FROM SCIENCE TO POLICY 6

Climate-Smart Forestry: mitigation impacts in three European regions

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EXECUTIVE SUMMARY

Forests and the forest sector play a significant role in climate change mitigation through the capture of CO_2 in forests and wood products, as well as through material and energy substitution. An earlier EFI study (Nabuurs et al. 2015) found that forests and the forest sector's role could be significantly strengthened through Climate-Smart Forestry (CSF). This is a targeted approach or strategy to increase the climate benefits from forests and the forest sector, in a way that creates synergies with other needs related to forests. The approach builds on three pillars:

- reducing and/or removing greenhouse gas emissions to mitigate climate change
- adapting forest management to build resilient forests
- active forest management aiming to sustainably increase productivity and provide all benefits that forests can provide.

However, CSF measures can be regionally very different due to significantly varying regional circumstances across Europe. This follow-up study to Nabuurs et al. (2015) demonstrates how a variety of concrete CSF measures would impact CO_2 removals through forestry activities in three different regions in Europe.

Simulation models were applied to conduct scenario analysis for Spain, the Czech Republic and the Republic of Ireland. Each region has different characteristics in their forests and forest sectors:

- Spain, in this study represented by the Mediterranean region of Catalonia, has very dry circumstances, a modest management intensity of forests and is confronted with wildfires.
- Forests in the Czech Republic have a high biomass stocking, which may be difficult to maintain over a longer period due to potential disturbance risks, such as droughts, storms, pests and pathogens.
- Forests in the Republic of Ireland are generally young, fast-growing forests with up to now a low harvesting rate, and a large share of forests are growing on drained peatlands.

Scenario projections for parts of Spain (1.6 million ha), the Czech Republic (2.7 million ha) and Republic of Ireland (0.8 million ha) provided insights in the carbon balance of the forest ecosystems, and harvested wood products material and energy substitution effects.

Results

- For these three rather small case studies an average overall **net additional mitigation effect of 7.1 Mt CO_2/yr after 50 years is achieved by implementing CSF measures. This can be considered to be a large effect.**
- Although circumstances are very different in these three case studies, they all show that **more active management leads to losses in the living biomass carbon sink in the short-run** (coming decades). However, **the time period considered can have a large impact on the results, and considering a typical full rotation cycle of 100–120 years could produce different results**.
- **Material substitution impact is a key factor determining whether CSF has mitigation benefits within the 50-year simulation period**. If we would have run a 100-year simulation period, the forest management impacts could possibly be at least as important.
- Results from the case studies highlight that **sustainably increasing harvest levels could have overall positive climate benefits, mainly through material substitution**. The exact substitution effect will depend on the type of wood product, the type of non-wood material that is replaced, and what is the use of wood at the end of its life-cycle.
- Only one set of CSF measures was identified and tested in each case study. We did not consider all possible mitigation measures nor optimised them, but tried to highlight that mitigation measures need to consider local- or country-specific conditions.

The extent to which each measure has been included in the modelling stayed rather close to ongoing policies and practices. Yet, **it is likely that more extensive and stronger implementation of all measures could lead to higher mitigation effects**.

- We included measures that would most likely reduce the sink in the forest ecosystem at least temporarily, and analysed their impacts by considering all carbon pools and substitution effects. These measures could include increasing harvest levels to be able to increase the long-run resilience of forests. **Drastic, but needed conversions, that could temporarily cause forest ecosystems to act as a source may also be part of a long-term adaptation and mitigation strategy.**

Implications

- **Properly accounting for substitution effects – and attributing them to the forestry sector –** is crucial to define optimal (forest management) strategies to mitigate climate change.
- The case studies reveal that **very different regional measures can be taken to mitigate climate change**. A **'one size fits all' solution across Europe will not work.**
- **This study focused mainly on the mitigation impacts of CSF, but there are likely to be many other benefits if planned and implemented carefully**. The CSF measures in this study intended to result in forest ecosystems that are better adapted to future conditions through a reduced vulnerability to storms (Czech and Irish case studies) and wildfires (Spanish case study). Furthermore, a conversion to a more natural tree species composition (Czech case study) may have positive benefits for biodiversity, a reduction in wildfires may result in a reduction of economic losses (Spanish case study), and increased wood removals may provide additional income to forest owners (Irish and Spanish case study).
- For a better understanding of the potential impacts of Climate Smart Forestry to climate mitigation, we would recommend the following analyses to be carried out: first, to **extend the current 50-year simulation periods to at least 100 years**. This would be important to be able to take into account the dynamic nature of forestry and fully capture forest management impacts in the long-run. Second, it would be useful to extend the cases studies to other regions with different characteristics in forests and the forest sector, such as the Nordic countries, Balkans and Central Europe.

1. Introduction

Forests and the forest sector play a significant role in climate change mitigation. Within the European Union (EU), the current annual mitigation effect amounts to 569 Mt CO_2/yr through capture of CO_2 in forests and wood products, as well as through material and energy substitution. **These net removals represent 13% of the total EU greenhouse gas emissions**. A review study (Nabuurs et al. 2015) found that this role could be significantly strengthened through Climate-Smart Forestry (CSF). Based on a broad set of measures that consider the forest sector as a significant part of the solution to climate change, the study estimated that the 28 EU Member States could achieve an additional combined mitigation impact of 448 Mt CO_2/yr by 2050.

The CSF concept considers the whole forest and wood products chain, including material and energy substitution effects that are – according to current accounting practices – not attributed to forestry. CSF is a similar concept to the Climate-Smart Agriculture concept developed by FAO and aims to find the optimal combination of measures to maximise climate change mitigation, while considering regional circumstances. CSF is more than just storing carbon in forest ecosystems, as it includes adaptation to climate change and strives to achieve possible synergies with other forest functions (e.g. ecosystem services and biodiversity).

CSF builds on three pillars:

1) reducing and/or removing greenhouse gas emissions to **mitigate climate change**
2) **adapting forest management** to enhance the resilience of forests
3) active forest management aiming to **increase productivity** and income and to sustainably provide all benefits that forests can provide.

CSF should not be understood as a concept which seeks to replace the *sustainable forest management* concept, but rather as a more targeted approach or strategy to increase the climate benefits from forests and the forest sector in a way that **creates synergies** with other needs related to forests.

The mitigation benefits of CSF have so far only been estimated at the EU level, providing indicative examples of the types of measures that could help to reach the mitigation benefits in the Member States. Examples of CSF measures include (Nabuurs et al. 2013; Nabuurs et al. 2015):

- regenerating full grown coppice;
- enhancing regeneration of old spruce stands that are susceptible to drought and bark beetle, with more climate-adapted species;
- using wood-processing residues more optimally;
- stimulating cooperation between fragmented forest owners who are currently not investing in forest management;
- avoiding deforestation;
- reducing disturbance risks in storm or fire-prone forest areas;
- afforesting abandoned farmland;
- increasing the use of wood in construction and other long-living wood products.

The aim of the current study is to make CSF and some of the measures more concrete by analysing case studies for Spain, the Czech Republic and the Republic of Ireland, and quantifying (with a variety of measures) mitigation effects for a 50-year period, covering the carbon balance of the forest ecosystem, wood products and material and energy substitution effects.

In the calculations, we do not follow current accounting rules. Instead, we estimate how the atmosphere sees the full effect of the forests and forest sector including substitution effects of energy and material products.

To explore and quantify the climate change mitigation impacts of CSF, a scenario approach has been adopted in this study. The scenarios relate to a Baseline scenario (BS) and a Climate-Smart Forestry scenario (CSFS). The CSFS intends to demonstrate what could happen if certain measures are implemented with regard to increasing the mitigation potential while also paying attention to adaptation and increasing productivity where possible.

The scenarios should not be considered as a prediction or reference to assess the impacts of currently (intended) national or international policies. Instead, **the CSF scenario illustrates what would be the optimal set of measures to address the three aims under CSF: mitigate, adapt and increase productivity**. The CSF scenario is considered in a setting that can be regarded as realistic in terms of practical implementation, and in some cases is rather close to ongoing policies. However, it assumes that countries are willing to make an additional effort to gain higher mitigation effects than is the case currently.

The case studies from Spain, the Czech Republic and the Republic of Ireland demonstrate how CSF could contribute to climate change mitigation in these regions. They take into account various conditions in biophysical circumstances, the state of forest resources and the forest sector in these countries.

2. Carbon cycles in forests and the forest sector

Forests impact net greenhouse gas (GHG) balances in two ways. First, they retrieve carbon dioxide (CO_2) from the atmosphere and sequester carbon in biomass, thus **acting as a gross carbon sink**. Subsequently part of this carbon is transferred into soils through litterfall, mortality and harvest residues, or through harvesting into a variety of products. Depending on the balance between CO_2 going into the system and CO_2 flowing out, a long-term net balance occurs. Forest management tools such as improved silviculture, afforestation, reforestation and reduced deforestation will often increase net carbon sequestration in forests. In addition, carbon sequestration in long-lived wood products, wood structural frames for instance, delays carbon release into the atmosphere (sequestration lever in Fig. 1).

Second, fuelwood and bioenergy (e.g. pyrolysis oil and second generation biodiesel) can **substitute fossil fuels**, and timber products can **substitute other more energy- and emissions-intensive materials**. Emissions linked to wood product consumption are generally lower than those created by the consumption of non-wood substitute products. Wood product consumption (substituting for products coming from other materials for building, insulation, packing, furniture, etc.) consequently may enable a reduction in fossil energy emissions (substitution lever in Fig. 1). Moreover, wood products can **store carbon** for decades or even centuries.

Forests and the use of forest products can therefore contribute to climate change mitigation by increasing sequestration and through substitution effects. These mitigation opportunities can also be enhanced by policy measures. Although both effects represent potential contributions to climate change mitigation, they have different implications in terms of forest management and harvesting. While the sequestration effect is maximised in the short term by a lower intensity of forest harvesting, enhanced use of the substitution effect implies an intensification of forest harvesting. In a long-run dynamic system (50–100 years) the mitigation impacts of harvesting and the forest carbon sink can enhance each other. In larger areas of forests, both mitigation options do not necessarily conflict with each other, as it is possible to balance carbon stocks in the forest biomass (and even increase productivity through management) and (over larger areas) simultaneously use the raw material for wood products and fossil fuel- and material substitution. At the regional and national level, it is possible and meaningful to combine both mitigation options. In some cases synergies can also be found where residue extraction in dry areas can reduce the fire risk.

The evaluation of forest-based climate change mitigation effects therefore requires careful consideration of **spatial and temporal scale, system boundaries**, as well as **regional settings**. When emissions are compared at the forest stand level, it is always beneficial to protect the stand and to maximise the carbon sink in the growing forest biomass, especially in the short-run (typically up to 50–70 years). Any harvesting activity leads to partial emissions of the CO_2 that has been accumulated in the forest biomass and only a fraction of the harvested carbon can be used to substitute fossil fuels or alternative materials. Increased harvest removals to generate bioenergy may create a carbon parity that can take decades or even centuries to be compensated by new carbon sequestration in forest regeneration. When comparing alternative resource management options at a regional level, any immediate loss of carbon from a single harvest is only minimally noticeable (although it exists) in the regional carbon budget. This is because at a regional level you tend to find a variety of forest age structures, and the carbon removal of the harvested forest stands is compensated by the carbon sequestration of the remaining growing stands. Sustainable forest management can stimulate growth even in this manner of regeneration. While carbon recovery times which are noticeable at stand level are dampened at the regional level, it is still possible that certain management interventions which result in long-term increases in carbon sequestration are associated with short-term net carbon release – for example in the case of salvage cutting of stands damaged by disturbances.

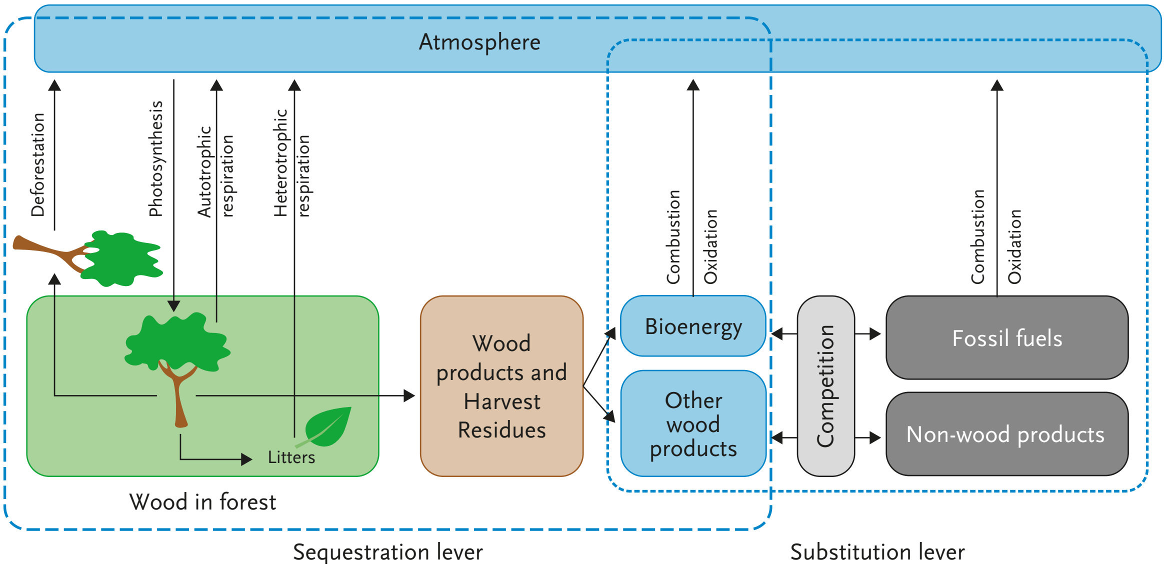


Figure 1. Overview of forest-related carbon stocks in reservoirs and flows between the atmosphere, biosphere and fossil reservoir (Nabuurs et al. 2015).

3. Case study: Spain

3.1 Trends and issues

Forest cover in Spain has expanded greatly during the last 150 years (Vadell et al. 2016); for example during the period 1990–2010 the forested area increased by 10%. Currently, what is classified as forest surface area is 27.7 million ha, which is 55% of the total surface area of Spain (Montero & Serrada 2013; MAPAMA 2015). However, only 33% of the total surface of the country is actually covered with forest (i.e., with a percentage of canopy cover ≥20%), while the forest area available for wood supply amounts to 14.7 million ha. The remaining 22% is treeless or just covered by a few trees.

Forest ecosystems in Spain can be classified according to the Atlantic and Mediterranean climatic zones. Forests in the Atlantic region are characterized by their high wood productivity, which often relates to the practice of short rotation forestry (e.g. *Eucalyptus sp*, *Pinus radiata*, *Pinus pinaster*, *Populus sp*). Forests in the Mediterranean region are characterized by their structural and species complexity and relatively low productivity.

Due to its location and climatic conditions Spain has a large diversity in forest ecosystems, and around 20 dominant tree species can be identified. Broadleaves dominate in 46% of the forest surface area, conifers in 35% and mixed forests occupy 19%.

The growing stock (m^3/ha) increased by 20% during the period 1996–2009 mainly due to low harvesting intensity. In Spain, 30% of the annual growth is harvested, while the average in the EU27 is 72% (Montero & Serrada 2013). The majority of timber production is harvested in the Atlantic region, which accounts for around 70% of the total timber production in Spain. Approximately two-thirds of the forests are privately owned. There is a high degree of fragmentation, with many properties smaller than 5 ha (Rojo-Alcoreca 2015). Some successful examples of reducing fragmentation through forest associations exist nowadays, but this could be further promoted in future. Spanish forests provide multiple goods and services, such as timber, grazing, firewood and biomass, carbon sequestration, cork, resins, mushrooms, aromatic and medicinal plants. Biodiversity and protected areas are important as well (Montero & Serrada 2013).

Abiotic (forest fires, erosion, drought, storms, etc.) and biotic (insects, diseases) natural hazards have also important impacts. Of these, forest fires have usually the strongest impact on the ecosystems in the country. In the period 2001–2014, the average yearly forest surface area affected by fires was 112,050 ha. The combination of extreme climatic conditions (drought, wind) with the large proportion of unmanaged forests presents a big challenge for the future. Erosion is another relevant risk. Most forests in the steepest alpine and subalpine slopes are public protection forests.

The case study in Spain focused on the region of Catalonia, which is located in the north-east of Spain and has a typical Mediterranean climate. It has a pronounced climatic bi-seasonality with dry and hot summers and moist and cool autumns and winters. The altitudinal factor also plays an important role in environmental conditions.

Large reforestation projects implemented in Spain during the 20th century and agricultural land abandonment has resulted in many forests in Catalonia nowadays being young and dense. Forest ownership is mainly private (77%) and fragmented (more than 200,000 owners), with an average size of 30 ha, although many of the properties are much smaller.

Additionally, most of the managed forests do not follow rigorous silvicultural guidelines. The lack of management in most forests, or the negligent management when applied, have led to a reduction in forest productivity and hazardous conditions regarding fire occurrence. Forest fires are a continuous threat to forests. A typical burnt area amounts to 5,000 – 8,000 ha/y, but extreme fire seasons such as the ones of 1994 and 1998 can result in over 60,000 ha burnt. Forest harvesting levels have increased recently; the amount of timber harvested in 2015 represents approximately 28% of the annual increment. Over 50% of the harvested wood is destined for energetic uses.

Climate change in the Mediterranean, and in NE Spain more specifically, is expected to cause a rise in temperatures and an increase in the seasonality (even daily accumulation) of rainfall, with a subsequent increase in the recurrence of floods and drought periods. If no precautionary measures are taken, an increase in the risk of drought-related tree decay and wildfires can be expected. These would cause a decrease in productivity and increase GHG emissions. Forest management can mitigate these effects by reducing competition on overstocked stands, avoiding at the same time the risk that ground fires can reach the overstory canopy.

3.2 Forestry contribution to climate change mitigation

Forests in Spain absorbed 35000 Gg CO_2 eq. (= 35 million tonnes) in 2015 (Spain 2017), and harvested wood products captured 1.5 million tons of CO_2 eq. Together, these compensated more than 11% of the annual CO_2 emissions in Spain.

Forests in Catalonia contain a stock of 180 million tons of CO_2 in living biomass stock (70% in the above ground parts and 30% below ground). The historical trend shows that over the past 25 years the forest has kept on accumulating more biomass (Fig. 3). However, if the organic soil, scrublands and grasslands are included, the stock reaches nearly 700 million tons of CO_2. Forests in the region capture approximately 4.65 million tons of CO_2 per year in living biomass and compensate nearly 10 % of the annual greenhouse emissions of the region (Ministry of Agriculture 2016).

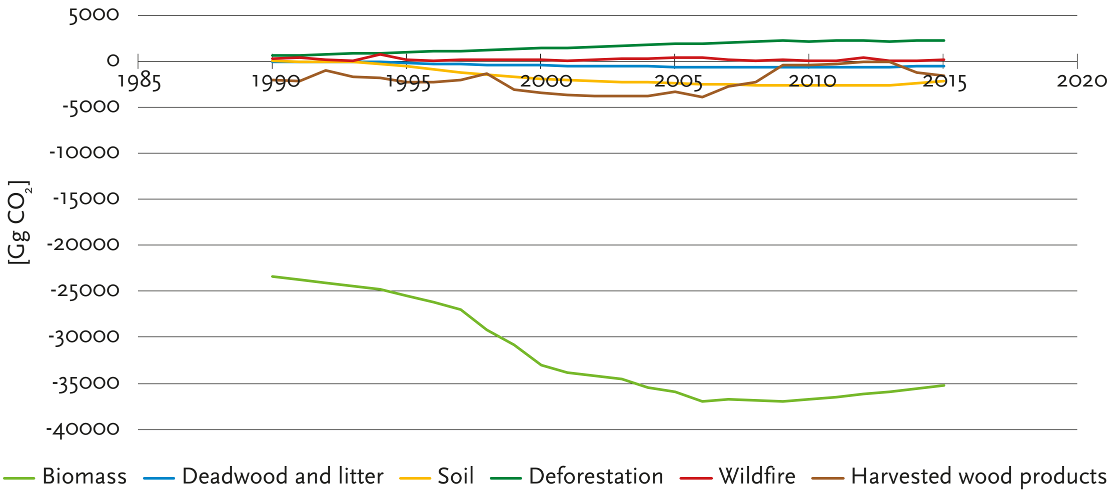


Figure 2. Historical CO_2 emissions and removals from forestry activities in Spain (Spain 2017).

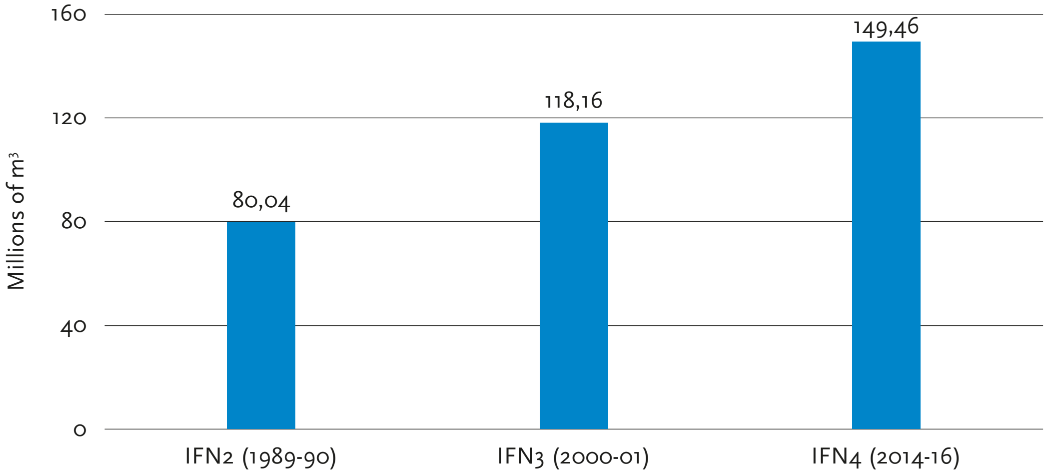


Figure 3. Evolution of the growing stock in Spanish region of Catalonia *(Data: Spanish National Forest Inventory (IFN). *The estimations for IFN2 and IFN3 are from official sources, the IFN4 are estimates computed during the present study).*

3.3 Scenarios

The two scenarios were applied to all forested land in Catalonia, represented by the 4,589 plots measured during the 2014–2016 period, for the 4th Spanish National Forest Inventory (NFI) of Catalonia (not yet published data from MAPAMA; Spanish Ministry of Agriculture, Food and Environment). The plots of the 4th NFI are assumed to represent the tree species composition and structural variability to be found on the 1,6 million ha of forested land in Catalonia.

Baseline scenario

The basic rationale of the Baseline scenario (BS) is that the current management practices and harvesting levels will be maintained over the entire study period 2015 – 2065. Specifically, the following measures are assumed:

- The current forest area will be kept, and no afforestation is considered.
- Harvest levels are assumed to remain similar to historical data at approx. 0.9 million m^3/y throughout the period 2015–2065.
- Flows and uses of harvested wood are assumed to remain similar to the period 2011–2015.

CSF scenario

The overall rationale behind the CSF scenario (CSFS) is that a larger share of the forest is actively managed through partial cuttings to enhance tree growth, and mitigate fire and drought-related tree mortality. The management instructions for all forests will be relaxed, choosing higher basal areas/stocking to trigger cuttings, but always leaving a share of large retention trees untouched, in order to maintain long-term carbon stock in the forest while favouring biodiversity levels on the partially harvested stands (Trasobares & Pukkala 2004). Additionally, an increase in the use of timber-related products will substitute (reduce) emissions originated by the use of other products (fossil fuels, construction materials, etc.). The main assumptions made in the CSFS were:

- An increase in the managed forest area by approximately 25% compared to the present managed area.
- Modified basal area limits that determine when harvest can commence.
- The increase in actively managed forest area allows an increase in harvest levels by approximately 1.4 million m^3/yr, which is almost 50% more compared to the BS, over the period 2015–2065.
- A reallocation of timber assortments to longer lifespan products (construction timber and MDF boards), and a decrease in the proportion of timber used for energy.

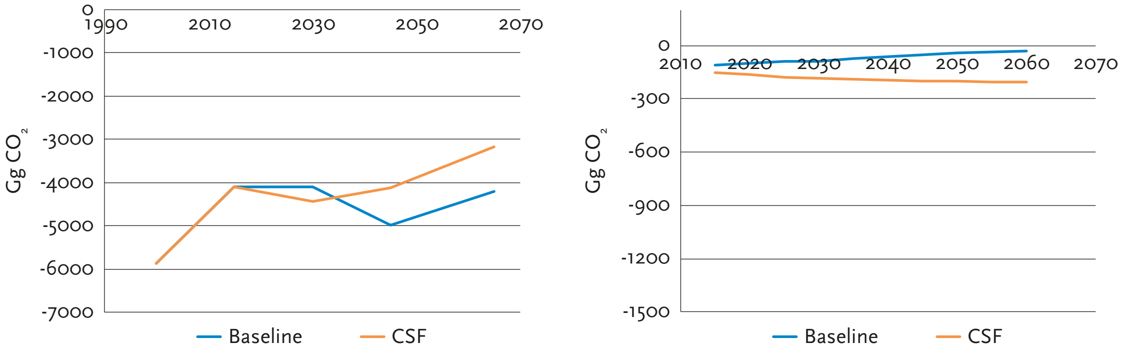
A detailed description of the methods is given in the Annex.

3.4 Results

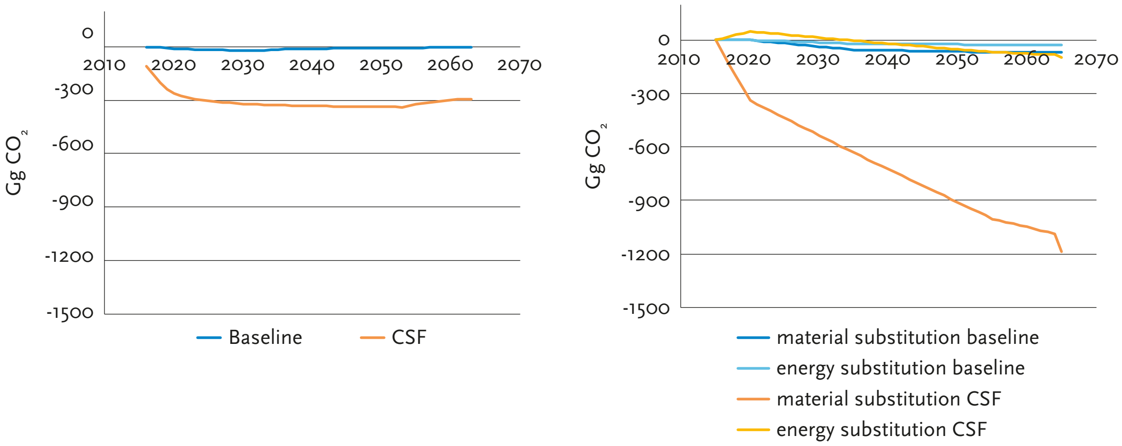
In the simulation, the emission balance for living biomass stock, roots of harvested trees in soil, harvested wood products (HWP) and material and energy substitution effects were estimated for BS and CSFS (Fig. 4). Those estimations were dependent on the impact of management strategies on forest growth, the amount of timber removed from the forest, and forest fires (Fig. 5).

In the CSF scenario the increase in area actively managed by choosing higher basal areas to trigger cuttings while leaving a share of large retention trees (see Annex), improves forest growth during 2050–2065 (Fig. 4a). The impact of increased managed area on the volume of living biomass (above and below ground) was a reduced volume after 2035 (visible in Fig. 4a in reduced sink line). This pattern came from an increase in forest growth and a reduction of fire-induced mortality, but still was unable to fully compensate the additional removal of trees (nearly doubled during the last 20-year simulation period) (Fig. 4b). In the CSFS the increase in individual tree growth and vigour (through reduced competition) on a larger share of the forest area should have a positive impact on the resistance and resilience of forests to future disturbances, either biotic or abiotic. For example, once the effect of fire was accounted for in both scenarios, we estimated a reduction of 2.5% in the area affected by fire and a reduction of 4.8% in the above ground biomass consumed by those fires when applying the CSF scenario. The changes in fire emissions are included in the biomass graph (Fig. 4).

Another effect of increasing the cutting levels in the CSFS is an increase in the deposition of organic matter in the soil. A larger number of harvested trees over the simulation period translates into a significant increase in the carbon soil pool of highly stable carbon in roots and stumps (Fig. 4b) (Melin 2014).

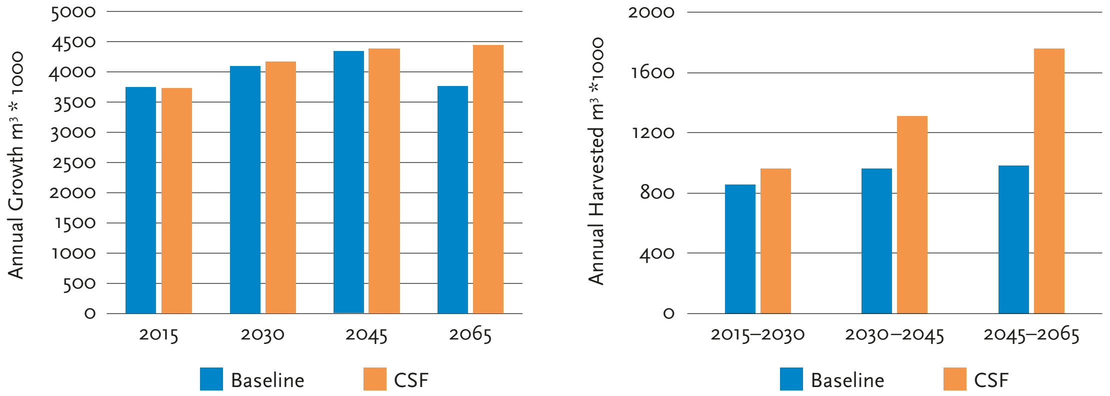

(a) Living biomass

(b) Soil (roots and slash)


(c) Harvested wood products (HWP)

(d) Substitution

Figure 4. Projected emissions (positive values) and removals (negative values) of CO_2 for the baseline and the CSF scenarios. *Results are shown for (a) living biomass, (b) roots and slash of harvested trees in soil, (c) harvested wood products, and (d) substitution effect.*


(a) Net annual increment

(b) Harvest levels

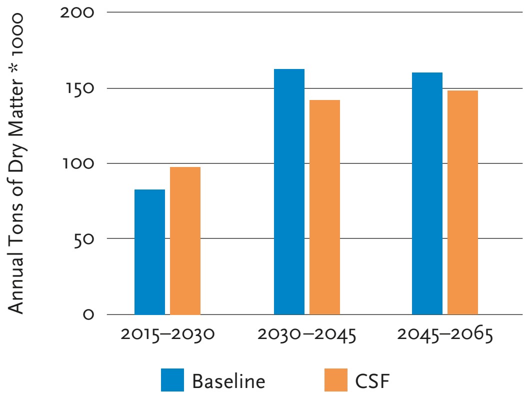

(c) Fire consumption

Figure 5. Evolution of (a) the annual forest growth (in thousands of m^3), (b) annual harvest levels (in thousands of m^3) and (c) annual combustion of above ground biomass (thousands of Dry Matter Tons).

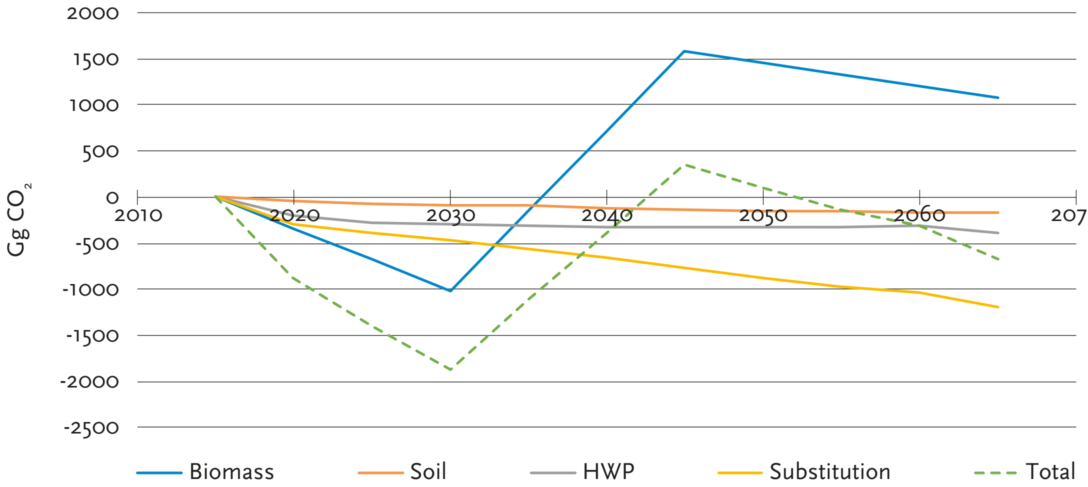


Figure 6. Total CO_2 mitigation benefits of the Climate-Smart Forestry scenario for Spanish region of Catalonia, as a difference compared to the Baseline scenario. *Positive values indicate additional emissions of CO_2 and negative values denote additional removals of CO_2.*

In the CSFS, the impact of harvested wood products substitution (replacing fossil-based materials) on CO_2 mitigation was clear. Harvest levels in the BS were kept similar to historical data, resulting in very limited net emissions or removals of CO_2 from the HWP pool. An increase in the harvesting levels in the CSFS, together with a reallocation of the timber to more long-lived products, resulted in a sharp increase of the products sink, and a very large material substitution effect (Fig. 4d).

In general, the emissions balance over the whole simulation period indicates on average net removals of 574 Gg CO_2. While at the start of the simulation period living biomass in the CSFS has a tendency to remove more CO_2, removals of CO_2 by living biomass are generally reduced due to increased harvest levels later in time. However, this negative impact on the CO_2 storage in living biomass through increased removals is compensated by the associated carbon sinks due to increased harvest (soil, reduced fire, increased HWP, substitution effects) (Fig. 6).

3.5 Key findings

In summary, the overall impact of the CSFS on CO_2 mitigation potential was an average mitigation benefit of 574 Gg CO_2/y over 50 years of simulation (or 0.57 million tonnes). This impact was to a large extent through material substitution and smaller extent due to the increased organic matter in the soil pool and fire mitigation. The impacts of improved growth on the living biomass stock take longer time, as the clear positive effect starts to be clear only by the end of the simulation period. Yet, this is significant, taking into account the challenging drought conditions in the region and what its impacts could be in the long-run. The comparison of the scenarios shows that by increasing the share of area actively managed in the CSFS (relative to the BS), the living biomass CO_2 sink decreases by 2065, but a clear improvement in growth rate takes place. This additional growth is to some degree also harvested, resulting in a smaller sink in living biomass towards the end of the simulation period.

The overall result is strongly related to the share of young forests in the region at the beginning of the simulation period. When larger areas of forests are not managed (BS), it takes time to reach a mature stage and more CO_2 is accumulated. However, once forests are fully stocked, the growth of trees is clearly affected by competition (limitation in light, water/nutrients availability) and mortality increases. If longer than a 50-year period were to be simulated, the negative impact of mortality would be far more relevant on unmanaged forests. Furthermore, under CSFS, more resilient forest conditions against the drought, biotic effects or fire risk are established, and other functions such as water balance, biodiversity conservation and amenity/recreation values may be improved when sustainable forest management is well implemented (Ameztegui et al. 2017).

In the CSFS, the positive effect of management intensity on the carbon balance is more evident through the use of harvested wood products. By increasing the share of longer-living wood products (and with added value in the market) and by substituting for fossil-based products, the mitigation impact is clearly increased. Emissions caused by fire are reduced by forest management increase in managed area and more resistant stand structures in CSFS. Still, a bigger impact can be expected by reducing fire spread and avoiding the possibility of catastrophic convection fires, which are driven by the accumulation of large and continuous amounts of biomass fuel on the ground. If the impact of forest and fuel management would be considered, and the allocation of the management actions optimized with the objective to minimize fire risk, fire occurrence is expected to be further reduced (González-Olabarria & Pukkala 2011).

In summary, this case study shows that the overall impact of the CSFS on CO_2 mitigation potential was an average mitigation benefit of 574 Gg CO_2/y over 50 years of simulation (or 0.57 million tonnes). This impact was to a large extent through material substitution and to a smaller extent due to the increased organic matter in the soil pool and fire mitigation. The impacts of improved growth on the living biomass stock take a longer time.

4. Case study: Czech Republic

4.1 Trends and issues

In the Czech Republic, forest ownership has changed dramatically since 1990 when nearly 95% of forest area was publicly owned. As of 2015, 59% of the forest area is in public ownership, 23% is privately owned and 17% is municipal forests. Forest land (cadastral forest land) covered an area of 2.7 million ha in 2015, representing 34% of the area of the country. There has been no strong trend in changes in forest land area, although it is slightly increasing. Since 1990, forest land has increased by nearly 40,000 ha, i.e, by a rate of about 1,600 ha/yr. About 98% of forest area is available for wood supply, which includes the categories of managed forests and special purpose forest. Excluded is the category of protective forest and the protected areas such as National Parks. The management of state forests is governed by Czech Forests, State Enterprise, operating on nearly 50% of the forest area.

The dominant tree species is Norway spruce which covers 51% of the forest area, pine only 17%, and broadleaved tree species account for 27% (stand-wise inventory data for 2015). The European beech pedunculate and sessile oak are the most important broadleaves. The share of broadleaves has been increasing by 6 since 1990 and this trend is expected to continue in future.

Czech forests are considered highly productive. The total mean annual increment is nearly 18 million m^3/yr (7 m^3/ha/yr) and the mean current increment is nearly 22 million m^3/yr (8.5 m^3 /ha/yr). The growing stock is estimated at 693 million m^3 (266 m^3/ha) (stand-wise inventory data; volume units refer "under bark").

The main concern facing Czech forestry is forest health status and the stability of forest stands. The share of sanitary fellings remains high, and reached on average 40% in the period 1990 to 2015 (over 50% in 2015). As sanitary interventions must be prioritized in managed forests, these disrupt ordinary planned forest operations. Dominantly even-aged spruce forests are specifically vulnerable to drought spells and wind disturbances, which result in more intensive bark-beetle infestations.

Forests receive attention in the Czech National Adaptation Strategy (NAS; adopted in 2015), which stresses "Site-specific differentiation of forest management focused on more natural management forms, changing species composition and stand structure" to combat the challenges of climate change. Specific prioritized measures were adopted in the National Action Plan on Adaptation (NAPA; 2017), working towards two goals concerning the forest sector: support the natural adaptive capacity of forest and strengthen its functioning in changing climate; and protection and revitalization of natural water regime in forests.

4.2 Forestry contribution to climate change mitigation

The forestry sector is the most significant component of the Czech LULUCF inventory. Emission removals from forest land reached 6.6 Mt CO_2 eq. in 2015 (Fig. 7), offsetting about 5% of Czech emissions. However, the contribution of forests varies annually depending on logging quantities and the actual share of sanitary logging.

4.3 Scenarios

Baseline scenario

In the Baseline scenario (BS), existing trends are continued from 2015–2100 with no additional efforts and investments to use forestry as a measure to mitigate climate change. Rotation lengths are defined in correspondence to standard management. A stable felling level of 17.6 million m^3/yr (under bark) is assumed until 2100, of which 40% is assumed to originate from sanitary fellings. Sanitary fellings are implemented as a 60% probability of all clear felling. Felled areas are always replanted with the same species. Out of the total harvest, 35% is assumed to originate from thinnings.

CSF scenario

The primary focus of the CSF scenario (CSFS) is to convert the unstable spruce forests vulnerable to droughts and bark beetle to forests with a species composition that is better adapted to the local growing conditions and more resistant to disturbances. A secondary effect is that a higher share of the harvest can be used for products with longer time spans. For each of the 27 management types we determined the share of the spruce forest that can be

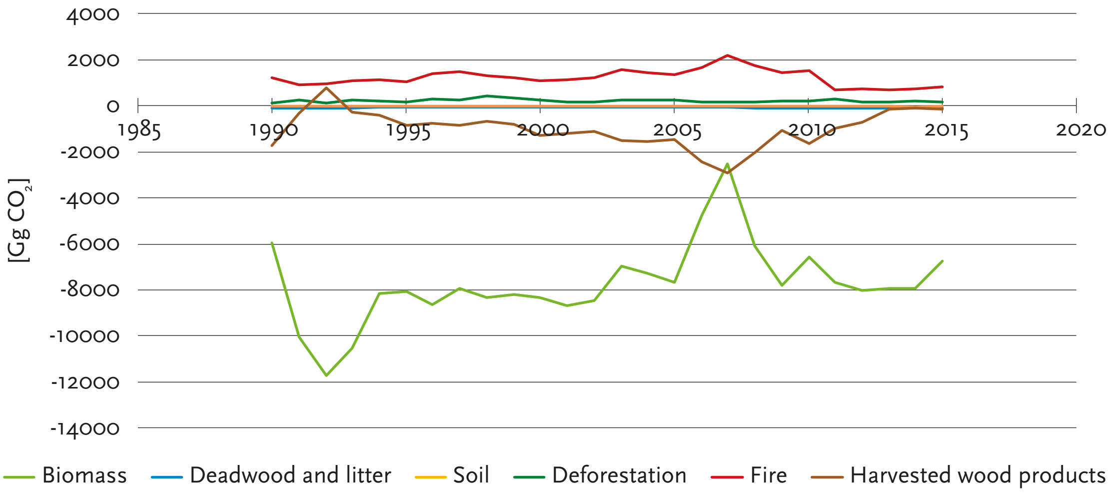


Figure 7. Historical CO_2 emissions and removals from forestry activities in the Czech Republic (Czech Republic 2017).

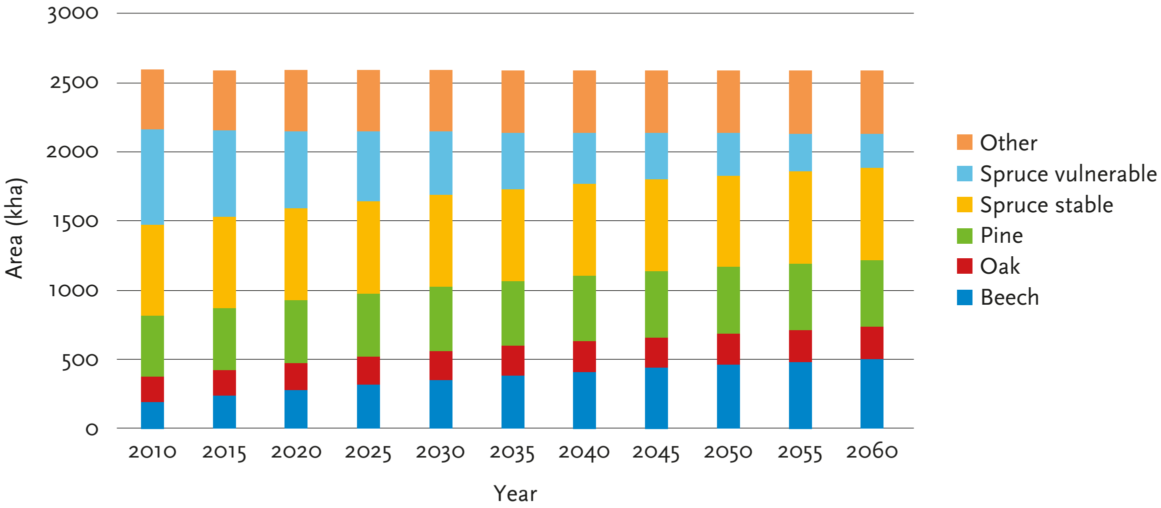


Figure 8. CSF scenario showing the tree species change over time (based on EFISCEN). *The total area of oak and beech increases from 372,000 ha in 2010 to 731,000 ha in 2060. By 2060 the area of unstable spruce has been reduced to 251,000 ha. After 2060 the conversion continues but slows down.*

considered as unstable. Rotation lengths in these unstable spruce forests are reduced by 10-20 years while simultaneously these forests are preferred when harvesting. The national level fellings volume is not changed compared to the BS. After clear-cut harvest these unstable spruce forests are replanted with more appropriate species, depending on the management type, e.g. beech and oak. Thus a fast conversion takes place (Fig. 8).

The share of sanitation fellings over time is reduced in accordance with the area that is converted to other species. The use of spruce wood for different product categories is differentiated between spruce originating from harvest in unstable forests and spruce from stable forests. Harvest from unstable forests is assumed to yield a 10% point lower share of long-term products than harvest from stable forests.

A detailed description of the methods is given in the Annex.

4.4 Results

In the BS, the share of sanitation fellings remains 40% because spruce remains to be replanted, while under the CSFS it decreases to 17% in 2060 and to 7% by 2100.

Initially, the biomass sink is lower under the CSFS (Fig. 10). The largest difference appears around 2050

Figure 9. A picture of Czech forest conversion in progress. In the background on the ridge is a salvaged spruce stand. In the right foreground are stressed spruces. On the left are a few fir trees. In the foreground, regeneration with beech (photo Emil Cienciala)

and amounts to 1700 Gg CO_2/yr. After 2080, the sink in the CSFS becomes quickly larger than in the BS due to the converted forests that are now long rotation deciduous forests in high growth age classes.

The harvested wood products (HWP, Fig. 11) sink is higher under the CSFS compared to the BS, but only about 90 Gg CO_2/yr in 2060. The difference in material substitution mitigation impact (Fig. 12) is considerable, being close to 600 Gg CO_2/yr in 2060, about 35% of the reduction in the biomass sink.

The mitigation benefits of the CSFS as compared to the BS are summarised in Fig. 13. The conversion of unstable forests (if we assume that no conversion maintains a growing stock) leads to net additional emissions in the living biomass. This switches to a net additional removal in 2080.

4.5 Key findings

Forests in the Czech Republic are generally characterised by having a high growing stock. The question is how to achieve a more stable forest without losing too much carbon in a short period of time. The CSF measures considered represent one transition path. This does not mean there might not be other or even more optimal paths.

Here in the CSFS, the rather fast conversion of unstable forests leads to a lower forest sink in the next 70–80 years. However, this sink can be considered to be much more stable than the higher sink in the BS, which could be subject to considerable risks due to disturbances causing high mortality. Given the expected future risks connected to climate change (which were not considered in the simulations), the disturbances are likely to become more severe over time, and therefore could even lead to net emissions in the long-run.

Towards the end of the century, the CSFS yields a higher sink than the BS. This indicates the sensitiveness of the results, and therefore the optimal mitigation strategies, to the time period considered in the simulations. Considering a short period

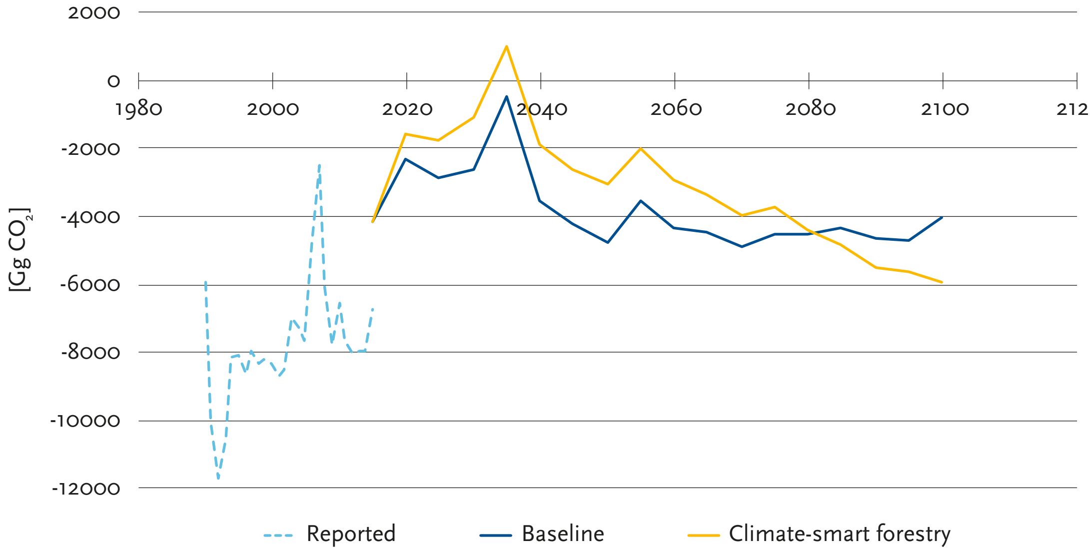


Figure 10. Reported and projected emissions (positive values) and removals (negative values) of CO_2 by living biomass in the different scenarios for the Czech Republic.

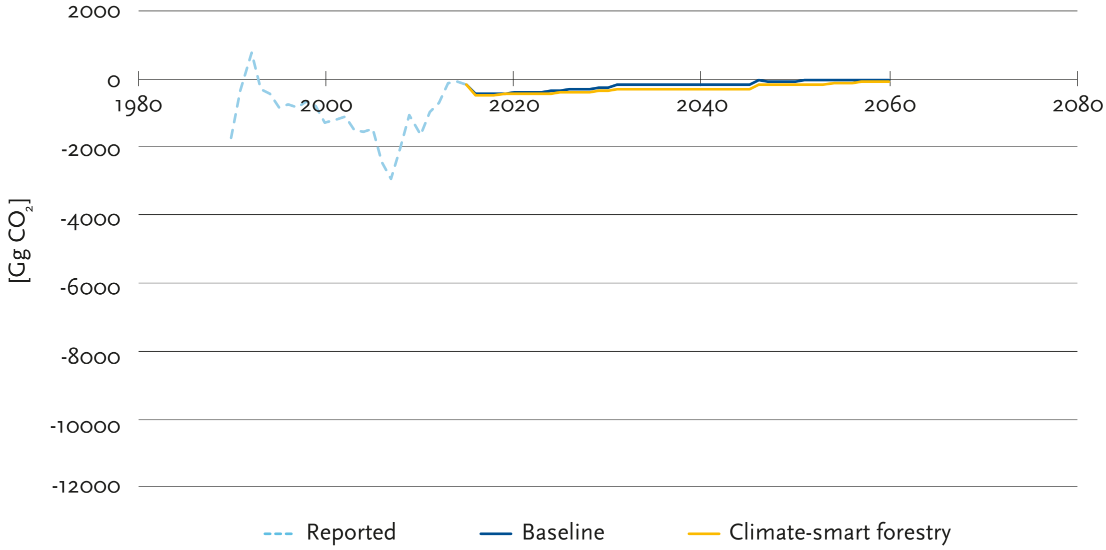


Figure 11. Reported and projected emissions (positive values) and removals (negative values) of CO_2 from harvested wood products in the different scenarios.

(the next 65 years) gives different results and policy implications than considering the long-run (over 65 years). About 35% of the lower sink in the CSFS is compensated by avoided emissions due to material substitution impact.

If CSF is applied as considered in this study – which is probably not the most optimal CSF strategy in terms of mitigation, but more geared at adaptation – an average net loss over a 50-year simulation amounts to 1268 Gg CO_2/yr compared to the BS (or 1.2 million tonnes of CO_2). After 2080, the sink in the CSFS becomes quickly larger than in the BS due to the converted forests that are then in fast growing stage.

Currently there is a legally binding lower limit of 80 years of age for an intentional final felling. Shortening the rotation age to speed up conversion of unstable forests as implemented in the CSF scenario is therefore not always legally permitted, and an amendment to the forest law would be needed.

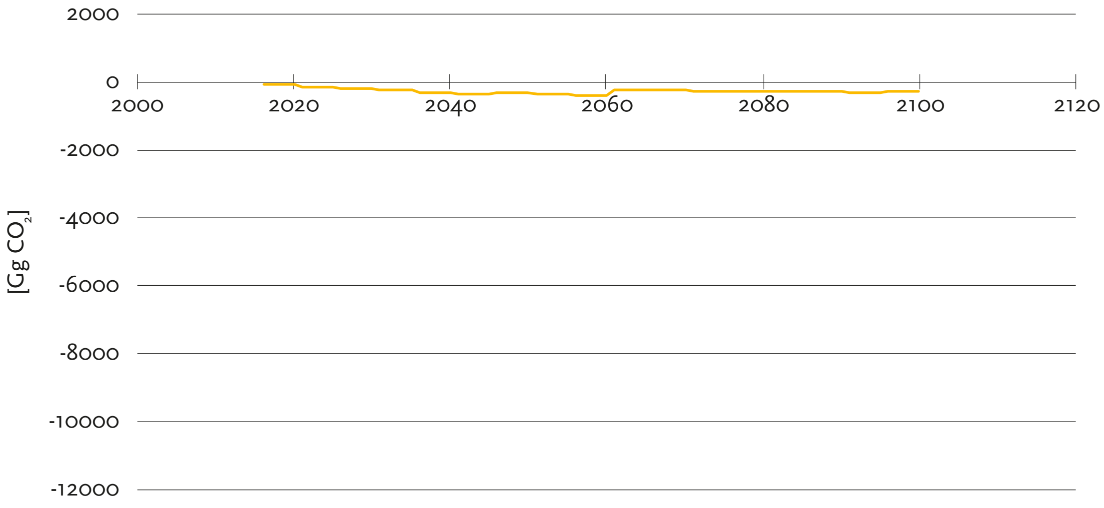


Figure 12. Projected removals (negative values) of CO_2 due to additional material substitution impact in the CSF scenario relative to the Baseline scenario.

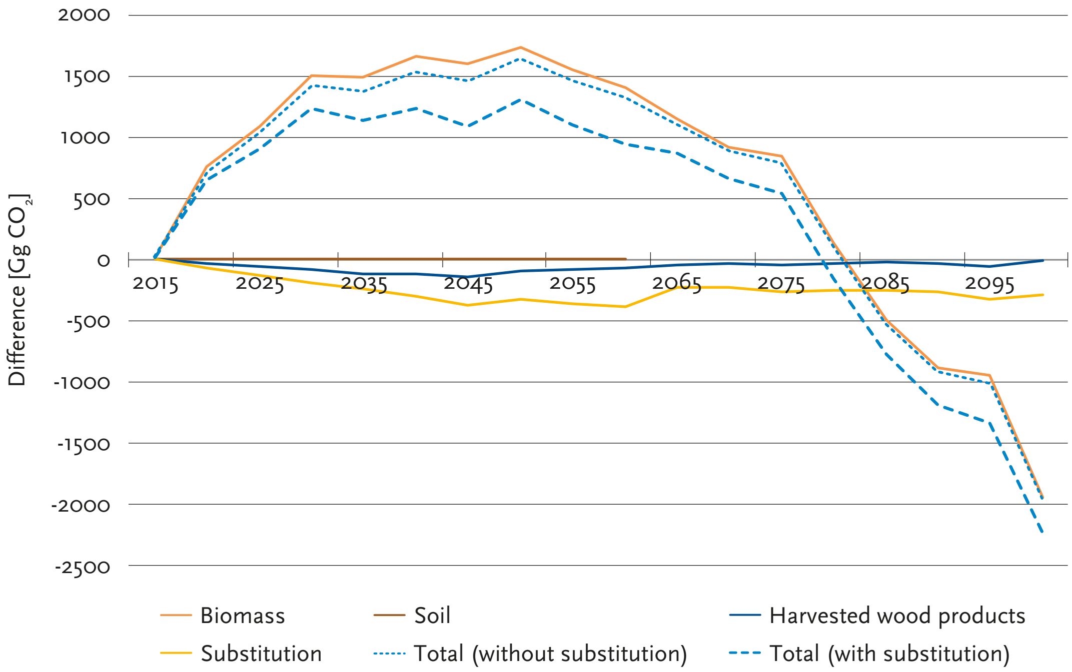


Figure 13. Climate benefits of the CSF scenario for the Czech Republic relative to the Baseline scenario. *Positive values indicate additional emissions of* CO_2 *and negative values denote additional removals of* CO_2.

5. Case study: Republic of Ireland

5.1 Trends and issues

The forest area in the Republic of Ireland has expanded greatly in recent decades. Between 1990 and 2015, the forest area increased by 58% from 481,000 to 760,000 ha, corresponding to an average annual afforestation rate of 12,000 ha/yr (Ireland 2017). The average afforestation rate decreased in recent years (2011–2015) to 6,400 ha/yr (Department of Food Agriculture and the Marine 2015). In Ireland, 44% of forests are established on peatlands (Department of Food Agriculture and the Marine 2012).

Policies in the past were mostly geared at forest area expansion, thereby ensuring sufficient volume production to underpin the competiveness of the forest sector and provide support to land owners with an emphasis on farmers. Since the mid-1990s grant aid has been predominantly given to private land owners. Public companies could not take advantage of premium payments from 1999 onwards, which means they have not engaged in afforestation to any appreciable extent since. The protection of the environment is an integral part of all schemes and licensing processes. The Native Woodland Scheme is aimed at protecting, enhancing and expanding Ireland's native woodland resource and associated biodiversity, through appropriate planting and management.

Of the forests, 53% were in public ownership and 47% in private ownership in 2012. The share of privately owned forests has increased by 4% since 2007. Private forest ownership is commonly reported as 'grant-aided' and 'other' private ownership. From the forest area, 34% is in grant-aided private ownership, and 13% in non-grant-aided ownership (Department of Food Agriculture and the Marine 2012).

The majority (83%) of Irish forests have no restrictions on timber supply and would be available for wood supply. A small portion (0.6%) of the estate is considered not available due to the National Parks and Nature Reserves designations. A significant portion (16%) of the estate is considered unlikely to contribute to wood supply, primarily due to the site constraints, physical productivity or wood quality limitations. Nearly two-thirds (64%) of the private (other) estate is classified as unlikely to contribute to wood supply, primarily due to the presence of poorly performing broadleaf forests, i.e. the native oak woodlands (Department of Food Agriculture and the Marine 2012).

The management of state forests is carried out by Coillte. Furthermore, Teagasc Forestry Department supports private forest owners with training etc.

The dominant tree species in Irish forests is Sitka spruce, which covers 52% of the total forest area. Pine tree species (Scots pine and other pines) cover 11% and birch as well as other short living broadleaves each cover more than 5% of the forest area. The tree species differs between ownership types with notably other private owners having a very different tree species composition with many broadleaved species (Department of Food Agriculture and the Marine 2012).

The mean annual increment per hectare is estimated at 11.5 m³/ha/yr in the whole forest estate. Public forests average 13 m³/ha/yr and private (grant-aided) 11 m³/ha/yr, with private (other) significantly lower at 7 m³/ha/yr. The differences are due to a combination of age, species composition and soil type (Department of Food Agriculture and the Marine 2012).

The increase in the Irish forest area results in a relatively young forest resource; the median age of Irish forests is around 20 years. The harvest in the young spruce is therefore low even though sawlog prices rose sharply in 2013–2014 due to higher demand. Wood production in Ireland in recent years (2011–2015) has been approximately 3 million m³/yr (Knaggs & O'Driscoll 2016) and the total, potentially harvestable volume is estimated to increase from 3.95 million m³/yr in 2016 to 7.86 million m³/yr by 2035 (Phillips et al. 2016).

Windthrow is an important disturbance, mainly in Sitka spruce forests. Several storms hit at the end of 2013/early 2014, resulting in damage over some 8,300 ha or 2.0 million m³ or 1.7% of the growing stock (McInerney 2014). From the total amount of roundwood production, 60% (1.9 million m³) was used for sawmilling to produce construction wood (26%), pallets (12%) and fencing (10%) in 2015. Approximately half of the wood for sawmilling is sawmill residues allocated to the production of wood-based panels and energy in combined heat and power plants. In addition, 769,000 m³ of wood-based panels were produced, of which 79% was exported (Knaggs & O'Driscoll 2016).

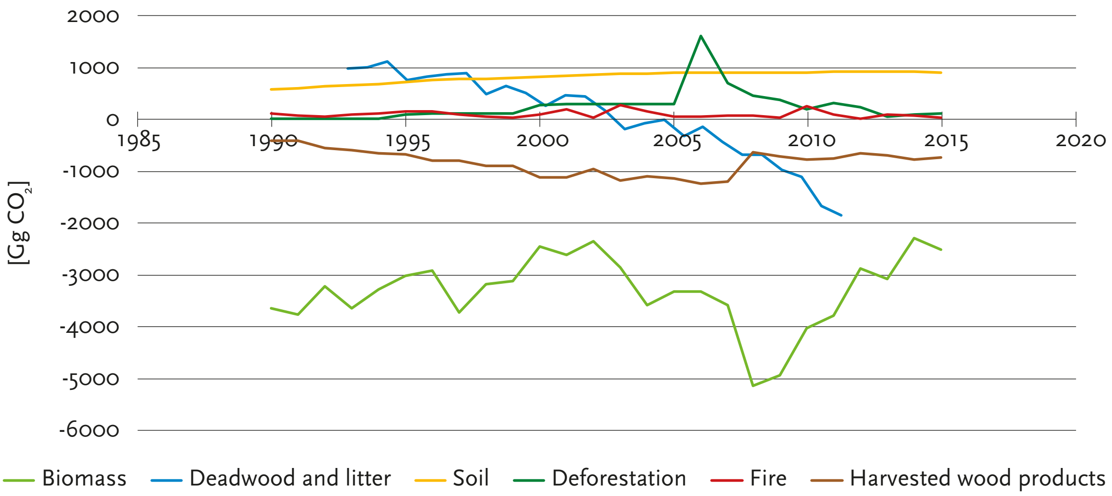


Figure 14. Historical CO_2 emissions and removals from forestry activities in Ireland (Ireland 2017).

5.2 Forestry contribution to climate change mitigation

Irish forests absorbed approximately 2% of the Irish annual CO_2 emissions over the period 1990–2015. Living biomass has been absorbing carbon for many years. Organic soils (or peat soils) act during the first rotation as a source of CO_2 emissions, as well as other GHGs. Emissions from organic soils are on average 0.59 tC/ ha.yr and only occur for the first 50 years after afforestation (Byrne & Farrell 2005; Duffy et al. 2017).

5.3 Scenarios

Baseline scenario

The basic rationale of the Baseline scenario (BS) is that existing trends are largely continued with no additional efforts and investments to use forestry as a measure to mitigate climate change. Specifically, the following actions are assumed:

- The current average forest area expansion of 6,400 ha/yr continues for the next 50 years. Following recent trends, afforestation is carried out with 73% coniferous species – predominantly Sitka spruce – and 27% with broadleaved species.
- Based on recent afforestation trends (2011–2015), 50% of the afforestation will be on organic soils (drained peatlands) and 50% on mineral soils.
- Roundwood production is assumed to grow following the average trend in roundwood production from 1990–2015 (i.e. from current 3.3 million m^3 to 5.3 million m^3 in 2065.
- The flows and uses of harvested wood are assumed to remain similar to the period 2011–2015.

CSF scenario for 2015–2060

The overall rationale behind the CSF scenario (CSFS) is that additional effort is made resulting in investments in forestry as a way to mitigate its emissions in other sectors. Specifically, the following actions are assumed:

- Based on existing policy targets, an annual afforestation rate of 15,000 ha/yr is assumed, consisting for 70% of a mix of conifers species (with reduced share of Sitka spruce) and for 30% long-rotation broadleaved tree species.
- Afforestation is carried out on mineral soils or soils with thin organic layers.
- Roundwood production is assumed to grow three times the average trend in roundwood production from 1990–2015 (i.e. from current 3.3 million m^3 to 9.4 million m^3 in 2062).
- An increased use of wood in construction is assumed. Based on current wood flows in Ireland (Knaggs & O'Driscoll 2016), all wood that is harvested in addition to the BS is initially allocated to sawmilling to produce construction wood (26%) and wood-based panels (23%). Sawmill residues (51%) are allocated to produce wood-based panels (25%), energy in combined heat and power plants (25%) or to other uses (1%).
- Harvested sitka spruce stands are regenerated for 16% with similar provenances, while 54% are regenerated with more productive material through improved breeding. Improved material, on

average, is 15% more productive compared to unimproved sources. The remaining 30% of the harvested sitka spruce stands are regenerated with mixed species for longer rotations;

A detailed description of the methods is given in the Annex.

5.4 Results

The simulated emissions and removals of CO_2 for the BS and CSFS are presented in Fig. 15. Focusing on living biomass, Irish forests are estimated to remain acting as a sink throughout the 50-year period under the BS, although the sink is estimated to decline over time. Increased levels of wood production in the CSFS result in a faster decline of the living biomass sink (Fig. 15a). This decline is in part compensated for by increased afforestation and use of better provenances when regenerating harvested sitka spruce stands, but these measures do not prevent Irish forests becoming a small source of CO_2 in the scenario.

Organic soils (Fig. 15b) are considered to emit CO_2 for the first 50 years after afforestation (Byrne & Farrell 2005; Duffy et al. 2017). As Irish forests are ageing, the emissions from organic soils under existing forests are estimated to decrease in the future. However, a continuation of current afforestation trends would result in a steady source of CO_2, according to the BS. Restricting afforestation to mineral soils or soils with a thin organic layer would lead to a gradual decline in the level of emissions from organic soils.

The modest increase in wood production in the BS is estimated to result in a steady harvested wood products (HWP) sink (Fig. 15c). The increased levels of wood production in the CSFS, as well as the use of the wood for construction materials (construction wood, boards and panels), is estimated to lead to a rapid increasing of the HWP sink. However, this increase does not compensate for the decreased sink in living biomass.

Substitution is estimated only for the CSFS for wood and wood products produced in addition to the production in the BS, because it is impossible to determine which products wood products would be substituting. In the CSFS, the additional wood production is used for construction materials, which displace other materials (e.g. concrete, bricks, steel, glass, etc.) with an average displacement factor of 2.1 kg CO_2 / kg CO_2 (Sathre & O'Connor 2010). The assumed strong increase in wood production and allocation to construction materials lead to a significant amount of avoided emissions by the end of the 50-year period (Fig. 15d).

The climate benefits of the CSFS compared to the BS are summarised in Fig. 16. The fast increase in felling levels under CSFS decreases the amount of CO_2 stored in living biomass, but this effect can approximately be compensated for by increased storage in wood products and by restricting afforestation to mineral soils or soils with a thin organic layer. In Ireland material substitution appears to be a key factor determining whether Climate-Smart Forestry has benefits as compared to managing forests and using according to current patterns and trends.

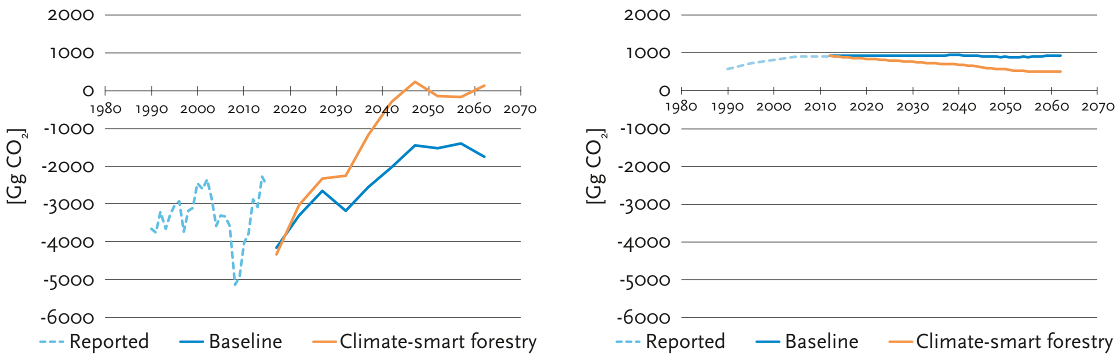
5.5 Key findings

A rapidly declining sink has been reported for the young Irish forests between 2009 – 2016. This trend is projected to continue both under the BS and the CSFS. The CSF approach considered intends to create a more stable forest, which is less susceptible to wind damage. However, the fast increase of harvest under CSF reduces the sink in living biomass of Irish forests, but enhances the HWP pool and especially the substitution effects. The average additional climate mitigation benefits of CSF over the 50-year simulation amounts to -1407 Gg CO_2/yr (or 14 million tonnes/y).

Restricting afforestation to mineral soils or soils with a thin organic layer attempts to avoid emissions from organic soils covered by forests. However, if these sites are left untouched they may absorb small amounts of CO_2 but may emit methane. The next effect on global warming is likely to depend on site conditions, peat type, etc. (Black & Gallagher 2010; Koehler et al. 2011).

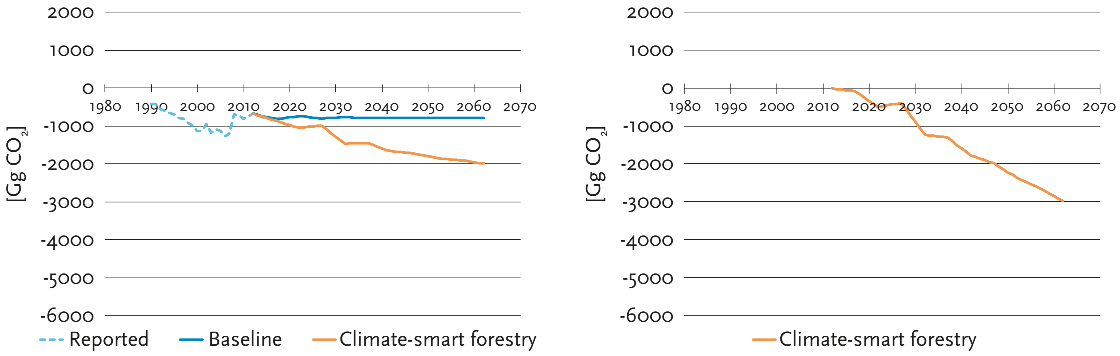
Increased wood production and using the wood for long-lived products such as construction materials (construction wood, boards and panels), can lead to a rapid increase in the HWP sink. However, this increase in the HWP pool does not compensate for the decreased sink in living biomass.

Material substitution is a key factor determining whether Climate-Smart Forestry has benefits as compared to if forests are managed and wood is used following current patterns and trends.



(a) Living biomass

(b) Organic soils



(c) Harvested wood products

(d) Substitution

Figure 15. Reported and projected emissions (positive values) and removals (negative values) of CO$_2$ for the Baseline and CSF scenario. *Substitution is only estimated for wood production in the CSF scenario complementary to wood production in the Baseline scenario.*

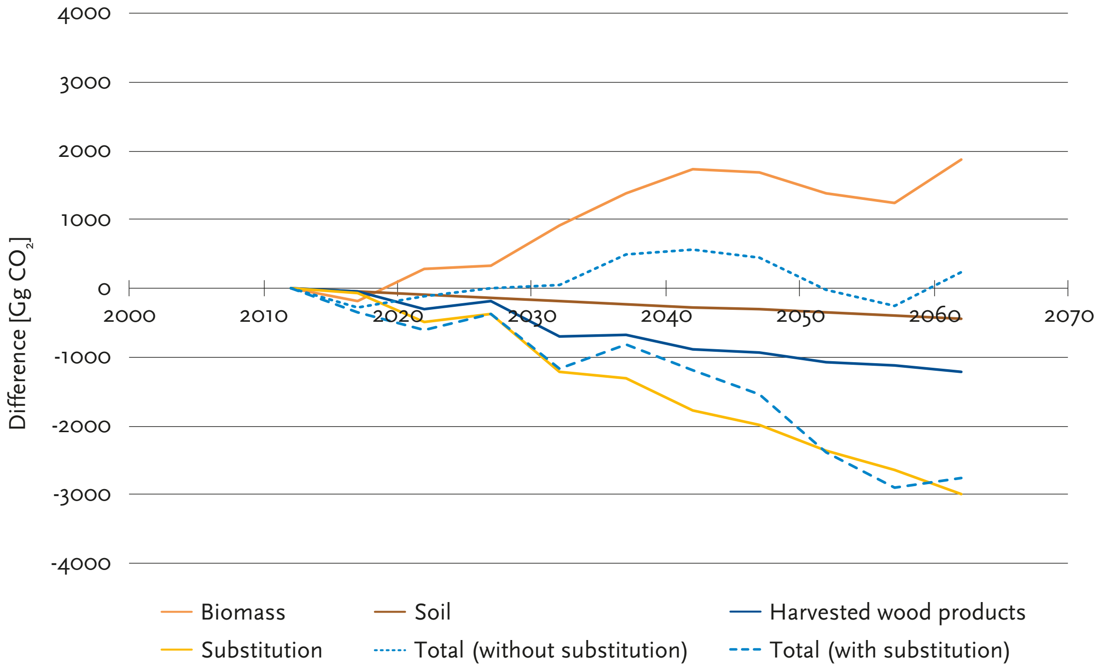


Figure 16. Benefits of the CSF scenario for the Republic of Ireland relative to the Baseline scenario. Positive values indicate additional emissions of CO$_2$ and negative values denote additional removals of CO$_2$.

6. Conclusions and implications

The Climate-Smart Forestry approach builds on three pillars:

- reducing and/or removing greenhouse gas emissions to mitigate climate change
- adapting forest management to build resilient forests
- active forest management aiming to sustainably increase productivity and provide all benefits that forests can provide.

However, CSF measures can be regionally very different due to significantly varying regional circumstances across Europe. The purpose of this study was to demonstrate how the variety of CSF measures would impact CO_2 removals through forestry activities in three different regions in Europe.

We applied simulation models to conduct scenario analysis for Spain, the Czech Republic and the Republic of Ireland, each with different region-specific characteristics in their forests and forest sectors. Spain, in this study represented by the Mediterranean region of Catalonia, can be characterised as having very dry circumstances, a modest management intensity of forests and is confronted with wildfires. Forests in the Czech Republic can be characterised by a high biomass stocking, which may be difficult to maintain over a longer period due to potential disturbance risks, such as droughts, storms, pests and pathogens. Forests in the Republic of Ireland are generally young, fast-growing forests with up to now a low harvesting rate and a large share of forests are growing on drained peatlands. Scenario projections for parts of Spain (1.6 million ha), the Czech Republic (2.67 million ha) and Republic of Ireland (0.76 million ha) provided insights in the carbon balance of the forest ecosystems, and harvested wood products material and energy substitution effects.

It should be stressed that this study did not follow the conventional climate policy **accounting** rules. Instead, we sum the impacts of the forests and forest sector to CO_2 mitigation as the atmosphere "sees it". If emissions are reduced e.g. in the energy sector through the use of forest biomass, these reduced emissions are, according to current accounting, by the energy sector. In this study, we attributed these effects to the forest sector.

All CSF measures have been implemented at a level that we consider **realistic** in practice, but still with some additional effort towards climate mitigation compared to the current situation. For example, we assume more active management activity in northeast Spain, but realise this is currently a region without a strongly developed forest sector. CO_2 emissions are reduced by reducing wildfire risks in the region through managing forests and by that, reducing fuel loads and fuel continuity to prevent fires from spreading over large areas. In the case study for the Republic of Ireland, we assume afforestation rates following existing policy targets. In the case study for the Czech Republic, we regenerate the unstable (beetle-attacked) spruce and regenerate with broadleaved species (oak and beech) that have somewhat lower productivity. Consequently, we reduce carbon stocks and uptake for several decades, which may not be the most optimal for short-term mitigation efforts. However, this reduction depends on the extent to which Norway spruce will be affected by climate change. Other measures could also be implemented such as better adapted and better growing provenances of spruce, using other domestic conifers, e.g. fir and pine species, and occasionally exotic species such as Douglas-fir. Or by promoting more close-to nature silvicultural approaches, such as structurally rich forest stands with diverse species composition. These may in practice strongly contribute to increased resistance and resilience of forests to climate change, which is the fundamental prerequisite for delivering the expected mitigation effect.

In Table 1, the mitigation impacts of the CSF scenario compared to the Baseline scenario are summarized. In Spain and Ireland there is a large additional mitigation impact due to CSF measures. The total average net mitigation impact in Spain is 0.6 and in Ireland 1.4 million ton CO_2/yr over 50 years simulation. In these case examples, the more active management and smaller forest sink impact (due to loss of carbon in living biomass) is more than compensated by the HWP pool and the substitution impact. However, in the Czech Republic CSF is estimated to result in losses of carbon of on average 1.3 million ton CO_2/yr over 50 years. This is because here a conversion to slower growing species is applied, but under the same harvesting level as in the past. Therefore, the additional product substitution effect is marginal and the whole balance shows more emissions under CSF.

Table 1. Summary of the average annual additional mitigation impacts over 50 years simulation due to Climate-Smart Forestry (Gg CO_2/yr). *A negative number denotes an additional climate mitigation effect.*

		Spain*	Czech Republic	Ireland
Forest area included (million ha)		1.62	2.67	0.76
Pools	Living biomass	+516	+1347	+1067
	Soil	-119 (only slash and roots)	NE	-244
	Biomass burning	Implicit on living biomass	NE	NE
	Harvested wood products	-306	-79	-711
Substitution	Materials**	-714	-258	-1519
	Energy	-7	NE	NE
Total		-574	+1268	-1407

*The forest area included in Spain is located in region of Catalonia and represents 11% of the total forest area available for wood supply in Spain.
**Includes fossil fuel substitution effects through combustion of wood-processing residues
NE: not estimated.

The time period considered can have a large impact on the results. The results from the Czech case study indicate that in the longer term, increased harvests could stimulate the uptake of CO_2.This is because if current forest stands would be left to grow, their growth rates would slow down and risks of beetle attacks will increase significantly, and if realized may result in a saturating forest carbon sink. Increased harvesting results in immediate reductions of the forest biomass sink also in the Spanish region of Catalonia. However, the harvested forests are assumed to be replaced by better-adapted forest stands securing stable productivity and hence mitigation in the longer term. If e.g. the Spanish region of Catalonia would have been run for a longer time period, the positive impacts of the higher growth rates would probably be visible as well.

Although circumstances are very different in these three case studies, they all show that **more active management leads to losses in the living biomass carbon sink in the coming decades**. However, the results from the Czech case study indicate that after 50 years again gains in CO_2 removals by the living biomass sink are possible although not yet all previous losses have been compensated by 2090. Furthermore, the conversion in the Czech case study was mostly geared at adaptation, not at increasing productivity.

Results from all three case studies indicate that **carbon storage in wood products may increase in the future**. This increase of the wood products pool sink is mainly caused by the assumed increased levels of wood production (except for the Czech case study). Without increasing wood production, the wood products pool is likely to saturate within a few decades (Pilli et al. 2015).

Using more wood in construction is considered an important measure to decarbonize society (Rockström et al. 2017). We estimated material substitution effects for the additionally harvested wood in the CSF scenario for the case studies for Spain and the Republic of Ireland and for reallocating to long-term uses in the case study for the Czech Republic. We found that **material substitution impact is a key factor determining whether Climate-Smart Forestry has mitigation benefits within the 50-year simulation period. If we would have run a 100-year simulation period, the forest management impacts could possibly be at least as important.**

Results from the case studies highlight that sustainably increasing harvest levels could have overall positive climate benefits, mainly through material substitution. (See also the Annex for a short reflection on material substitution). The exact substitution effect will depend on the type of wood product, the type of non-wood material that is replaced and the post-use fate of the wood (Sathre & O'Connor 2010; McKechnie et al. 2011). A few studies have been published more recently and suggest substitution factors that are lower (e.g. Rüter et al. 2016; Smyth et al. 2017), while confirming that (material) substitution effects highly depend on the type of products that are considered. Nevertheless, the results of the three case studies corroborate previous findings that substitution effects create durable and sustainable mitigation of CO_2 emissions (Poudel et al. 2011; Lundmark et al. 2014; Gustavsson et al. 2017; Jasinevičius et al. 2017). Indeed, **properly accounting for substitution effects – and attributing them to the forestry sector – is crucial to define optimal (forest management) strategies to mitigate climate change.**

The case studies reveal that **very different regional measures can be taken to mitigate climate change**. The Spanish case showed that increasing the area under management reduces emissions from wildfires, especially if the impact of forest and biomass fuel management would be considered. Another example of a regional measure is the restriction of afforestation to mineral soils, or soils with a thin organic layer in Ireland. The simulations indicate that emissions from organic soils could be approximately halved. Thus, **CSF measures should be identified and implemented regionally; a 'one size fits all' solution across Europe will not work.**

How do these regional mitigation results compare to the EU-level results indicated by Nabuurs et al. 2015? For these three (rather small) case studies (5.05 million ha), **an average overall net additional mitigation effect of 7.1 Mt CO_2/yr after 50 years is achieved. This can be considered to be a large effect.** However, the impacts of CSF on the living biomass sink could result in larger and longer losses than anticipated. **The overall positive mitigation impacts of CSF are to a large extent caused by the material substitution in the short run (up to 50 years)**.

Could the mitigation results be even more positive? Probably yes. Although we included the effect of wildfires in the Spanish case study, we could not quantify disturbances effects in the Baseline scenarios for the Czech and Irish case studies. Existing climate change projections suggest that damage from wind, bark beetles and forest fires is likely to increase in future and could have significant implications for the European forest carbon sink (Seidl et al. 2014). They may exaggerate productivity declines or cancel out productivity gains associated with climate change (Reyer et al. 2017). Thus, it would have been reasonable to assume increased wind damage in Ireland and increased spruce mortality in the Czech Republic in the estimated development without CSF for these regions.

In the present study, only one set of CSF measures was identified and tested in each case study. We did not consider all possible mitigation measures nor optimised them, but tried to highlight that mitigation measures need to consider local- or country-specific conditions. The extent to which each measure has been included in the modelling stayed rather close to ongoing policies and practices, but **it is likely that more extensive and stronger implementation of all measures could lead to higher mitigation effects**. Furthermore, we included measures that would most likely reduce the sink in the forest ecosystem at least temporarily, and analysed their impacts by considering all carbon pools and substitution effects. These measures could include increasing harvest levels to be able to increase the resilience of forests. **Drastic, but needed conversions, that could temporarily cause forest ecosystems to act as a source may also be part of a long-term adaptation and mitigation strategy.**

Finally, **this study focused mainly on the mitigation impacts of CSF, but there are likely to be many other benefits if planned and implemented carefully**. The CSF measures in this study intended to result in forest ecosystems that are better adapted to future conditions through a reduced vulnerability to storms (Czech and Irish case studies) and wildfires (Spanish case study). Furthermore, a conversion to a more natural tree species composition (Czech case study) may have positive benefits for biodiversity, a reduction in wildfires may result in a reduction of economic losses (Spanish case study) and increased wood removals may provide additional income to forest owners (Irish and Spanish case study). These are all benefits that positively add up to the results presented in this study.

For a better understanding of the potential impacts of Climate-Smart Forestry to climate mitigation, we would recommend the following analyses to be carried out. First, to extend the current 50-year simulation periods to at least 100 years. This would be important to be able to take into account the dynamic nature of forestry and fully capture forest management impacts in the long-run. Especially for long rotation forests, 50 years is too short to consider all the dynamic impacts of forest management. Moreover, the impacts climate change and adaptation may have start to be only gradually seen over the longer-term, for which 50 years is likely to be too short. Second, it would be useful to extend the case studies to other regions with different characteristics in forests and forest sector, such as the Nordic countries, Balkans and Central Europe.

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We are living in a time of accelerated changes and unprecedented global challenges: energy security, natural resource scarcity, biodiversity loss, fossil-resource dependence and climate change. Yet the challenges also demand new solutions and offer new opportunities. The cross-cutting nature of forests and the forest-based sector provides a strong basis to address these interconnected societal challenges, while supporting the development of a European circular bioeconomy.

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