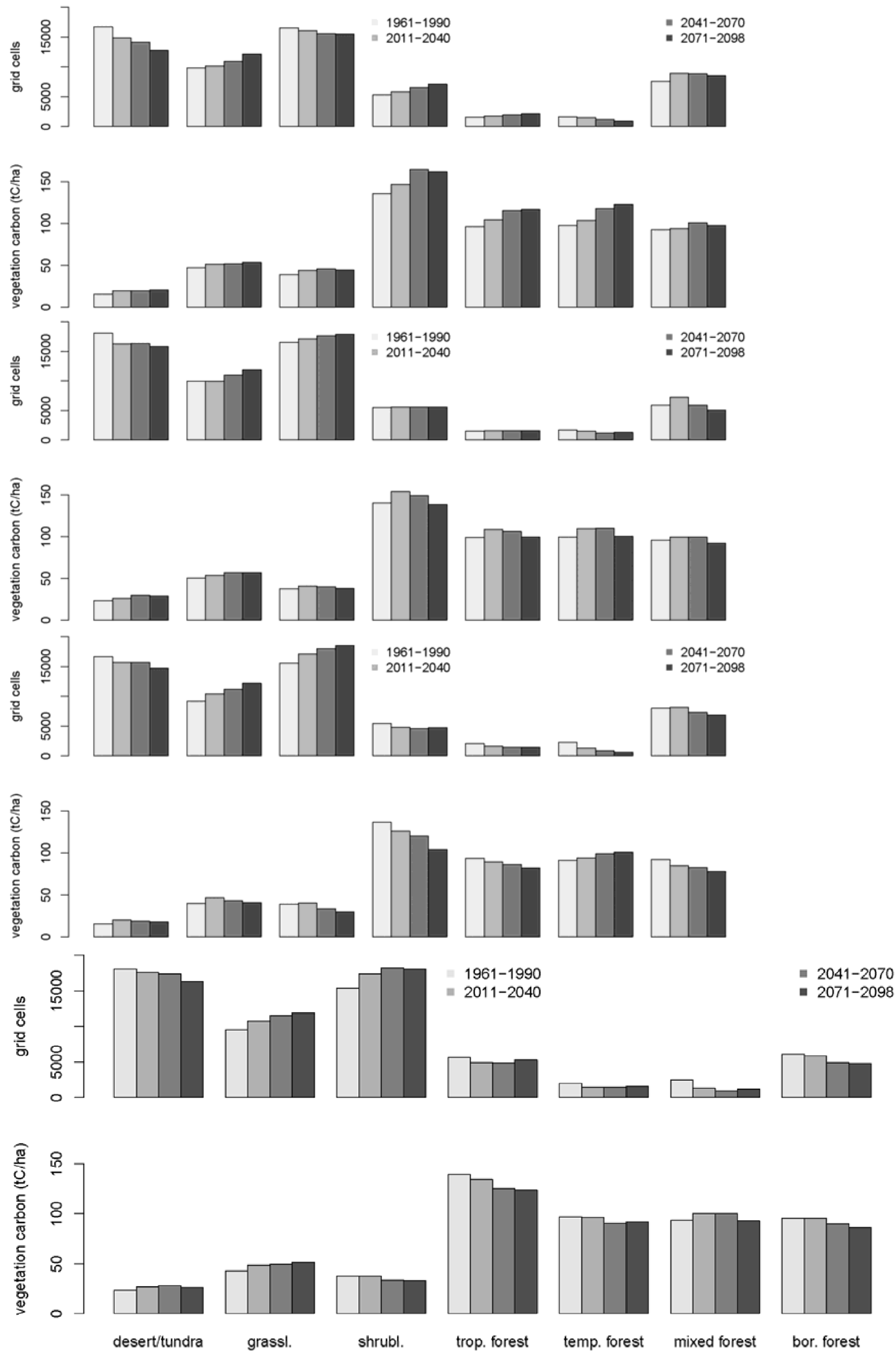


Figure 8: Biome characteristics of seven broad biomes at four time slots: number of grid cells that are classified into the specified biome and mean vegetation carbon within a biome with the effect of carbon fertilization for the a) A1B scenario and b) E1 scenario and without the effect of carbon fertilization for the c) A1B and d) E1 scenario.

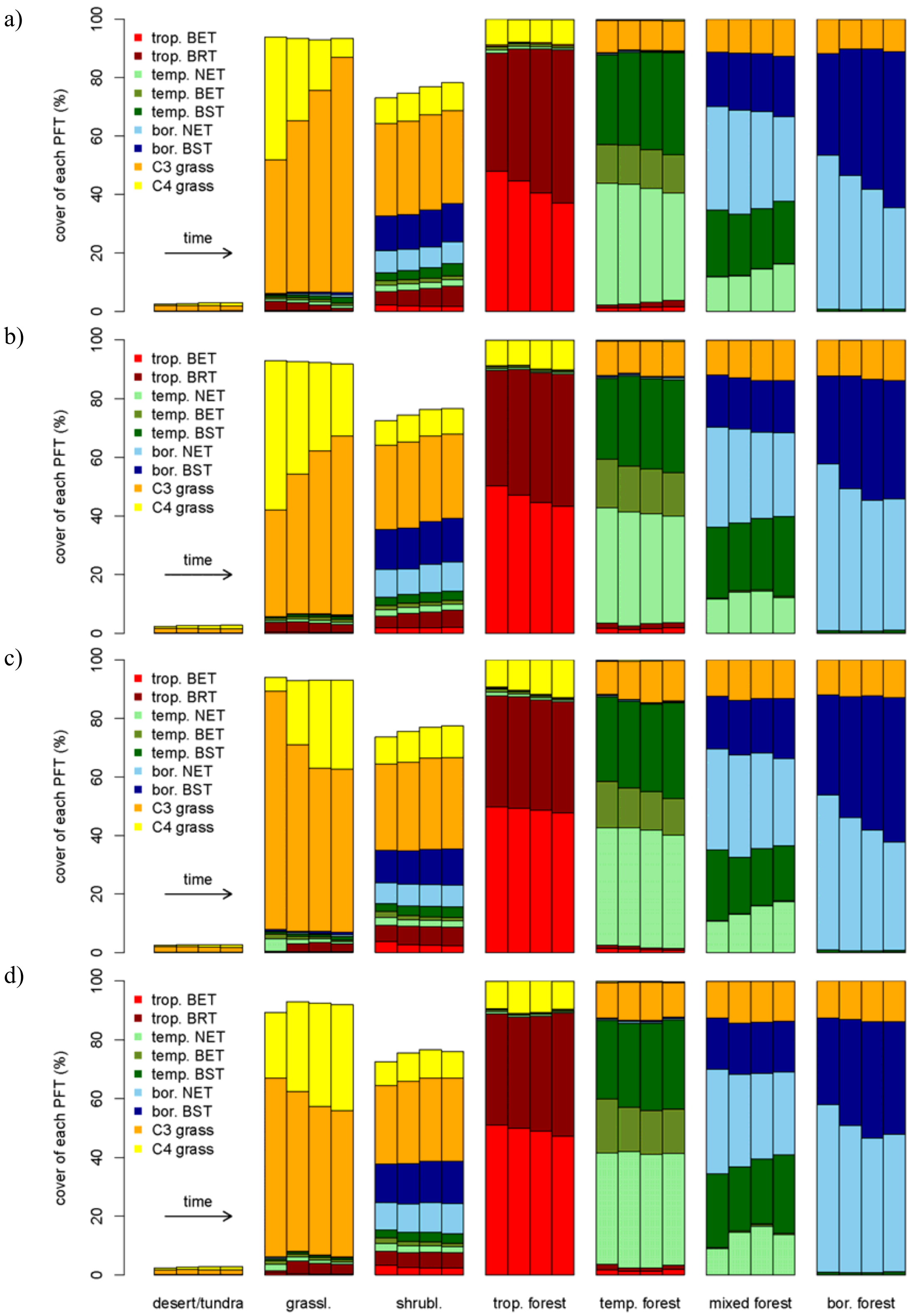


Figure 9: Cover of the main plant functional types in seven broad biomes with the fertilization effect of elevated atmospheric CO_2 for the a) A1B and b) E1 scenario and without the fertilization effect of CO_2 for the c) A1B and d) E1 scenario at four time slots (1961-1990, 2011-2040, 2041-270, 2071-2100). Abbreviations: trop. BET – tropical broad leaved evergreen trees; trop. BRT – tropical broad leaved rain green trees; temp. NET – temperate needle leaved evergreen tree; temp. BET – temperate broad leaved evergreen tree; temp. BST – temperate broadleaved summer green tree; bor. NET – boreal needle leaved evergreen tree; bor. BST – boreal broadleaved summer green tree; C3/C4 grass – grasses following the C_3/C_4 pathway.

A similar picture can be found for tropical forests. Here, broadleaved evergreen trees will be replaced by rain green trees. This can lead to a shift from equatorial evergreen rainforests to moist forests. Equatorial evergreen rainforests are characterised by high rainfall (MAP > 2000 mm) and have the highest biological diversity and have a well-developed canopy "tier" form of vegetation (Rhett 2006). In contrast, moist forests receive less annual rainfall (~ 1300 mm) and undergo a cooler dry season. During this dry season, many trees shed some or even all their leaves. This leads a seasonal reduction of canopy cover, increasing light availability for understory vegetation (Rhett 2006).

The plant functional type composition of shrublands is relatively constant regardless of the SRES scenario and CO_2-fertilization. Total plant cover is expected to increase slightly, which is mainly caused by slightly denser woody vegetation. In contrast, grasslands will undergo strong changes. Dependent on the strength of the CO_2-fertilization effect, either grasses following the C_3- or the C_4-photosynthetic pathway will increase in cover. C_4-grasses evolved under lower CO_2 concentrations are assumed to be at a near-saturation state under present conditions, while present CO_2 availability is a limiting factor for C_3-grasses. Therefore, the latter benefit from rising atmospheric CO_2. But in contrast to C_4-grasses, C_3-grasses are limited by high temperatures, which will benefit C_4-grasses under temperature increase.

Since LPJmL assumes instantaneous migration of PFTs if the climatic conditions are suitable, the potential of colonization of new habitats is overestimated. Extinction rates are likely to increase because of unfavourable conditions for present species, while establishment rates can be low due to migration limitations. That is, although habitats might be suitable for new species, it will take time to build new stable biomes with high biodiversity.

Additionally to limitations in migration, it has to be kept in mind that huge parts of the global landscape are formed by agriculture and forestry. While climate is the main driver of natural vegetation, the dynamics of agricultural landscape are driven by human decisions. That is, in addition to the impacts of climate change biodiversity is also closed related to the degree of fragmentation and changes in land use.

3.1.1.4 Variability between years

The temporal variability of ecosystem state variables is an indicator of how different the habitat conditions of species living within this system will shift between years. For example, grasslands with many annual species or with perennial species with a high annual productivity compared to the stored biomass will undergo a higher variability between years than boreal forests with a large amount of standing biomass. Especially the area covered by different vegetation types can undergo significant changes between years.

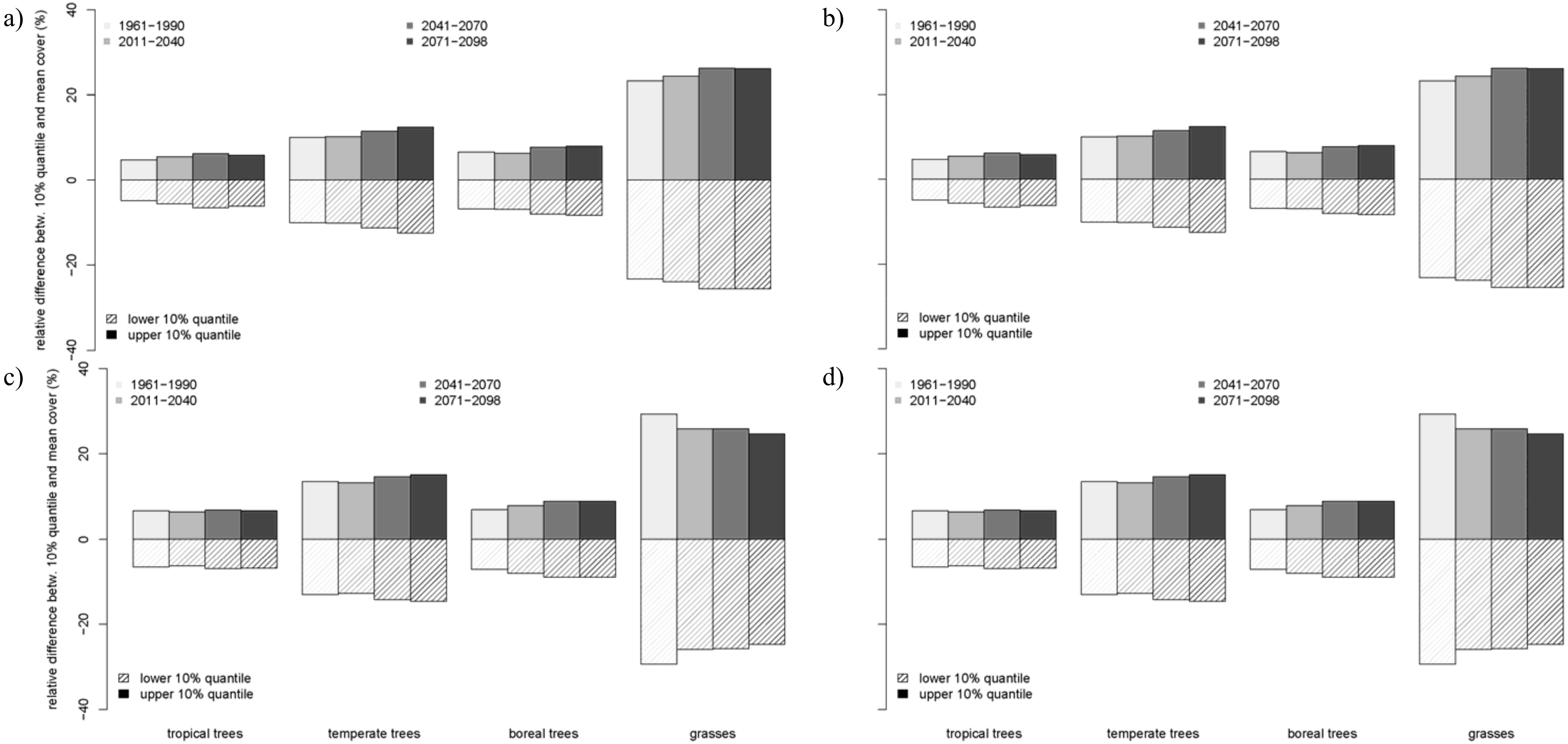


Figure 10: Temporal variability of the cover of temperate trees, boreal trees and grasses within one time slot of 30 years with the fertilization effect of elevated atmospheric CO_2 for the a) A1B and b) E1 scenario and without the fertilization effect of elevated atmospheric CO_2 for the c) A1B and d) E1 scenario. Bars represent the difference between mean cover values and the upper and lower 10% quantile (filled and striped boxes, respectively) within the same time slot, whiskers represent the standard error. A larger absolute difference indicates more variable cover.

To assess how this variability is affected by climate change, we determined for each grid cell the relative difference between the mean area covered by temperate trees, boreal trees and grasses and the upper and lower 10% quantile reached during the simulation time slots of 30 years ([mean – quantile]/mean). This difference not only shows the order of the variability for the three groups of PFTs in relation to the absolute cover, but also, how this variability changes within the next century. Figure 10 confirms that grasslands are highly variable compared to areas covered by boreal trees: grass cover can shift up to ±30% around the mean value, while the cover of tropical and boreal trees shifts between ±6 to ±8% (temperate trees: around ±15%). The high variability for grasslands can be explained by the high turnover rates of aboveground biomass. A large part of the aboveground living biomass is lost during the dry/cold season, therefore the cover in the following growing season is mainly dependent on prevailing climate conditions and therefore highly variable. This applies in a similar way to deciduous trees, which in temperate forests have a higher relative cover compared to evergreen trees than in boreal or tropical forests. Therefore, the variability for temperate trees is higher then for tropical and boreal trees.

There is only a marginal trend in future variability, the difference between the A1B and the E1 storyline is very low. If high CO_2-fertilization effects are assumed, there is a slight increase in variability until the end of this century. Especially in highly dynamic grasslands that are used for livestock production, the increase in variability can exacerbate management problems. The increasing variability in tree cover can also have concatenating effects on animals, e.g. by the availability of nesting sites.

If no CO_2-fertilization effects are assumed, the variability of tropical tree cover will remain constant, the variability of temperate and boreal trees increases slightly and the variability of grass decreases. This decrease in relative variability is not caused by an absolute decrease in variability, but rather by an increase in mean grass cover in large areas of the world (see Figure 6).

3.1.1.5 Management strategies

Fire events can strongly impact vegetation dynamics in various ways. Fires can initiate succession, benefit plants adapted to the fire regime in fire-dominated ecosystems, and influence vegetation productivity (Thonicke et al. 2010). Therefore, fires can be used to manage natural and semi-natural ecosystems. But additionally, fires feedback to the climate system: Biomass burning is thought to contribute more than 50% of both the NO_x and CO in the boundary layer over major source regions (Galanter et al. 2000).

On the global scale fire leads to losses in vegetation, litter and soil carbon (Table 5). However, huge regional differences can be found (Figure 11). While forest fires mainly leads to carbon decreases, fires in shrublands (e.g. Savannahs) can even increase vegetation carbon. This is caused by the impact of fires on the highly sensitive shrub-grass-ratio. This effect is stronger, if a high CO_2-fertilization effect is assumed. In the course of climate change, the trend in carbon storage is ambivalent and highly dependent on CO_2-fertilization effects (Table 5). Also, the difference between storyline A1B and E1 become evident: while total carbon storage is highest for the A1B with strong CO_2-fertilization effects and lowest without fertilization effects, the results for the E1 storyline lie in-between this range.

Table 5: Vegetation, litter, soil and total carbon (global sum, GtC) for four time slots. The last columns reflect the trend in carbon storage.

			1961-1990		2011-2040		2041-2070		2071-2100		trend	
		With fires	yes	no	yes	no	yes	no	yes	no	yes	no
Vegetation carbon	A1B	CO_2 effects	603	738	683	843	740	924	765	940	↑	↑
		no CO_2 effects	654	739	584	716	518	636	472	577	↓	↓
	E1	CO_2 effects	631	758	689	841	680	826	648	780	→	→
		no CO_2 effects	680	758	606	728	563	676	569	684	↓	↓
Litter carbon	A1B	CO_2 effects	178	194	178	199	186	210	190	215	↑	↑
		no CO_2 effects	191	194	181	199	165	183	147	164	↓	↓
	E1	CO_2 effects	183	198	182	200	190	209	189	208	→	↑
		no CO_2 effects	197	199	183	198	172	187	166	180	↓	↓
Soil carbon	A1B	CO_2 effects	1169	1187	1176	1208	1188	1219	1199	1238	↑	↑
		no CO_2 effects	1189	1187	1184	1210	1156	1186	1109	1142	↓	→
	E1	CO_2 effects	1183	1196	1189	1204	1197	1217	1202	1226	↑	↑
		no CO_2 effects	1197	1194	1195	1203	1172	1189	1149	1167	↓	↓
Total carbon	A1B	CO_2 effects	1950	2119	2037	2250	2114	2353	2154	2393	↑	↑
		no CO_2 effects	2034	2120	1949	2125	1839	2005	1728	1883	↓	↓
	E1	CO_2 effects	1997	2152	2060	2245	2067	2252	2039	2214	→	→
		no CO_2 effects	2074	2151	1984	2129	1907	2052	1884	2031	↓	↓

The results show that the losses of carbon due to unmanaged forest fires will increase in future. Therefore, fire management has to be adapted to avoid uncontrolled very hot and intensive fires with high losses. For a strategic framework see Millar et al. (2007).

3.1.1.6 Ecosystem Services

As stated in the introduction, ecosystems provide various services to the human well-being. Directly measurable services from agriculture and forestry will be described in the report of WP 2B and in section 3.2 of this report, respectively. Changes in carbon storage as regulating ecosystem service were assessed in section 3.1.1.1. Figure 9 showed that the composition of biomes will likely change during the next century: The proportion of evergreen trees in forests is expected to decrease and deciduous trees will probably take

a)

b)

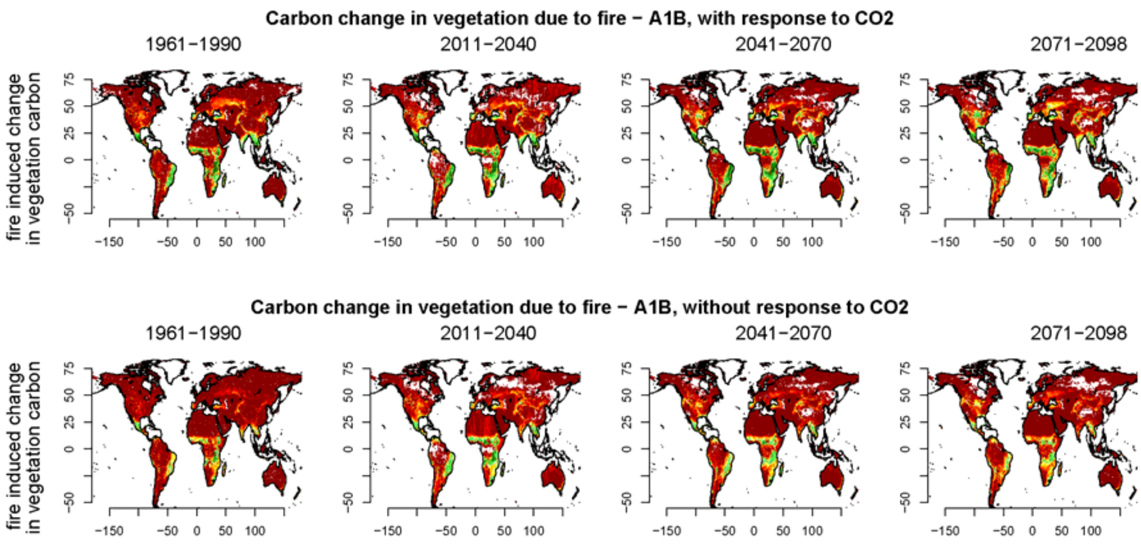


Figure 11: Changes in vegetation carbon for the A1B scenario as a result of fire events a) with and b) without elevated atmospheric CO_2 at four time slots. Red colours indicate carbon losses (light to dark red: higher losses), green colours indicate carbon gains (light to dark green: higher gains), white indicates no change.

over. This will affect water regulation and gas regulation, since evergreen trees can be photosynthetically active throughout a longer time span of the year. The expected losses in biodiversity due to low migration rates will likely lead to less stable ecosystems systems, since important buffer mechanisms against disturbances need time to evolve.

3.1.1.7 Uncertainty

Uncertainty in emissions

We compared the mean global total vegetation carbon for each time slot of the eight model runs following the A1B storyline with vegetation carbon from of the eight E1 model runs (Figure 12). For both scenarios with and without high CO_2-fertilization, the A1B storyline shows the stronger response to climate change. With the effects of CO_2, a strong increase in global vegetation cover (from ~600 GtC in the reference time slot to ~780 GtC at the end of this century) can be found. In contrast, there will be a strong decrease in vegetation carbon (~450 GtC until the end of this century), if CO_2-fertilization effects are low. The impact of the E1 scenario is more moderate, here stabilising effects can be found at the end of this century.

Uncertainty between climate models

We looked at the mean value and especially the standard deviation of simulated vegetation carbon for different climate models following both storylines. Since the climate data from the various models was not bias corrected, a relative high deviation between the models occurs already in the reference time slot (Figure 12). The relative deviation increases over time, as the values for the coefficient of variation (standard deviation divided by mean) show (Table 6). These results show that there is a high uncertainty in global climate models, which cascades to global vegetation results.

But having in mind the maps of vegetation carbon (Figure 3, Figure 4), for most areas in the world there is a high agreement between different climate models on the direction of

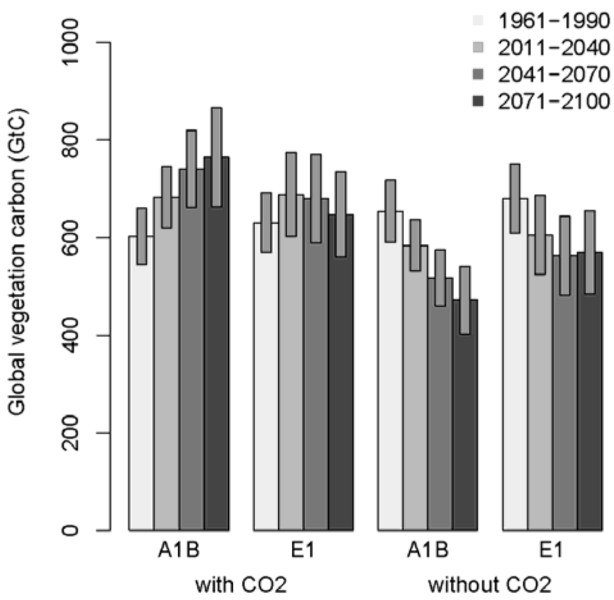


Figure 12: Global vegetation carbon at the four time slots. Upper rectangles indicate the standard deviation between different climate models of one storyline.

Table 6: Coefficient of variation for global vegetation carbon between models of one storyline.

	Storyline	1661-1990	2011-2040	2041-2070	2071-2100
with CO_2-effects	A1B	0.096	0.093	0.107	0.133
	E1	0.098	0.125	0.134	0.135
without CO_2-effects	A1B	0.097	0.091	0.110	0.147
	E1	0.103	0.134	0.143	0.150

change, i.e. whether we have to expect increases or decreases in vegetation, soil and litter carbon. Greater uncertainty arises still from the emissions storylines and from the uncertain response of vegetation to CO_2 fertilization.

3.1.2 European Runs

A detailed description of the European runs is given in Deliverable 2F2. Here, we present a summary of the most important results.

3.1.2.1 Carbon storage

We evaluated carbon storage for natural ecosystems in three major compartments, namely vegetation carbon, soil carbon and litter carbon. The results refer to simulations with natural disturbances by fire. Present vegetation carbon ranges from 20-30 t/ha in Spain and south-east Europe to more than 100 t/ha in highly productive Ireland and Britain (Figure 13). If, the atmospheric CO_2 concentration is kept constant (conservative estimation), high carbon losses are expected throughout Europe with the exception of Scandinavian countries and Poland within this century.

Soil carbon will likely stay relatively stable during the next century, independent on CO_2 fertilization effects (see Deliverable 2F2). However, these results do not account for elevated soil carbon losses due to the melting of permafrost soils. Here, great additional losses have to be expected (Heimann and Reichstein 2008; Schuur et al. 2008).

The litter carbon pool is generally low (see Deliverable 2F2). Results show relative constant litter carbon content if for rising atmospheric CO_2 and decreasing litter carbon content, if CO_2 is kept constant.

3.1.2.2 Biomes

We evaluated the distribution of natural biomes in Europe according to the potential cover of natural vegetation without anthropogenic impacts. Dependent on the fraction of covered ground by the simulated nine plant functional types (PFTs), we categorized grid cells into such biomes following Haxeltine and Prentice (1996) (Figure 5).

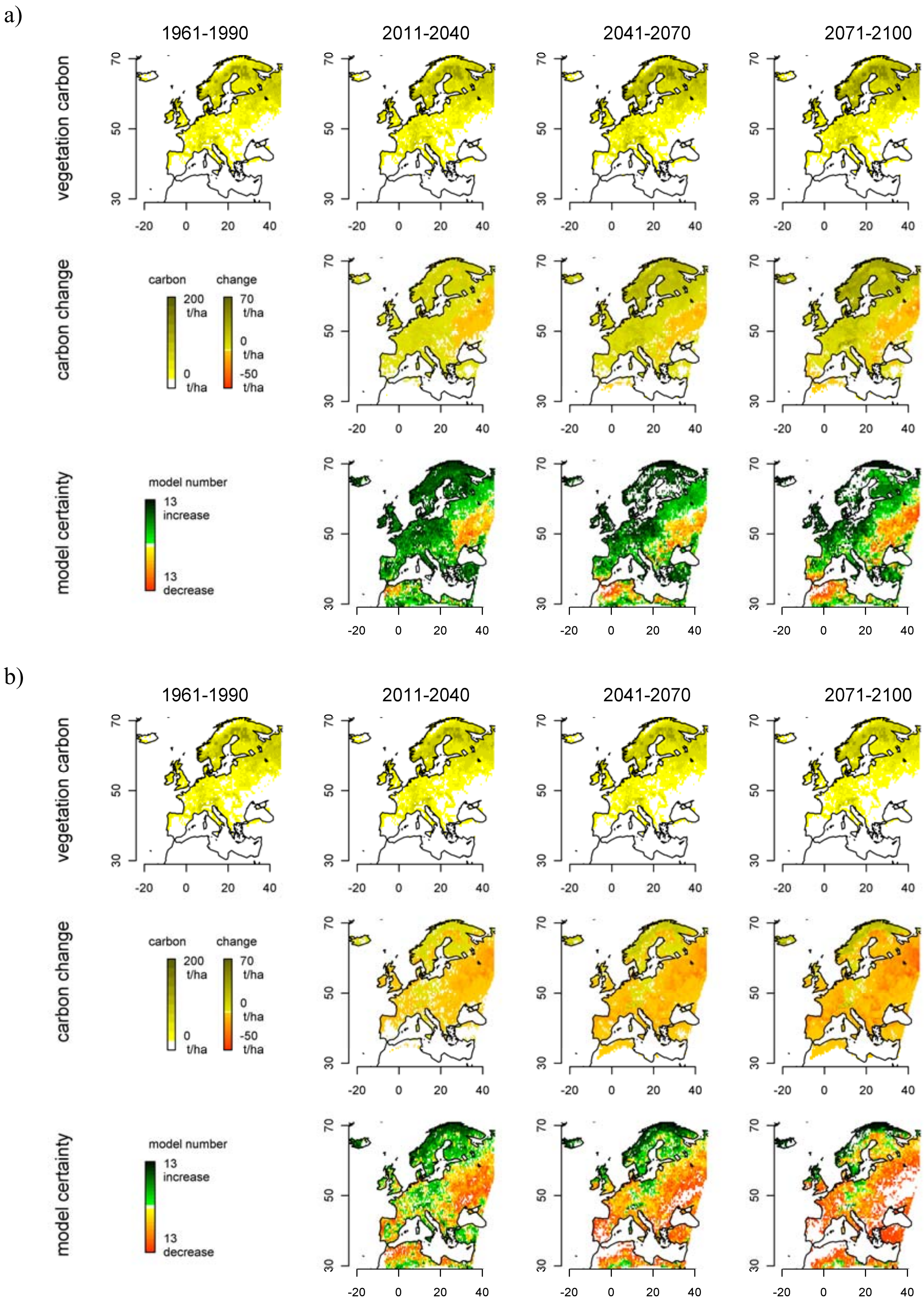


Figure 13: Mean vegetation carbon a) with and b) without elevated atmospheric CO_2 at four time slots (upper panels), its change compared to the reference scenario 1961-1990 (middle panels) and the number of models predicting this direction of change, i.e. the uncertainty between climate models (lower panels).

Boreal forests

Boreal forests are the highest productive biomes in Europe with vegetation carbon storage above 80 t/ha. Independent on the effect of carbon fertilization, boreal forests in Scandinavia will likely shift towards the poles and boreal forests in the Alps will likely shift to higher altitudes as empirical studies have shown already (Figure 14). Our scenarios show that they could replace taiga vegetation, which is here classified as shrubland or grassland. The overall number of grid cells occupied by the boreal zone, however, will according to our scenarios not change until the end of this century. If the effect of carbon fertilization is high, increases in the carbon storage capacity of vegetation, but also in losses by fire events can be expected. If on the other hand the effect of carbon fertilization is low, the overall area occupied by boreal forests as well as their structure will stay relatively stable.

LPJmL assumes instantaneous migration of plant functional types: If climatic conditions are suitable for the establishment of new types, they can expand their range without any time lag. This will generally overestimate the speed of biome migration, since soil conditions, dispersal limitations or other factors can prevent fast migration, which is not accounted for in LPJmL. The degree of overestimation is however highly species specific and therefore has to be approached with species specific empirical and modelling tools.

Mixed forests

Scenario results suggest that mixed forests will shift northward and replace retreating boreal forests. However, this shift is highly dependent on carbon fertilization effects. Assuming only low effects leads to a replacement of temperate forests by less productive shrublands at the south-eastern extent of their areal leading to high losses in their spatial extent. But independent on carbon fertilization, their vegetation carbon storage capacity will increase, since they will likely shift to regions with higher rainfall allowing for higher productivity.

Temperate forests

Temperate forests occupy central and south-western Europe. According to the simulated scenarios, climate change alone will reduce this distribution to a core area in central Europe and the UK/Ireland. However, if CO_2 fertilization effects are strong, the

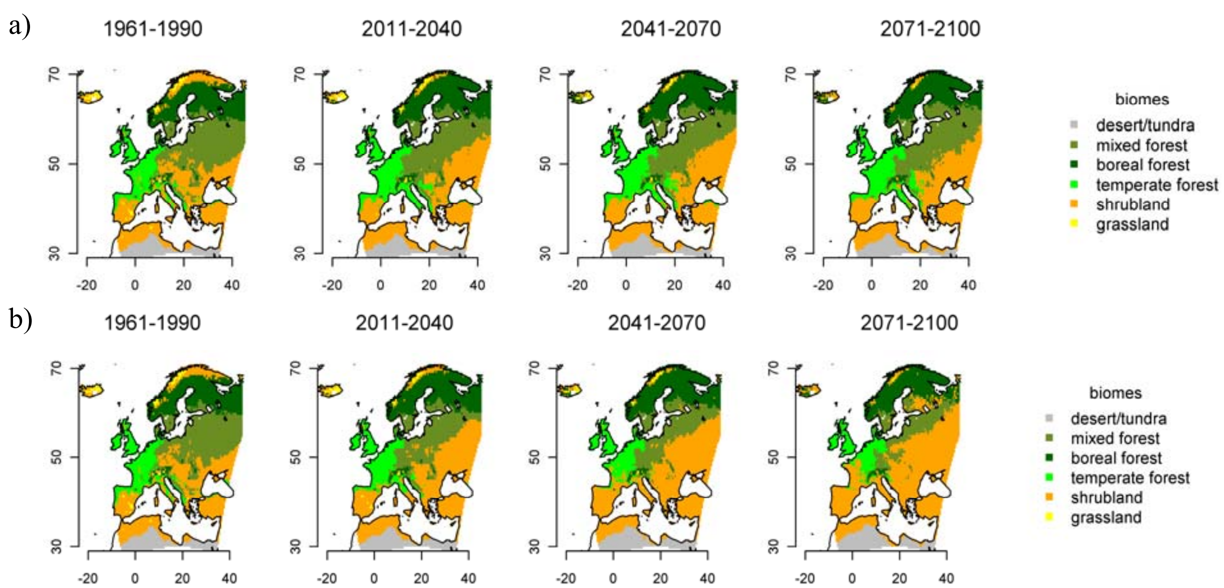


Figure 14: Biome distribution of six broad European biomes a) with and b) without elevated atmospheric CO_2 at four time slots (A1B scenario).

distribution area will remain similar to the reference scenario and slight increases for vegetation carbon are expected.

Shrublands

Shrublands highly benefit from the retreat of other biomes, when low CO_2 fertilization effects are assumed. They will likely spread from south-eastern Europe and south-western Europe to central Europe and regions further north. Shrublands belong to the low productive regions of Europe with vegetation carbon storage below 20 t/ha.

Replacement of forests by shrublands will lead to a highly evident shift of the landscape structure: instead of dense forests, only light mixtures of grasses and trees form the landscape, which leads to high losses of refuge sites for many species.

Grasslands

Natural grasslands only play a minor role in Europe. Their distribution is expected to even decrease slightly within the forthcoming century, since they will be replaced by shrublands or boreal forests.

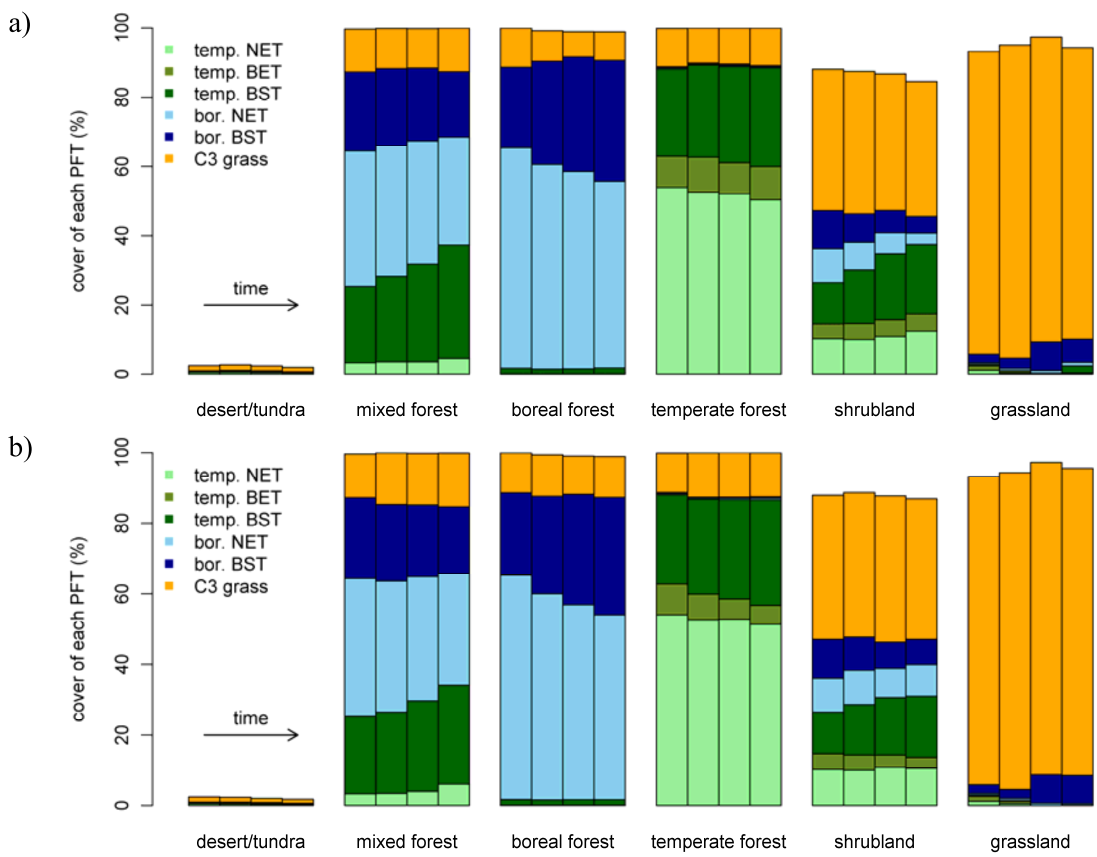


Figure 15: Cover of the main six plant functional types (PFTs) in six broad European biomes a) with and b) without elevated atmospheric CO_2 at four time slots (1961-1990, 2011-2040, 2041-270, 2071-2100). Abbreviations: temp. NET – temperate needle leaved evergreen tree; temp. BET – temperate broad leaved evergreen tree; temp. BST – temperate broadleaved summer green tree; bor. NET – boreal needle leaved evergreen tree; bor. BST – boreal broadleaved summer green tree; C3 grass – grasses following the C3 pathway.

3.1.2.3 Biodiversity

According to the simulated scenarios biomes will likely shift their range and their size, leading for example to a huge restructuring and displacement of the tundra. The phenology of plants within one biome could change, implicating shifts in plant-animal interactions and therefore in the food web. But also the composition of biomes will likely change, and dominant plant functional types will be replaced by others (Figure 15). Simulations with LPJmL show that generally, the proportion of needle leaved trees in forests is expected to decrease and summer green trees will probably take over. This is caused by the longer growing period levelling of the advantage of needle leaved trees, which can respond fast to the first warm days in spring. Resolving this change on the species level would probably even lead to more pronounced changes, where some species can adapt fast to new conditions while others go extinct.

3.1.2.4 Uncertainty

Uncertainty in emissions

For each biome, we compared mean vegetation carbon in Europe for each time slot of the 13 model runs following the A1B storyline with vegetation carbon from an E1 model run (Figure 16). Until 2040, accumulated carbon is higher for the E1 scenario if strong CO_2 fertilization effects are assumed. Afterwards the carbon content is lower for the woodland biomes. On first glance this inconsistent result is somewhat surprising, since the A1B storyline is characterised consistently by higher carbon emissions and stronger climatic changes and therefore the results should also be consistent with time. However, the E1 scenario is characterised by an initially stronger warming than the A1B scenarios because of faster reduction in sulphate aerosol loading. This leads to higher growing rates because of longer growth periods. But after this initial time period, carbon fertilization effects become more dominant and lead to higher vegetation carbon accumulation for the A1B scenario. If the CO_2 fertilization effect is not taken into account, simulated vegetation carbon is generally higher for the E1 scenario compared to the A1B scenario for all biomes and time slots since vegetation carbon losses are less pronounced.

Uncertainty between climate models

We looked at the standard deviation of simulated vegetation carbon for different climate models following the A1B storyline. Thanks to the bias correction of climate data, the standard deviation is especially for the reference scenario very low in comparison to mean vegetation carbon. The further the climate predictions lie in the future, the bigger the standard deviation becomes, especially if CO_2 fertilization effects are taken into account. This shows that it would be beneficial if simulation results from more climate models would be available also for the E1 storyline in future simulations. But having in mind the maps of vegetation carbon and vegetation carbon losses, for most areas in Europe there is a high agreement between different climate models on the direction of change, i.e. whether we have to expect increases or decreases in vegetation, soil and litter carbon. Greater uncertainty arises still from the emissions storylines and from the uncertain response of vegetation to CO_2 fertilization.

3.1.3 Comparison with literature

The literature review in the first report of work package 2F showed several evidences for possible effects of climate change on various biomes. We re-evaluated these possible effects with simulations performed with LPJmL (Table 7) and could confirm most of the trends found in the literature review.

In the course of recent climate change, Tundra vegetation has retreated further to the north and boreal forests have taken over (Serreze et al. 2000; Hinzman et al. 2005). While shifts at the range limits often occur gradually via increased establishment and growth rates at the northern range and decreased rates at the southern range, shifts within a biome can occur rapidly (Chapin III et al. 2004). In LPJmL simulations, we found a strong increase of vegetation carbon in boreal forests (with CO_2 fertilization), indicating such a change in the forest structure. But also the predicted longer growing period within one year and its consequences have been documented in the literature (Badeck et al. 2004). This can, however, be critical, since interactions between vegetation and animals depend on synchrony between species, for example the presence of specific food at a specific point of time (McCarty 2001).

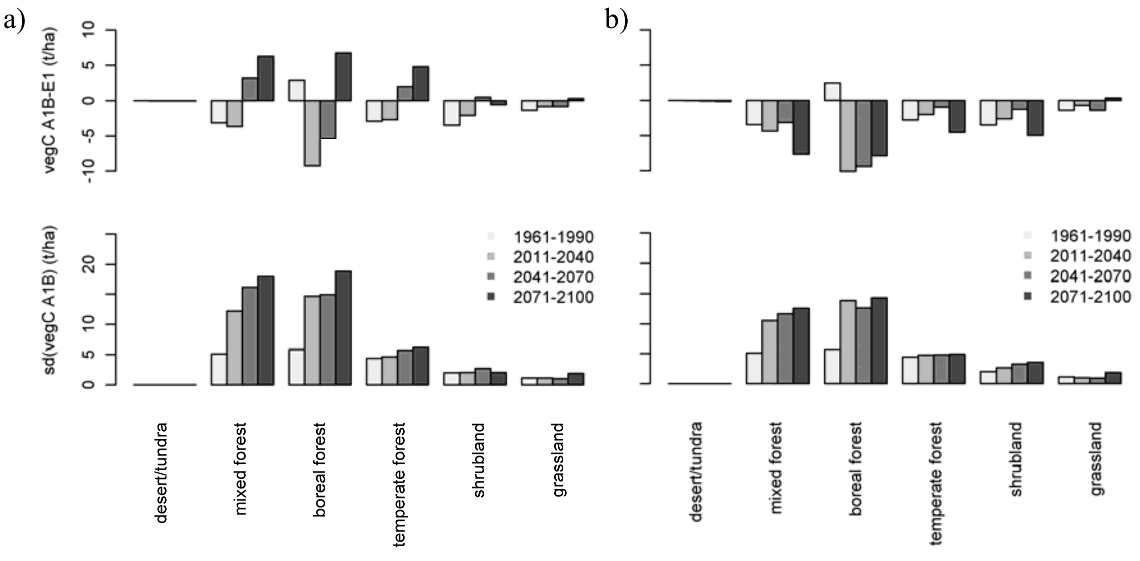


Figure 16: Difference in mean vegetation carbon between simulations following the A1B and the E1 scenario (upper panels) and standard deviation (sd) of mean modelled vegetation carbon for all models following the A1B scenario (lower panels) for six major European biomes a) with and b) without elevated atmospheric CO_2 for four time slots.

The northward shift of boreal species goes along with a northward shift of mixed forests. The predicted shift in species composition within mixed or temperate forests (Badeck et al. 2001) can also be found in LPJmL simulation results. The fraction of temperate trees in mixed forests increases and the needle leaved evergreen trees in temperate forests slightly decrease. But changes will be much more pronounced for single species dependent on their capacity to adapt to changes and migration ability. Although we did not investigate the impact of single aspects of climate change such as precipitation or temperate changes alone, LPJmL results indicate changes in carbon sequestration as indicated by the literature (Angert et al. 2005).

The alpine zone should be investigated in a higher resolution than a grid size of 0.5° by 0.5°, since changes in vegetation cover and composition occur within much smaller distances. However, LPJmL results can still reproduce the observed upward shift of the alpine tree line (Kullman 2001): simulations show that the maximal altitude at which boreal forests can be found shift from 2200 m in 1961-1990 to 2275 m in 2071-2100. There is evidence for changes in phenology, e.g. in the flowering of shrub, forb, and graminoid species (Dunne et al. 2003). If CO_2 fertilization effects are taken into account, simulation results indicate an earlier beginning of net primary production for grasslands, implicating earlier flowering and seed production.

Table 7: Evidence from the literature for potential effects of climate change on various biomes and the comparison with LPJmL simulations.

Ecosystem	Climate change	Potential effects	Source
Arctic Zone			
Tundra	*Evidence in the literature*		
	Increased temperature	Invasion by coniferous trees	Landhäusser and Wein (1993), Johnstone and Chapin (2003)
		Northward migration of tundra into current polar desert	Callaghan et al. (2005)
	LPJmL simulations within ClimateCost		
	Boreal forests shift further north and replace tundra vegetation: - The extent of arctic grasslands decreases - The maximal northern extent of the range of boreal forests shifts from 68.75 °N to 70.75 °N (same without CO_2 fertilization) - 10% of all grid cells occupied by boreal forests are further north than 67.25 °N in 1961-1990 and further north than 68.75 °N in 2071-2100 (67.25 °N and 69.25 °N without CO_2 fertilization)		
Taiga (Boreal coniferous forest)	*Evidence in the literature*		
	Increased temperature	Shift of tree lines towards poles	Walther et al. (2005)
	Increased temperature and droughts	Increased insect outbreaks	Logan et al. (2003)
	Increased temperature and droughts	Intensified fire regimes	Flannigan et al. (2000)
	Increased temperature	Changes in the phenology	Kramer et al. (2000)
	LPJmL simulations within ClimateCost		

	- Northward shift of boreal forests: see above
	- Carbon losses by fire depend on the effect of CO_2 fertilization:
	  - strong fertilization effects lead to increased losses, but to a slightly lower frequency of fires
	  - climate change alone leads to slightly lower losses and also to a lower fire frequency
	- Phenology: higher production in early spring, this can lead to earlier flowering and a mismatch of migratory species coming later than the peak flowering period		

Temperate Zone			

deciduous forest / mixed forests	*Evidence in the literature*		
	Increased temperature	Changes in the phenology	Kramer et al. (2000), Badeck et al. (2004)
	Altered mean annual precipitation	Shift in species composition	Badeck et al. (2001)
	Combined changes	Shifts in carbon sequestration, dependent on water limitation, fire regime, summer droughts	Angert et al. (2005), Boisvenue and Running (2006)
	LPJmL simulations within ClimateCost		
	- Phenology: higher production in early spring, this can lead to earlier flowering and a mismatch of migratory species coming later than the peak flowering period - A change of plant functional type composition is predicted for mixed forests, but also slightly for temperate forests - Carbon sequestration will increase in mixed forests (boreal + temperate trees) and will slightly increase (no CO_2 fertilization effects: remain constant) in temperate forests - Carbon losses by fires will change accordingly: higher carbon contents in the ecosystem will also lead to increased losses of carbon by fire - Fires will be less frequent in mixed forests, but dependent on the CO_2 fertilization effect, they can be more frequent in temperate forests		
Steppe / Pampa	*Evidence in the literature*		
	Increased temperature	Change in fire frequency and intensity	IPCC WG2 (2007)
	LPJmL simulations within ClimateCost		
	The simulated area does not cover any steppes		
Alpine Zone			
Subalpine coniferous forest	*Evidence in the literature*		
	Increased temperature	Shift of tree lines to higher altitude	Kullman (2001)
	Increased temperature and droughts	Forest dieback	Bugmann et al. (2005)
	LPJmL simulations within ClimateCost		

	- The boreal biome shifts to higher altitudes:
	  - the maximal altitude increases from about 2200 m to 2275 m (both, with and without CO_2 fertilization)
	  - 10% of all grid cells occupied by boreal forests are at higher altitudes than 668 m in 1961-1990 and 773 m in 2071-2100 (661 m and 779 m without CO_2 fertilization)
	- The biome classification does not distinguish between alpine and arctic boreal forests. In general, boreal forests do not dieback in LPJmL simulations, however, this might be attributed to the better performance of boreal forests in northern regions		

Alpine ecosystems	*Evidence in the literature*		
	Earlier snow melting	Changes in phenology	Dunne et al. (2003)
	Lack of snow cover	Exposition of plants and animals to frost	Keller et al. (2005)
	LPJmL simulations within ClimateCost		
	- Phenology: much higher production in early spring (with CO_2 fertilization effects), this can lead to a high exposition of vegetation to frosts		
Mediterranean Zone			
Macchia /Garrigue	*Evidence in the literature*		
	Combined climatic changes and CO_2 increase	Change in fire frequency and intensity	Pausas and Abdel Malak (2004)
		Expansion to the North	Peñuelas and Boada (2003)
	Temperature increase	Desert and grassland expansion, mixed deciduous forest expansion	Hayhoe et al. (2004)
	Decreased precipitation	Reduction in ecosystem carbon and water flux	Reichstein et al. (2002)

		Delayed flowering and reduced flower production	Llorens and Peñuelas (2005)
	Increased CO_2	Minor impact due to reduced precipitation	IPCC WG2 (2007)
	Altered precipitation patterns	Change in phenology	Kramer et al. (2000)
	LPJmL simulations within ClimateCost		
	Shrublands in LPJmL simulations cover a larger area than the Mediterranean Zone. However, most findings can be transferred to the Macchia/Garrigue - LPJmL simulations do not show large changes in the fire regime. However, this can change with an improved fire model component (see above) - Shrublands will expand further north, if the effect of CO_2 is lower than assumed in LPJmL simulations, this expansion will be very strong - higher production in spring, possibly leading to a change in phenology		
Tropical Zone			
Deserts / savannas / dry forests / moist forests	*Evidence in the literature*		
	Increased temperature and decreased precipitation	Decreased productivity	Woodward and Lomas (2004)
	Combined changes	Change in fire regime	Bond et al. (2003)
	Increased CO_2 level	Species shift	Ainsworth and Long (2005)
	LPJmL simulations within ClimateCost		
	- decreased vegetation carbon without CO_2-fertilization effects - changes in the losses of vegetation carbon due to fire events - shift towards raingreen trees (instead of evergreen trees)		
All Zones			
Bogs, marshes, aquatic systems	*Evidence in the literature*		
	Sea level rise	Losses in wetlands	van der Wal and Pye (2004)
		Replacement of grassy marshes by mangroves	Ross et al. (2000)
		Decreases in salt marsh area	Hartig et al. (2002)
	LPJmL simulations within ClimateCost		
	LPJmL does not simulate wetlands or aquatic ecosystems		

Shrublands in LPJmL simulations presently cover large parts of the Iberian Peninsula and of south-east Europe, i.e. they dominate not only in the Mediterranean region but also further north. Nonetheless, simulation results of shrublands can be transferred to the typical Mediterranean Macchia /Garrigue vegetation. A drier climate will lead to a northward shift of this biome. In LPJmL simulations, this can be partly mitigated by the enhanced water use efficiency under elevated atmospheric CO_2, but the trend shown in the literature (Peñuelas and Boada 2003) is evident.

3.2 Forestry

3.2.1 Implementation of LPJmL results

For Europe LPJmL has estimated NPP for each year of the time span 2000-2100 using the DMI-CNRM, ETH-METO-HC Standard and SMHI-MPIMET Standard Climate for the plant functional types temperate needle leaved evergreen tree, temperate broadleaved evergreen tree, temperate broadleaved summer green tree, boreal needle leaved evergreen tree, boreal broadleaved summer green tree (see Table 3). These NPP estimates have been transferred to stem wood increments by comparing NPP estimates of the average climate scenario (DMI-CNRM) of the time span 2000-2010 with stem wood increments estimated by G4M. This comparison shows that around 55% of the NPP is used for the stem wood increment. This relation ship is held constant for the following investigations even though this relation ship might change under a changing environment.

After estimating the potential increments for different plant functional types, it is necessary to allocate the information to the current forest and species distribution and current stocking biomass to have a starting point for future management scenarios. The forest area distribution was taken from the GLC2000 map. The tree species distribution was taken from JRC where each species was allocated to one of the available plant functional types. Estimates of the currently stocking biomass where taken from Kindermann (2008). Given the yield level and the stocking biomass and assuming a normal forest is present (each age class occupies the same area) it is possible to create an age structure for the entire forest landscape.

3.2.2 Options of species and management change as adaptation and mitigation measures in forestry

As a response to climate change, both, mitigation and adaptation measures are currently discussed in the forestry sector. Tradeoffs and benefits of both types of responses are assessed in this report by applying a combination of these measures (Table 8).

First, to assess model sensitivity and explore the ranges of climate change implication on yield an instant species change is implemented. This is a (theoretical) instant change to the best growing species (decided on an annual basis) by keeping the age structure compared against no species change. Such an abrupt change is not possible as it would require replacing existing forest with forest of a different species but same age. Consequently, this is an extreme case that can be used to assess the sensitivity of the model yield estimates to varying climate and species change but cannot be interpreted as a realistic management scenario.

Second, an alternative case of realistic adaptive management response to climate change addressing species is considered. The rotation time of a forest is mainly determined by the management target, species and site conditions. In European forestry rotation times of up to 100 years are typical. Such long rotation times prevent a fast change of the species composition in forests that can only occur at the end of a rotation. A species change scenario shows therefore delayed effects in which species are exchanged gradually wherever appropriate (based on a comparison of increment) and whenever a rotation time ends in the forest. Results are compared to model runs under climate change where species composition is kept constant.

Species choice is only one option of management that can be considered by a forest owner within G4M. A change of rotation length to manipulate biomass accumulation and increment is another one that was implemented. Such an option reflects the discussion on increasing carbon storage in existing forests through building up higher biomass stocks as a measure to mitigate carbon concentration in the atmosphere and offset emissions. A management target which will increase the stocking biomass is prolonging the rotation time which will lead to smaller annual harvest areas and a further delay in the change from one species to another. The mitigation measure of biomass increase is therefore in conflict with the adaptation measure of rapid species change. An alternative mitigation strategy would target forest biomass increment and would implement measures that lead to a maximization of increment. Although this might lead to reduced carbon storage in the forest ecosystem, a mitigation effect would be achieved through biomass harvest and substitution of fossil fuels in energy production and energy intensive products. Such measures could lead to a reduction of rotation lengths and would therefore speed up the potential replacement of species. Both options, maximization of biomass stocks and biomass increment are compared to continues business as usual management (managing forests with continued observed rotation lengths).

Table 8: Overview of forest management options assessed covering adaptation (species change) and mitigation (maximization of biomass stocks) measures.

		Adaptation measures	
		No species change	Gradual species change
Mitigation measures	No management change, keep current rotation times	X	X
	Management change, extension of rotation times to maximize biomass stocks in forests	X	X
	Management change, change rotation times to maximize increments in forests	X	X

3.2.3 Yield development under climate change considering instant species change

Figure 17 shows the differences in yields of stem wood increment for the DMI-CNRM Climate for the case of a theoretical instant species change versus no change. When keeping the current species distribution, boreal needle leaved evergreen forests in Europe potentially produce the highest increments. Yield estimates from LPJ suggest boreal broadleaved summer green species being more competitive, what could lead to an expansion at the cost of boreal needle trees. Such a divergence is plausible as large areas with a potential natural vegetation of broadleaved trees in Europe are currently stocked by needle trees introduced through forest management. However, the differences of the total forest increment between the two options are not too large.

Also it can be seen from **Figure 17**, that the share of boreal needle trees in the species change scenario of total increment is further decreasing until 2100. The share of temperate broadleaved summer green trees is increasing instead. Another fact that can be observed in both options is that the yields are decreasing dramatically in some years. Increment decreases of 30% to 50% are very frequent. Compared to increment decreases of the pointer years 1913, 1948, 1973 and 2003, which showed a diameter increment decrease of around 20%, the predicted decreases are very large. Possible reasons for these discrepancies can be the circumstance that tree ring width changes of pointer years are typical only observed on trees which could have survived the bad situation in the pointer year. On the other hand there will very likely be no additional mortality rate of 30% in one single year. Also the constant transition from NPP to stem wood increment will not be constant in real live. But usually the growth reaction of trees typical is overestimated by only observing its diameter increment.

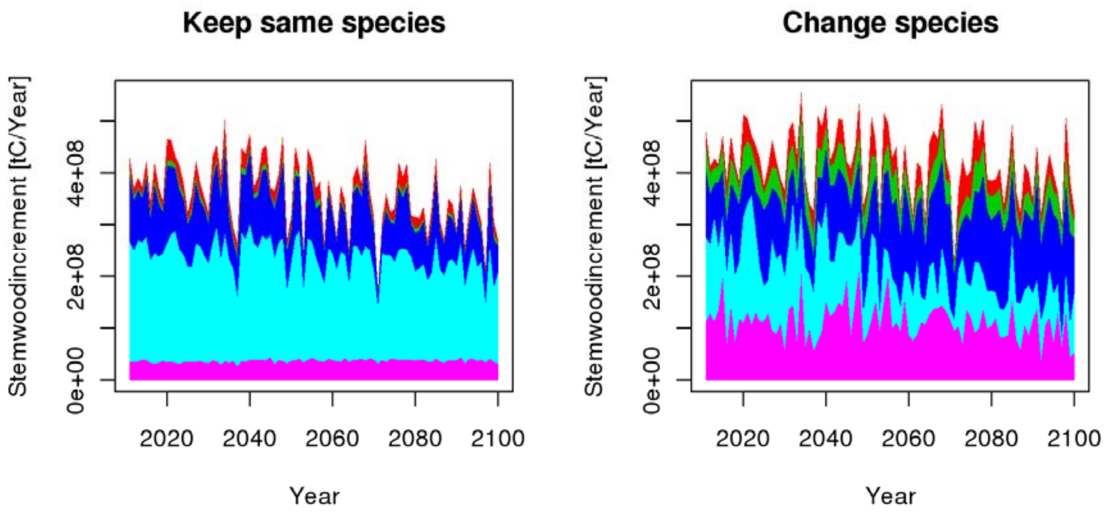


Figure 17: Total potential stemwood increment under the DMI-CNRM climate. Left: Management keeps the same species composition. Right: theoretical instant species change to species with highest growth. Plant functional types displayed are temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

Figure 18 and **Figure 19** show results for the other two climate sources. Both show annual increment variation in the range of historical pointer years. The species composition of ETH-METO-HC Standard (**Figure 18**) of the best growing species is close to the current species shares. Only temperate broadleaved summer green trees are currently more present. In the years 2011 to 2100 temperate broadleaved summer green trees get more competitive and boreal needle leaved evergreen trees loose their competitiveness. In the SMHI-MPIMET Standard climate also boreal needle leaved evergreen tree will loose competitiveness during 2011 to 2100 but temperate broadleaved summer green trees and boreal broadleaved tree will gain.

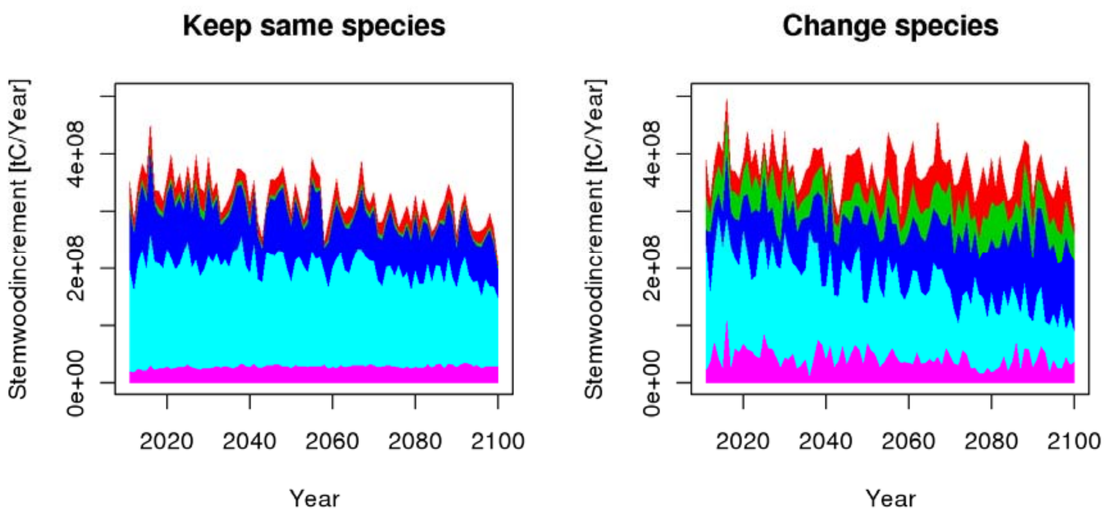


Figure 18: Total stemwood increment under the ETH-METO-HC Standard climate. Left: Management keeps the same species composition. Right: theoretical instant species change to species with highest growth. Plant functional types displayed are temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved

summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

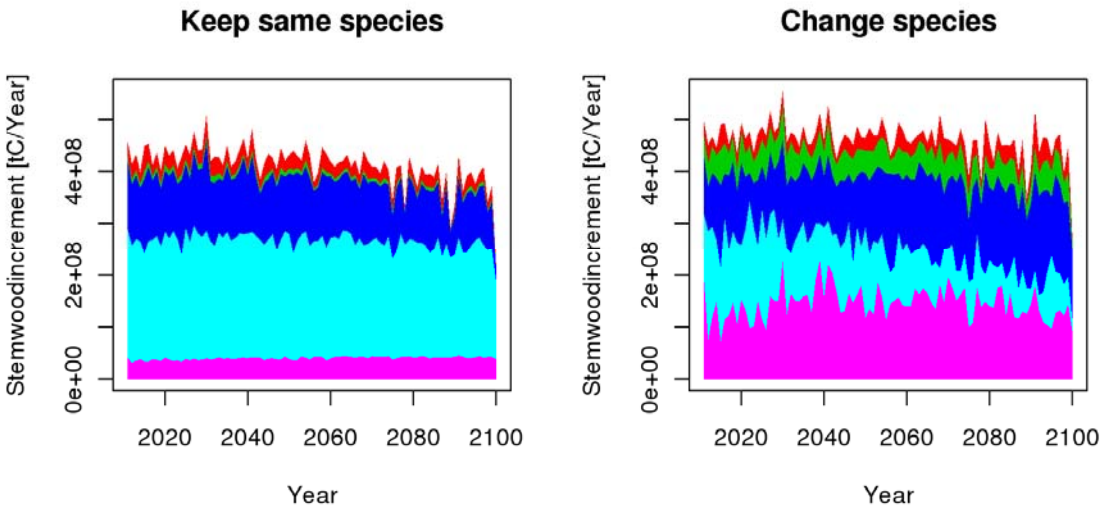


Figure 19: Total stemwood increment under the SMHI-MPIMET Standard climate. Left: Management keeps the same species composition. Right: theoretical instant species change to species with highest growth. Plant functional types displayed are temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

3.2.3.1 Differences between climate scenarios

Figure 20 compares the yield development estimated with the climate data from DMI-CNRM, ETH-METO-HC Standard and SMHI-MPIMET Standard. By keeping the same species DMI-CNRM shows until 2050 constant to slightly increasing increments and afterwards an increment decrease, ETH-METO-HC Standard show a slow decrease until 2100 and SMHI-MPIMET Standard show an increment increase until 2030 and afterwards an increment decrease. In total, SMHI-MPIMET Standard shows the highest increments at the end of the 21st century compared to DMI-CNRM and ETH-METO-HC, which are approximately on the same level. By allowing simulating an immediate species changes, the increments would be about 10% higher in the year 2010 already. Overall the estimated increment could decrease for both options but a species change would mitigate this decrease. ETH-METO-HC Standard and SMHI-MPIMET Standard show until 2050 a more or less constant increment superiority by choosing the best species. After 2050 it becomes more and more important to change from one species to another to sustain high increments of European forests. As a species change needs a long horizon in forestry to become effective, this change needs to be initiated already now to be able to reach the calculated increment in the species change scenario.

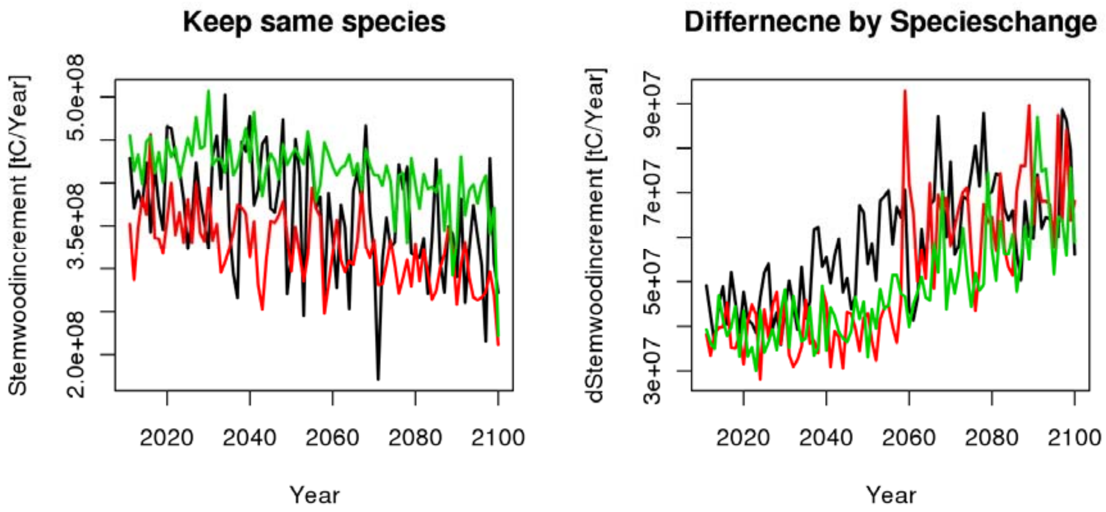
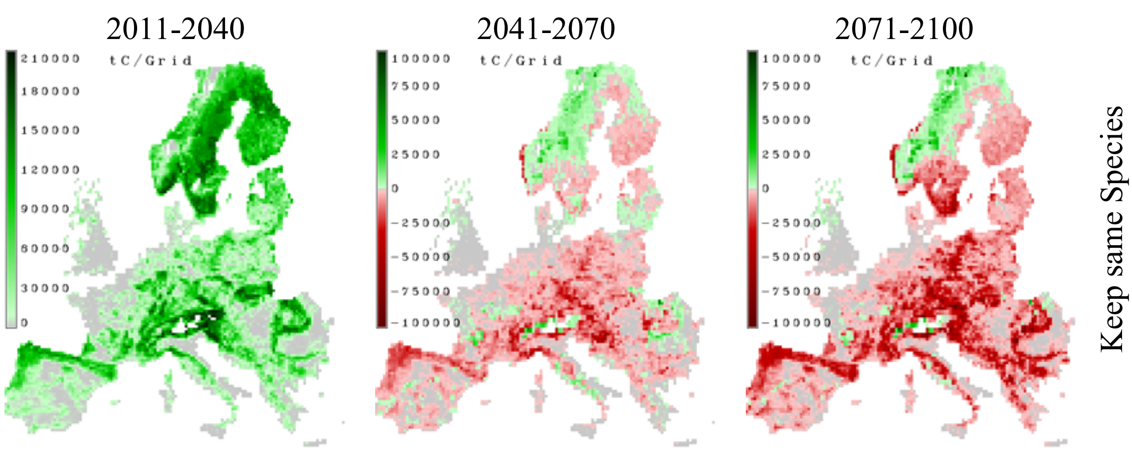


Figure 20: Comparison of the stemwood increments estimated with DMI-CNRM (black), ETH-METO-HC Standard (red) and SMHI-MPIMET Standard (green) climate. Left: Management keeps the same species composition. Right: instant species change to species with highest growth.

3.2.3.2 Spatial assessment of climate change effects with and without instant species change

Figure 21 shows the spatial distribution of the estimated increments for the DMI-CNRM climate. High increments per grid cell are in regions where the forest cover is high like in Scandinavian countries, the Alpine region, the Carpathian Mountains and the Pyrenees. By keeping the same species composition, the increment losses compared to the time span 2011-2040 will increase in most regions in Europe until 2100. Only some larger regions in Scandinavia and some smaller in France, Spain, Italy, the Alps and the Carpathian mountains will show an increment increase. By changing the species still large areas show a decrease of the estimated increment. But compared to the picture of the option of no action, the decrease is smaller and in some regions, especially in the north of Europe, the increment would increase on large areas. The picture of 2011-2040 and 2041-2070 with species change shows that in most regions a species change will bring an advantage in increments. Keeping in mind, that the anticipated immediate species change would in reality need a long time, the real live path with an ambitioned species change management would substantially delayed. While the situation under species change in the medium time range (2041-2070) is far less realistic than the situation described in the long-term time range (2071-2100).



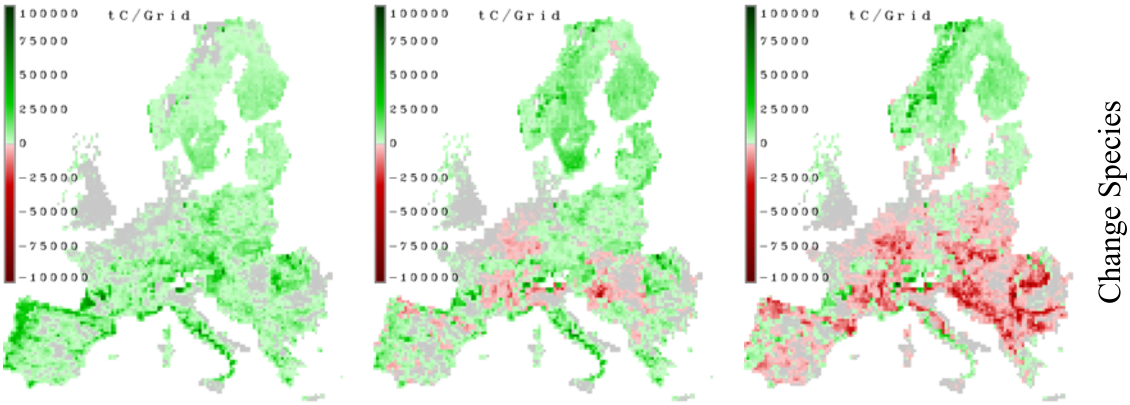


Figure 21: Regional distribution of stem wood increments on grids with 25x25km size with the DMI-CNRM climate. The left column shows the absolute increments. Other columns show the difference to left.

Figure 22 and **Figure 23** show the same comparison as displayed in Figure 21 for the ETH-METO-HC Standard and SMHI-MPIMET Standard climate, respectively. All three climate estimates show a similar pattern. ETH-METO-HC Standard shows a yield decrease of a wider geographical extent by keeping the same species. The region of relatively increased growth in Scandinavia is smaller and the "islands" of higher increment are reduced. On the other hand the huge decreases of DMI-CNRM in southern Sweden are relatively smaller in the ETH-METO-HC Standard climate and some regions in the Baltic region show a relative increment increase in 2071-2100 by keeping the same species composition. Changing from one species to another would reverse the increment decrease in many regions and regions which still will show an increment decrease will have only small increment losses. SMHI-MPIMET Standard climate (**Figure 23**) also does not show so dramatic increment losses in southern Sweden compared to DMI-CNRM. In addition, large regions in Poland are less affected compared to the other two climates. Changing the species composition will mitigate the increment decrease but some regions in central and southern Europe will still be strong affected.

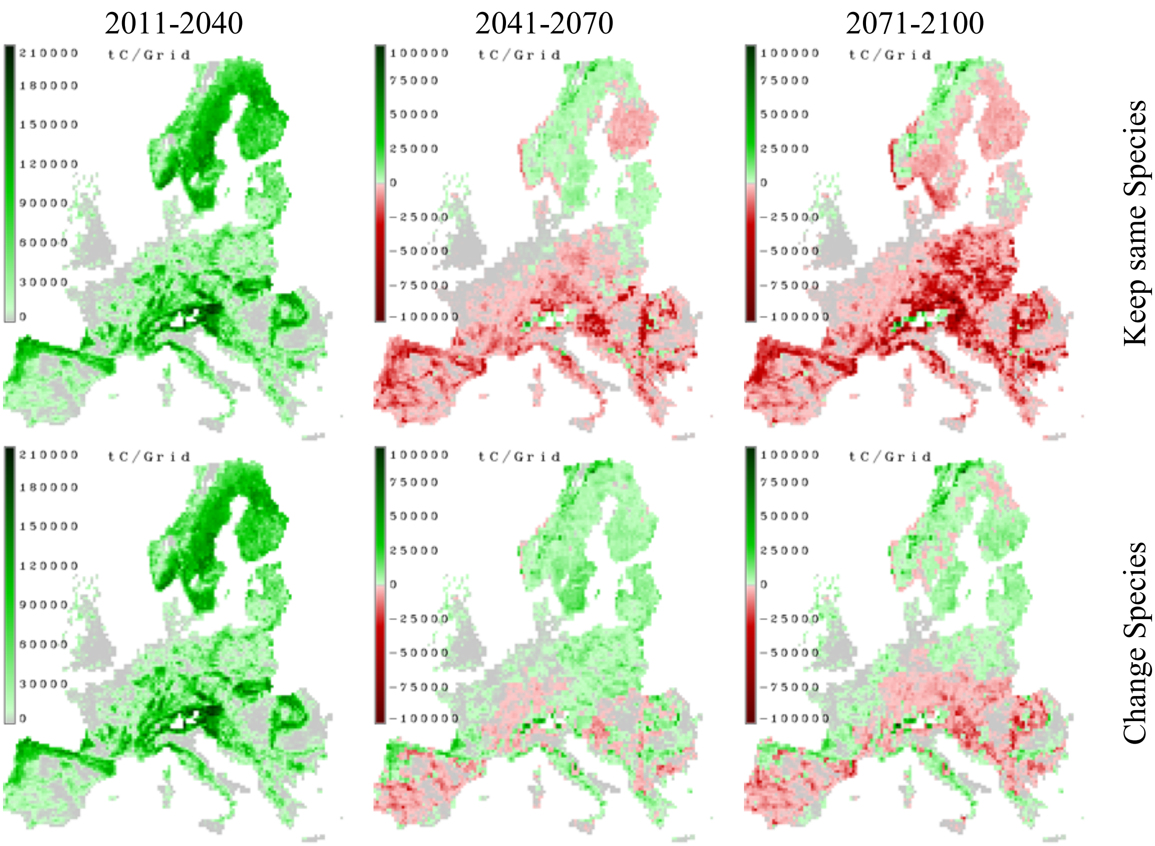


Figure 22: Regional distribution of stem wood increments on grids with 25x25km size with the ETH-METO-HC Standard climate.

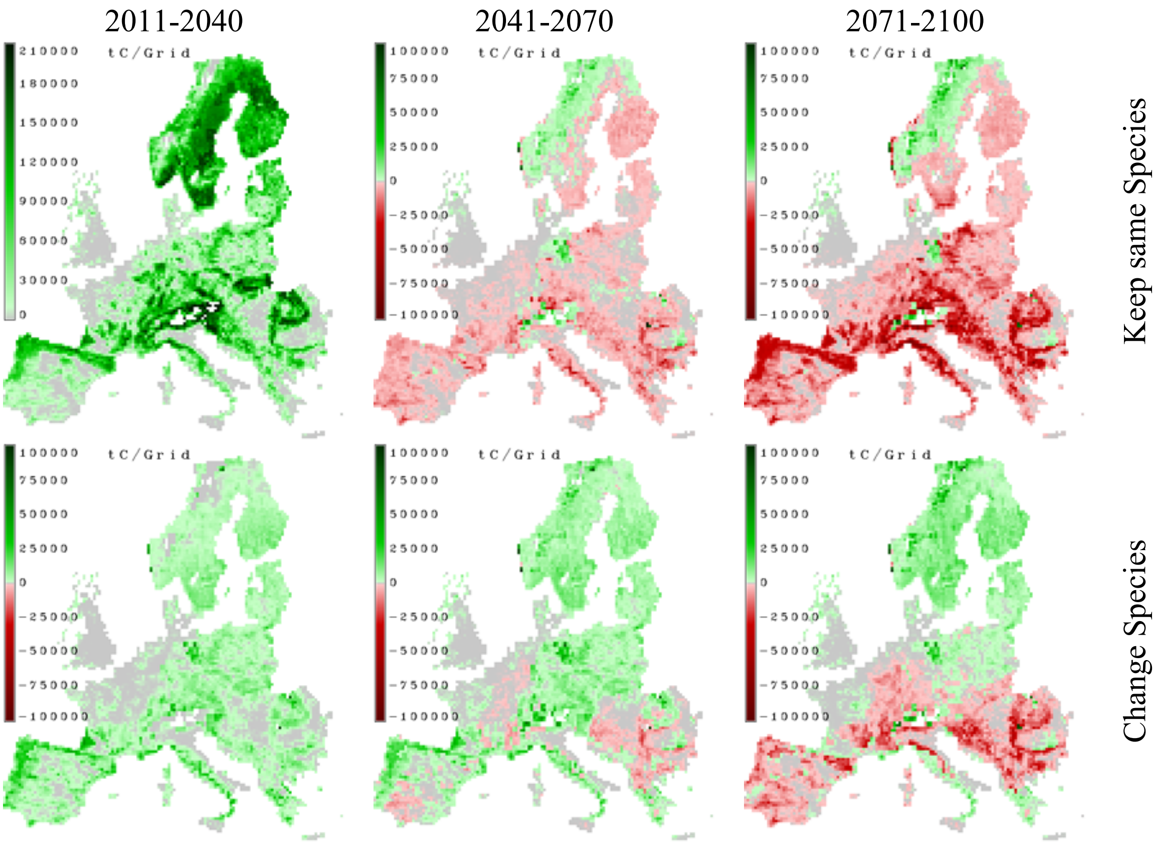


Figure 23: Regional distribution of stem wood increments on grids with 25x25km size with the SMHI-MPIMET Standard climate.

3.2.4 Assessment of adaptation and mitigation options

A set of model simulations is used to assess the effects of mitigation and adaption measures in forestry. Mitigation measures target at a maximization of biomass carbon stocks in forests or at a maximization of yield for bioenergy and timber production. Adaptation measures aim at a change in species composition to better adapted species after the end of a rotation to avoid yield decline and loss of biomass through increased disturbances. We do not examine effects of additional afforestations or avoidance of deforestations that could also be regarded as mitigation options.

Figure 24 shows the development of stocking stem biomass when keeping species composition and management for the next 100 years (left) versus the option of species change as an adaptation measure and management change toward biomass maximization or maximizing wood increments as a mitigation measure. Keeping species and management will lead to a nearly linear biomass decrease of 20% until 2100.

The scenario that maximizes increments is similar to the one keeping the same management. The biomass is decreasing in the first years somehow faster compared to keeping the same management. In the last years the biomass decrease is slowing down. This is caused by current rotation times being longer than increment optimal rotation times. A shortening of rotation times decreases biomass but allows for a faster transition form one species to another.

Having a target to increase biomass, forests will accumulate biomass until 2050, level off and sustain high stocks over the following years of the simulation.. Natural disturbances like forest fires, insects or pests will decrease the stocking biomass. Many of these disasters can be prevented by appropriate management and interventions, e.g. effect of fires can be limited with fire-breaks and removing dead wood and those of insects by species selection, pheromone traps, trap trees, insecticides or antagonists. The calculations are done with the assumption that in the European region those disasters can be limited to a small amount.

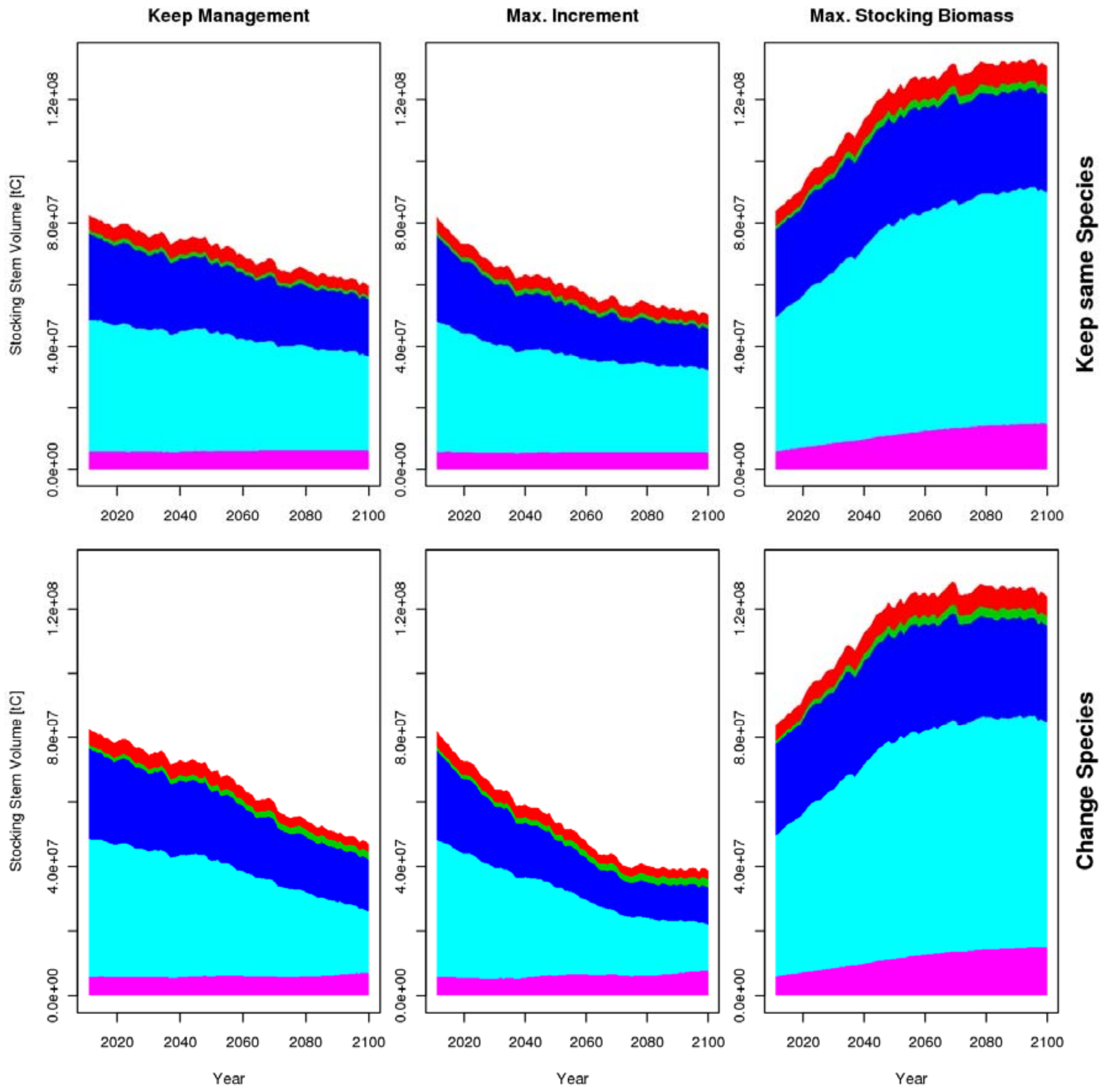


Figure 24: Development of the total stocking stem volume with DMI-CNRM climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

Figure 25 and Figure 26 show results for ETH-METO-HC Standard and SMHI-MPIMET Standard Climate, respectively. ETH-METO-HC Standard shows that without changing species and management biomass stocks might increase for the first years. Until 2100 the biomass decrease compared to the year 2010 is less than 10%. Some species groups are able to increase their stoking biomass slightly. When allowing species change the stocking biomass is lower. In a scenario that maximizes increments the biomass decreases fast in the first years and slows down in the last years. The management that targets high stocking biomass shows an increase until 2070 and a slight decrease afterwards. The total amount of additional gained biomass is lower compared to the DMI-

CNRM climate. Under the SMHI-MPIMET Standard climate the biomass stock is changing very smoothly. The total decrease is in the range of that observed under DMI-CNRM climate. With this climate the total possible stocking biomass is higher than in the other two scenarios, what is not surprising as this scenario shows also the highest yields.

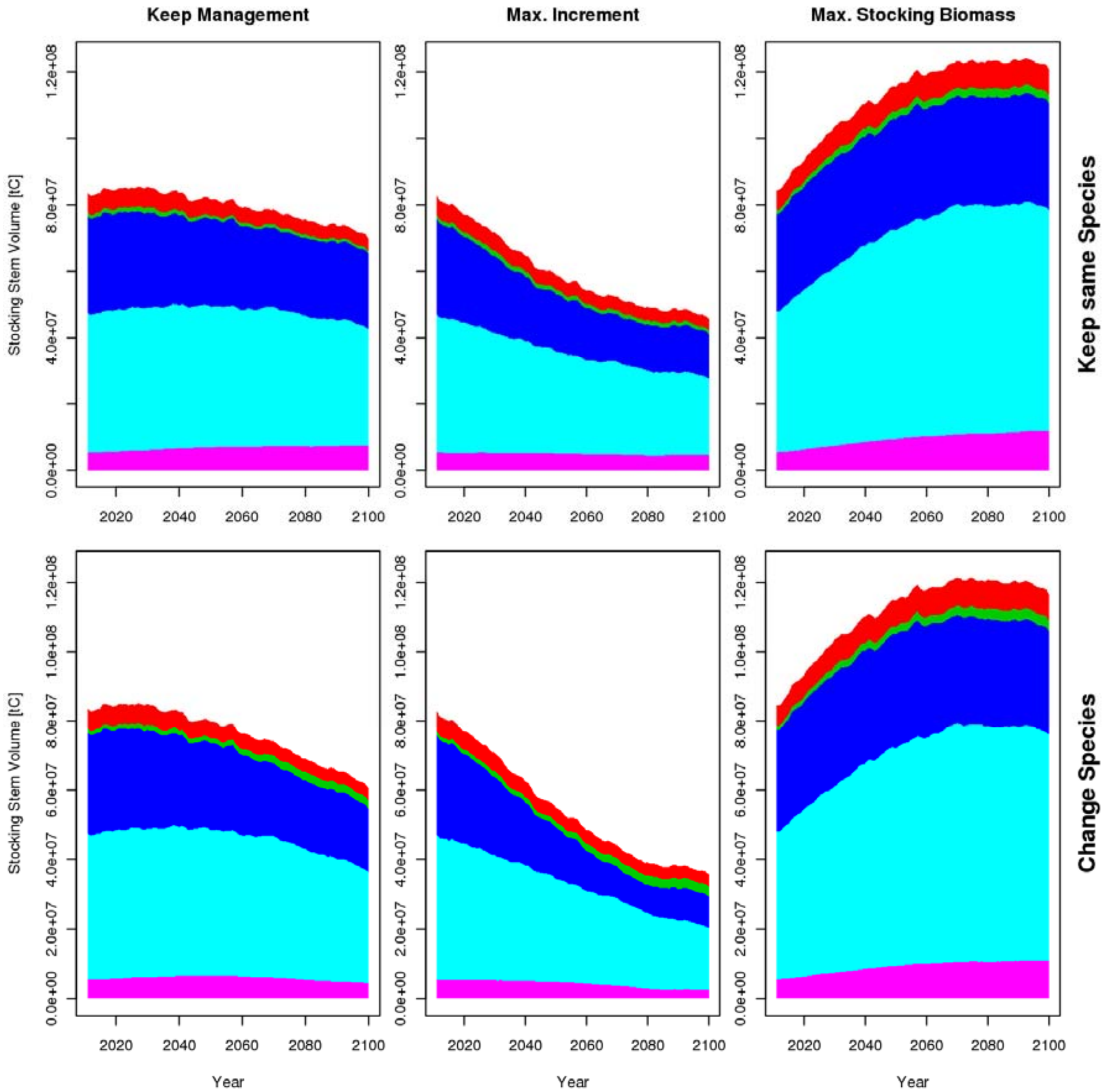


Figure 25: Development of the total stocking stem volume with ETH-METO-HC Standard climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

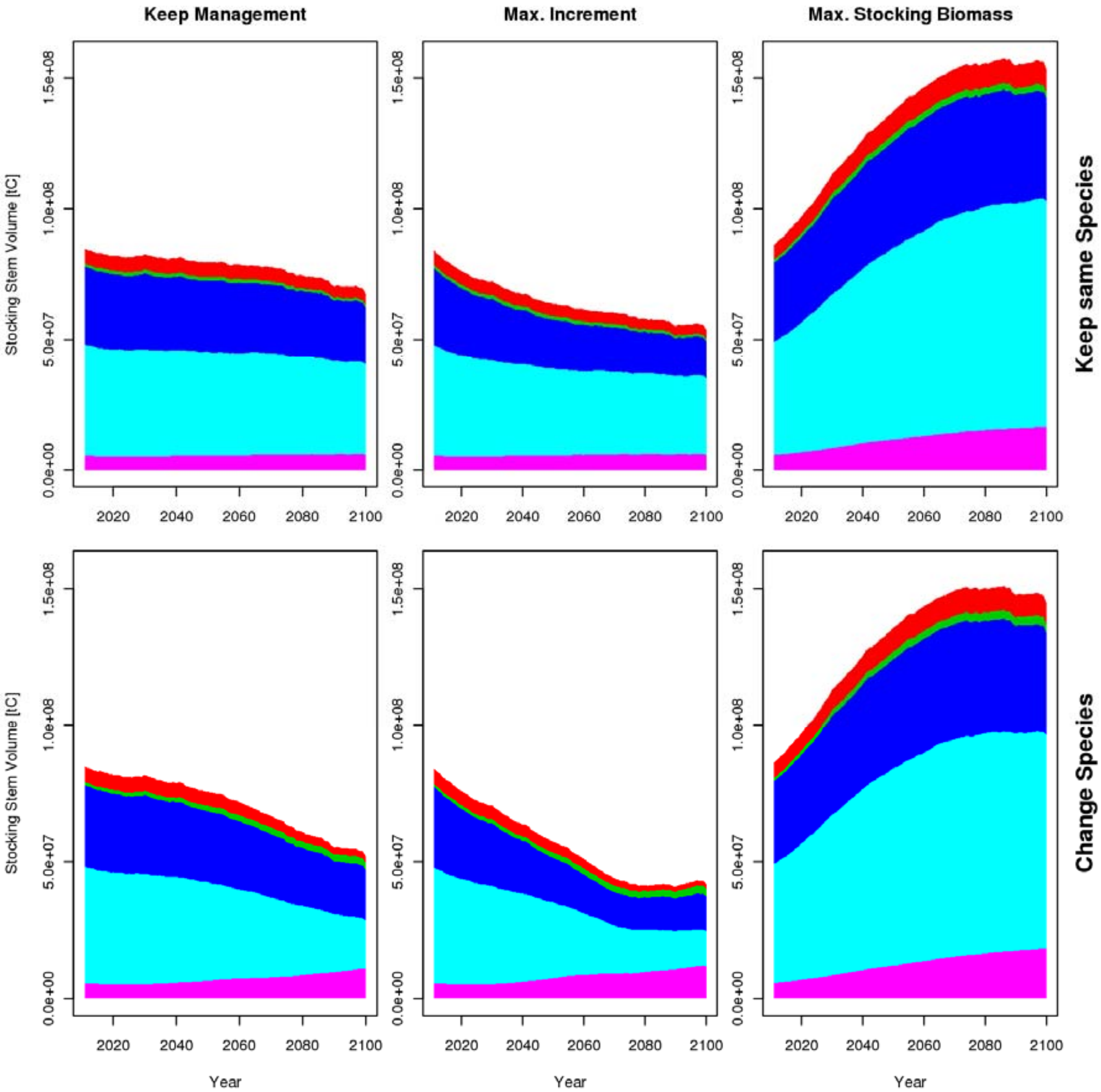


Figure 26: Development of the total stocking stem volume with SMHI-MPIMET Standard climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree(fuchsia).

Figure 27 shows the area development for the three climate scenarios and three management scenarios in the case of gradual species change. The area of boreal needle leaved evergreen tree is decreasing in all scenarios. In SMHI-MPIMET it changes fastest and the ETH-METO-HC Standard scenario suggests the slowest change. When maximizing biomass stock species change is slowest and fastest when maximization of wood increments is targeted. Under the ETH-METO-HC Standard climate area of boreal broadleaved summer green trees is decreasing, in the other climates it is increasing.

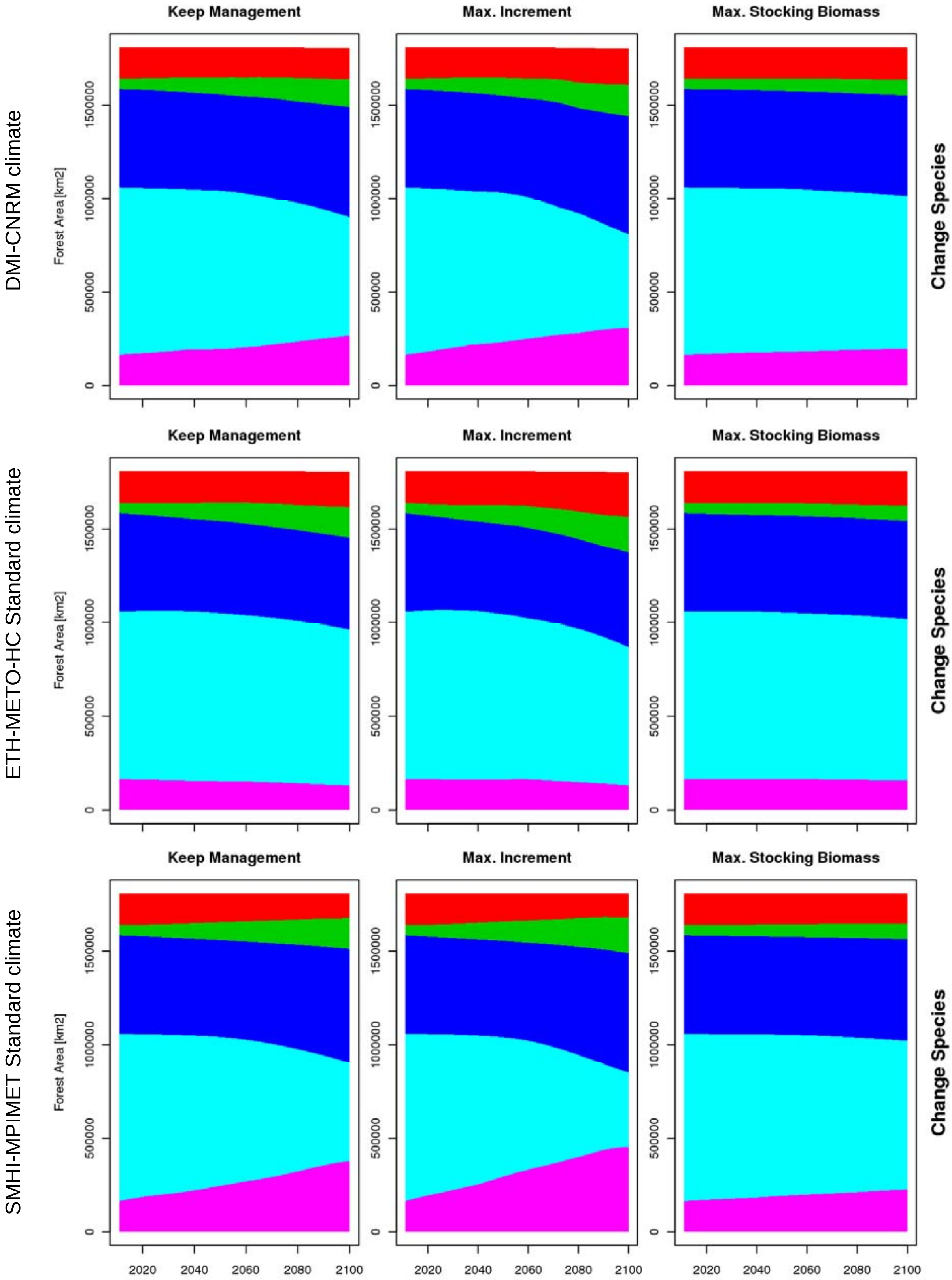


Figure 27: Development of the total species area with three climate models and species change. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

Figure 28 Figure 29 and Figure 30 show the development of removed stem volume during harvests for the three climate scenarios and three management scenarios if a change of species was done. Here the opposite of the pictures showing stocking biomass can be seen. The scenario with targeting highest increments has also the highest harvests, those keeping the same management are a little behind and this one maximizing the stocking biomass has the lowest harvests. The harvests with target highest increments are decreasing in the beginning because in these years the stocking biomass is decreased to come to an increment optimal rotation time. In the last years the harvests keep more or less constant as also the stocking biomass is kept constant. Compared to the possibilities of mitigation the management option in increasing the increment has the advantage that it will produce this higher level of harvests for infinite time – the option in maximizing biomass will only accumulate in the first years and stays afterwards constant. Also in comparing the possibilities of adaptation the management maximizing increments is in advantage. Another advantage will be in case of a disaster like forest fire, where forests which don't have high stocking biomasses can not lose to as much and younger forests are usually fitter than very old trees. The only disadvantage of maximizing increments is that someone needs to be there to use the harvested wood. It can be seen that with DMI-CNRM climate the fluctuation is very high and in SMHI-MPIMET Standard low. This is caused by the more dramatic weather extremes in DMI-CNRM which will cause higher mortality rates and in the model assumptions dying trees are removed e.g. also to keep the danger of insect disease low. It can also be seen, that the fluctuation is very high in the scenario which is accumulating biomass. This is caused by losing the flexibility to adapt to climate changes when trees are getting older. Species changes will bring down the harvests as in the transition phase of one to another species in these assumptions the area of young forests is increasing and young forest will not be harvested. It can be seen, that especially in the management optimizing increments, that harvests decrease until 2080 and stay then constant. So for a mid term view is looks like that keeping the same species is the better option but for a long time view a management which is adapting by changing species will have higher increments, higher stocking biomass and less risk of damages.

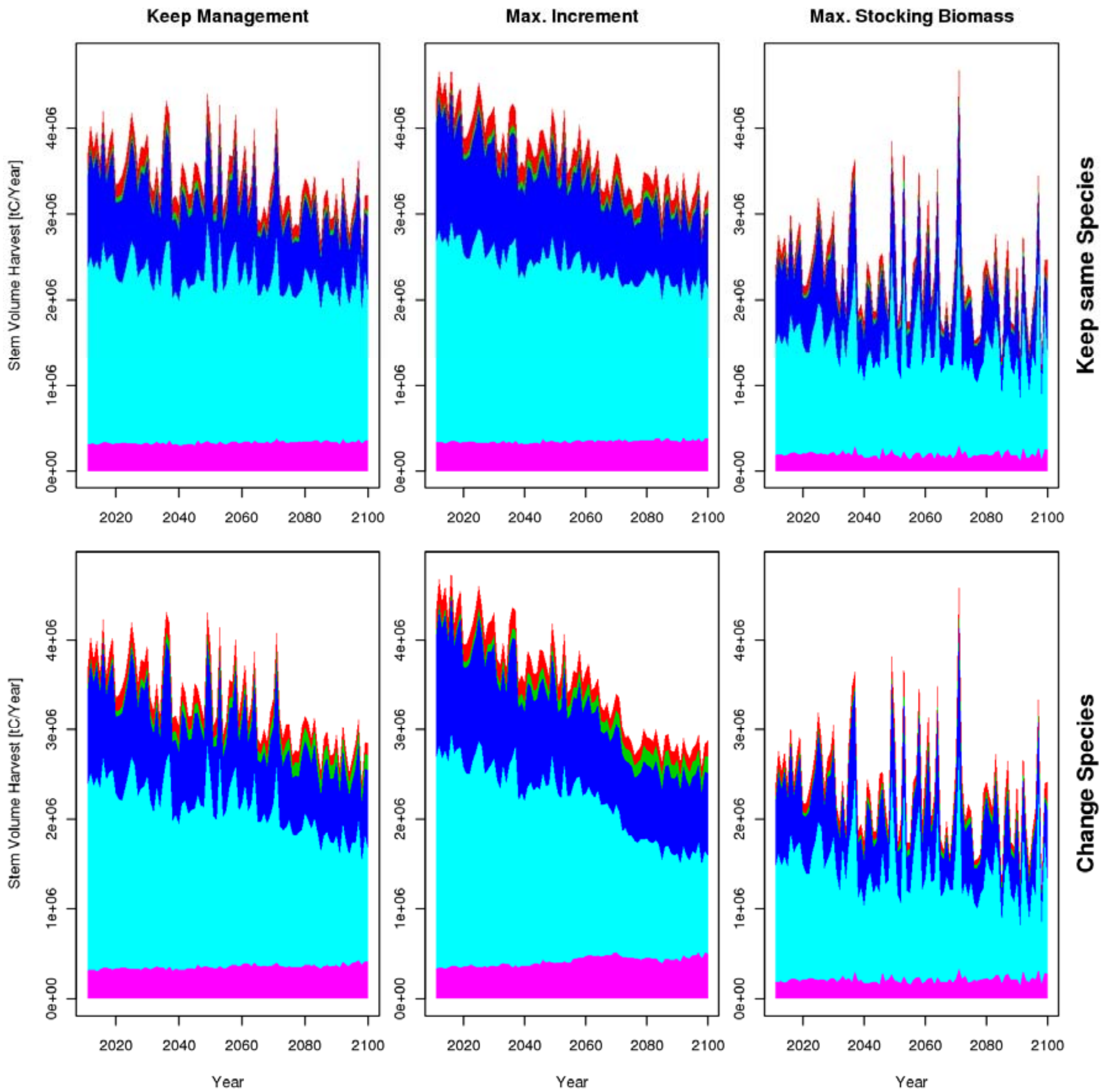


Figure 28: Development of the total removed stem volume during harvests with DMI-CNRM climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species changeBottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

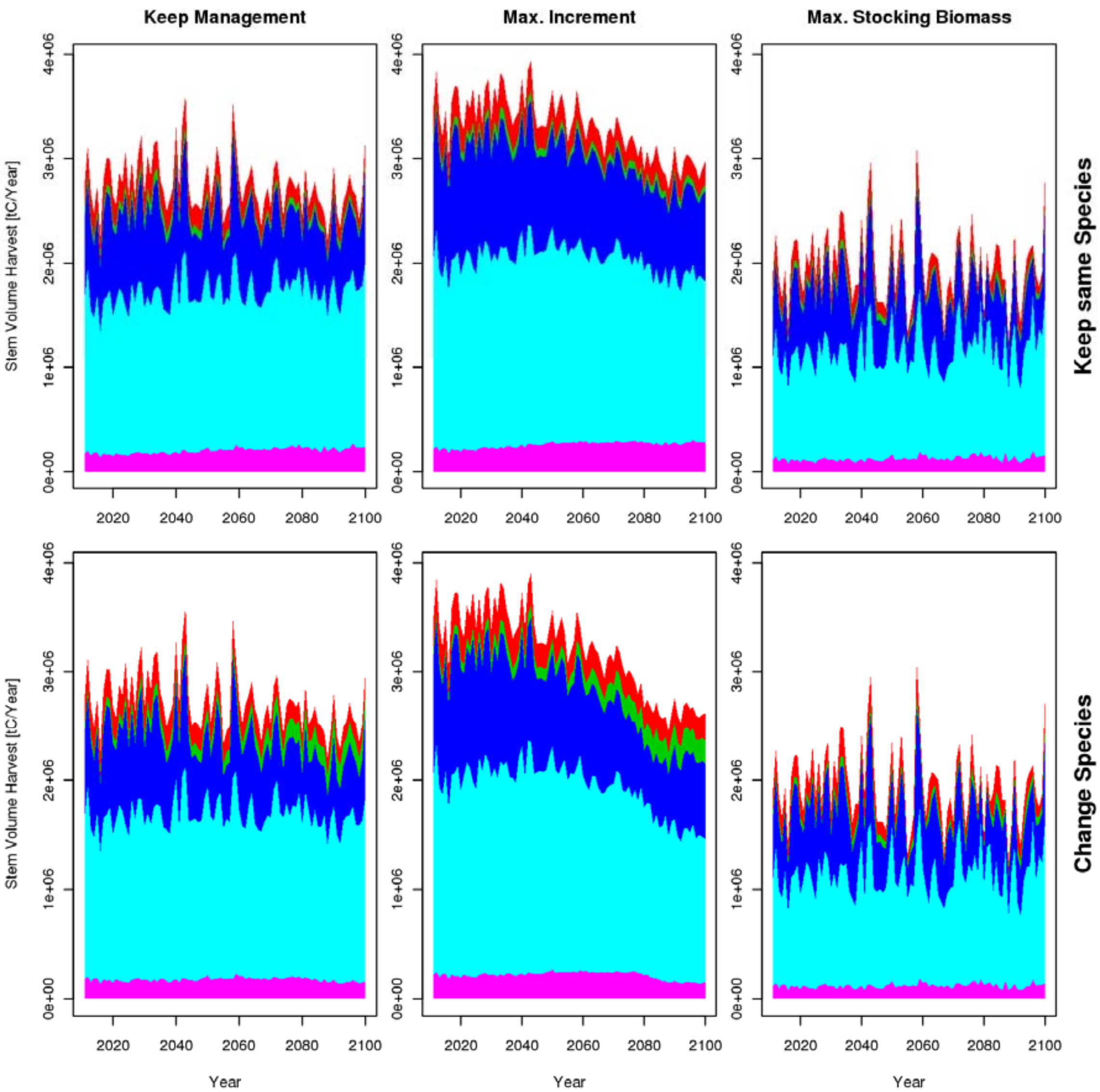


Figure 29: Development of the total removed stem volume during harvests with ETH-METO-HC Standard climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

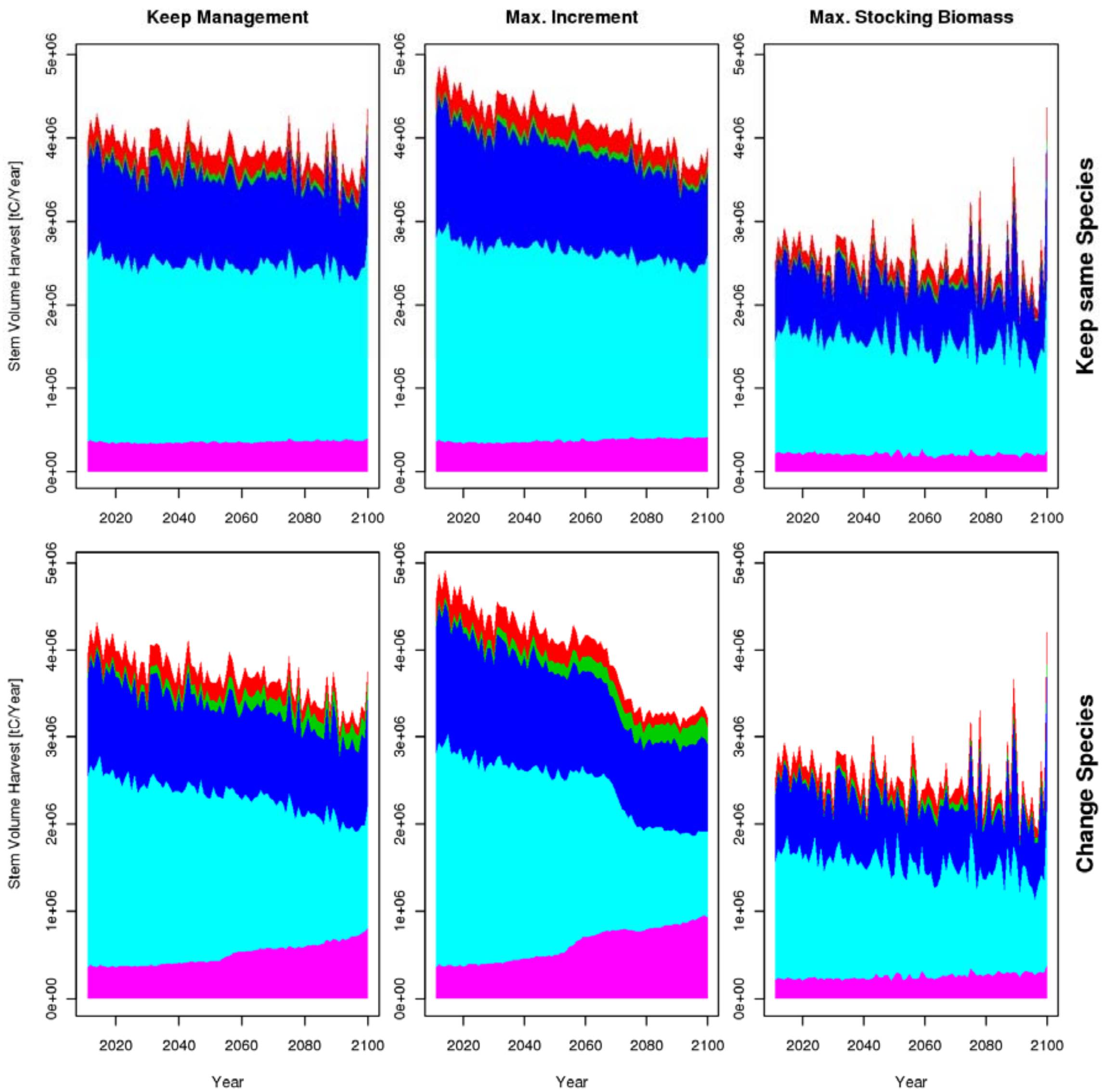


Figure 30: Development of the total removed stem volume during harvests with SMHI-MPIMET Standard climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species changes. The forest area is kept constant in all options. The plant functional types displayed are: temperate needle leaved evergreen tree (red), temperate broadleaved evergreen tree (green), temperate broadleaved summer green tree (blue), boreal needle leaved evergreen tree (aqua), boreal broadleaved summer green tree (fuchsia).

Figure 31 shows the share of the assortments of sawn wood and low quality wood and harvest losses for the DMI-CNRM climate scenario and three management scenarios. The other climate scenarios show very similar patterns and are not shown. The difference between the six shown management options are not very large. A small trend of decreasing the sawn wood and increasing the harvesting losses can be observed in the scenario which is maximizing increments. The opposite is the case when maximizing the stocking biomass. This picture is clear as maximizing increments will have smaller tree dimensions compared to maximizing increments.

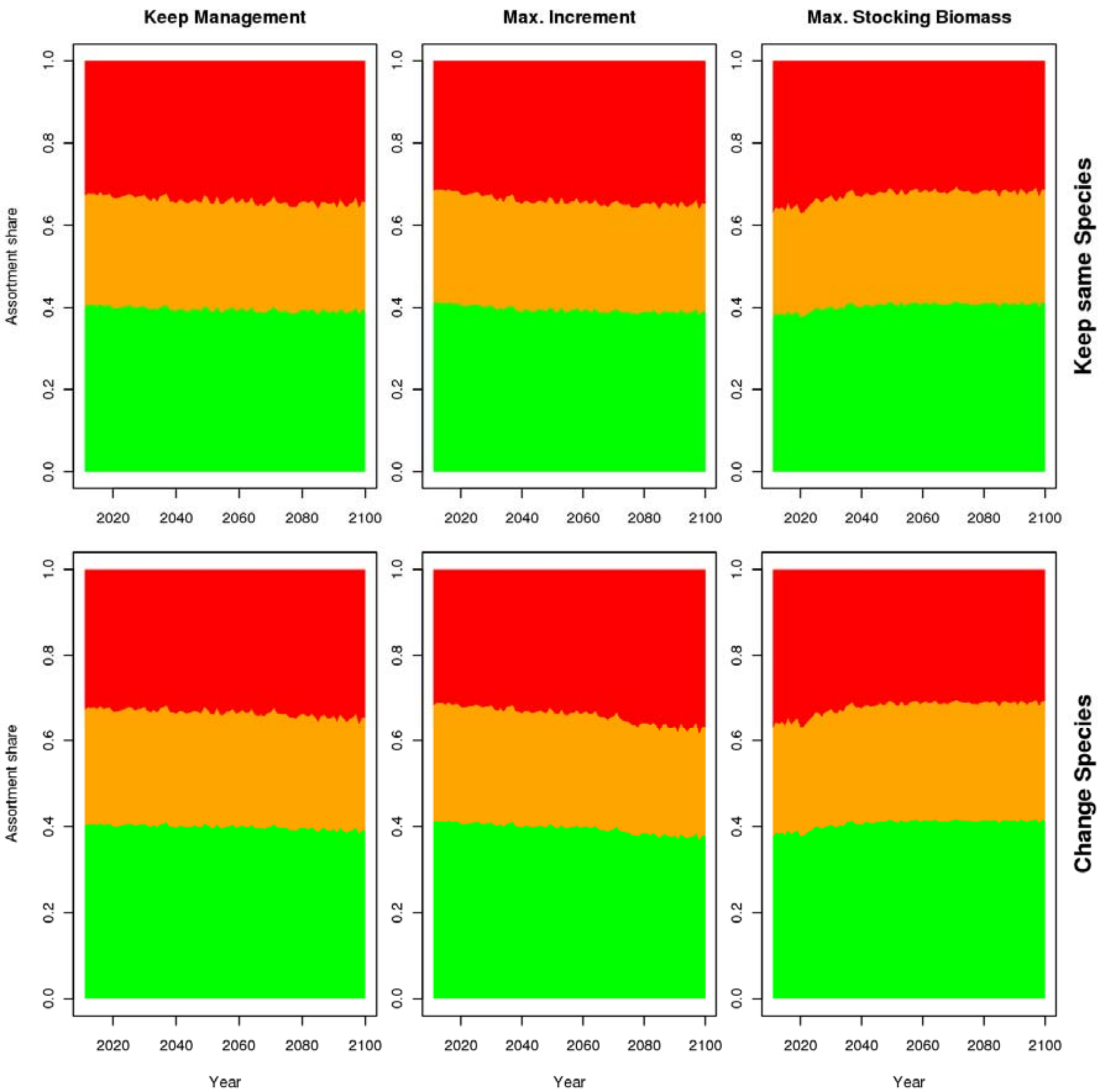


Figure 31: Assortments and harvest losses in DMI-CNRM climate. Left: Management keeps the same rotation time. Middle: Rotation time change towards maximizing wood increments. Right: Rotation time change towards maximizing biomass stock. Top: no species change. Bottom: gradual species change. Red gives the share of harvest losses, orange the share of low quality wood and green the share of wood which could be used as sawn wood.

3.2.5 Implication for forest management

Historically in Europe there was a preference for needle leaved trees that can be explained by higher yields (in terms of cubic meters), cheaper production costs, higher utility for construction wood, and higher wood quality of needle leaved tree species. However, under climate change scenarios many of these forests would have to be restructured to ensure stability and sustained long-term yields as presented in the results above.

All observed differences between the two options of management concerning species choice in European forests only apply for the scenario of an immediate change to the optimal species. The assumption that all trees that should (from a yield perspective) be exchanged in the next 100 years are exchanged immediately is theoretical. Neither can existing trees be replaced immediately, nor exists a perfect foresight that would allow a change to the optimal species in 100 years from now for a particular site. In European forestry rotation times of up to 100 years and more are typical. Such long rotation times prevent a fast change of the species composition in forests that can only occur at the end of a rotation. A realistic species change scenario would show delayed effects as species are exchanged where necessary whenever a rotation time ends in the forest. However, stand replacing disturbances might lead to opportunities for a faster change – associated with considerable costs in the short run, though.

Moreover, there is uncertainty about the optimal future species composition, too. Suboptimal species selection decisions are possible. To keep the possibility to change species not only after one rotation time there is a need to plant mixed forests which allow for flexibility during the rotation (e.g. by selected cuttings of the inferior species) but will probably cause higher costs for managing them.

4 Conclusions

This report has presented an assessment of the damages from climate change on ecosystems in physical impacts, for the scenarios from WP1. In particular, WP2F has used the Lund-Potsdam-Jena Dynamic Global Vegetation Model for managed Land LPJmL simulating the dynamics of natural and managed vegetation grouped into plant functional types for this task. To assess the impacts of climate change on forestry a linkage between the Global Forest Model (G4M) and LPJmL has been established for Europe as described in the report. This enables to model forestry and alternative land use and to quantify climate change impacts and impacts of responses of forest management of forest management.

The results obtained for this report are largely in line with the existing literature. Detailed uncertainty analysis has furthermore shown that, until 2040, accumulated carbon is higher for the E1 scenario if strong CO_2 fertilization effects are assumed. Afterwards the carbon content is lower for the woodland biomes. This result is due to the E1 scenario being characterised by an initially stronger warming than the A1B scenario. Later, carbon fertilization effects become more dominant and lead to higher vegetation carbon accumulation for the A1B scenario. Concerning the uncertainty between climate models, the standard deviation of simulated vegetation carbon for different climate models for A1B has been found to be rather low in comparison to mean vegetation carbon, but also to be growing over time.

Results for the impact analysis for the forestry sector in Europe and a selection of climate change scenarios are presented. These show a strong climate feedback on forest growth and biomass accumulation that can be mitigated through species change. However, species change needs time to become effective. Moreover, such adaptation strategies might conflict with mitigation measures in the forestry sector such as biomass maximization.

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