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Survey of technical and management-based mitigation measures in forestry

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Executive summary

Forests contribute considerably to the terrestrial carbon sink. Although the speed of uptake is generally low, the stocks in both biomass and soil are high. Within the Kyoto Protocol, active forest management can be used to reach the goals for emission reduction. In this report, an extensive list of measures is compiled detailing the ways in which forestry could contribute to an enhanced sink, or could reduce emissions. Most measures in forest management will have small effects, and these effects will generally only become visible in the long term. Effective measures can be divided into three categories; firstly, those that protect existing carbon stocks. Such measures include avoiding deforestation, not harvesting stands with high carbon contents, increased fire prevention and minimising site preparation. Secondly, those that aim to increase average carbon stocks, such as afforestation, conversion to continuous cover forestry and changes in rotation length. The third category are measures that aim at harvesting biomass to create bioenergy. Such measures could be the use of logging residues, increasing the amount of fellings aimed at bioenergy wood, the (re)introduction of pre-commercial thinnings, and the establishment of short rotation coppice.

1. Background
1.1 The carbon cycle in forest ecosystems

Every day, forests exchange large quantities of CO_2 with the atmosphere. During photosynthesis CO_2 is absorbed, while respiration and decomposition release CO_2. The net balance between these processes (Net Primary Production, NPP) determines if the forest is a sink or a source. Carbon can be stored in living biomass (trees and other vegetation) or soil (including litter and deadwood), usually referred to as Soil Organic Matter (SOM). An additional carbon stock is found in products that are made of harvested wood. Figure 1 gives an overview of these three compartments and the processes that influence the size of these stocks. By manipulating these processes, the size of the stocks can to a certain extent be manipulated as well. However, the stocks in different compartments are not independent. Management that focuses on enhancement of carbon in e.g. forest biomass therefore has an impact on soils and wood products as well.

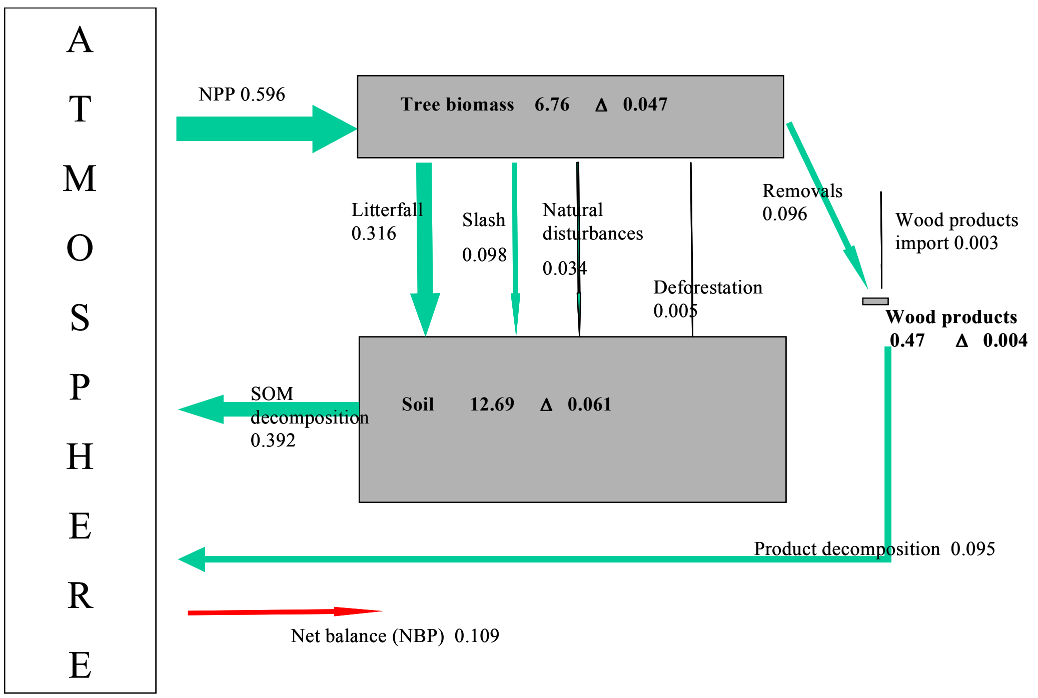

Figure 1. The carbon cycle in the forest ecosystem. Values in the three compartments (tree biomass, soil and wood products) are European stocks in 1990 (Pg C), flows between those stocks and net changes (Δ) in those stocks (Pg C y^{-1}). The width of the arrows indicates the relative size of the flows, and the size of the three boxes indicates the relative size of the stocks. The width of the arrows is not in relation to the size of the boxes (Nabuurs et al. 2003).

1.2 Biomass
The biomass carbon stock is a balance between net primary production and removals of biomass, either due to natural processes (litterfall, natural disturbances) or human-induced measures (harvest, deforestation). Net primary production is determined by many factors, such as climate (temperature, precipitation), site conditions (soil type, fertility), tree species, age, genetic quality and stand density. Litterfall rates depend on

productivity, tree species and tree age. The occurrence of natural disturbances depends on a complex range of factors. First of all, climate determines where disturbances can occur (wind climate for storms; hot and dry weather for fires; suitable climate for insect species). Secondly, the state of the forest determines if a disturbance will occur and how large the impact is. Windthrow not only depends on wind speed, but also on a range of stand and site characteristics, such as tree species, height, stand density, rooting depth and management history. Forest fire risk is determined by the amount of fuel, the flammability of the fuel, stand structure and surrounding landscape. Occurrences of insect damage are linked to preferences and characteristics of the species in question: tree species, age, forest structure, availability of weakened trees, climate conditions, dispersal possibilities, etc.

1.3 Soil

The earth's soils contain approximately 1500 Pg C (comparison: total EU15 annual emissions are in the range of 1.1 Pg C y^{-1}), making soils the largest surface terrestrial C pool, about 2–3 times greater than the amount of C stored in the earth's vegetation (Post et al. 1990). Later estimates for deeper soil profiles even concluded that the total stock may exceed 2300 Pg C (Jobbagy and Jackson 2000). Out of this total global stock, some 70% may be in forest soils.

This finding has been the reason for a large research interest in options to maintain soil C stocks, and management options to further increase the sink. All studies agree that the net balance of the soil C stock is the result of, on the one hand, the input rate of detritus (litter, dead wood) and on the other hand, the decomposition rate (as influenced by tillage, quality of the litter, temperature and moisture). Studies also agree that the influence that man has on the build-up of soil C stock is rather small. However they do not agree on the sign (increase or decrease of the stock) that certain measures will have on the soil C pool. Figure 2 depicts a theoretical soil C stock development over time in relation to the biomass dynamics.

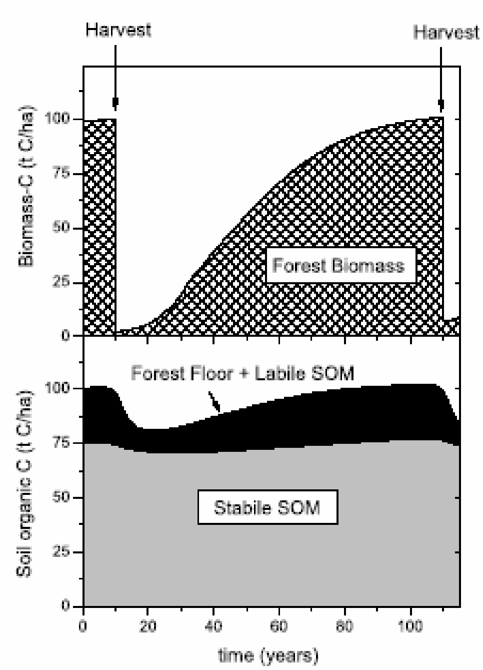

Figure 2. Dynamics of soil organic matter and litter layer (= forest floor) in relation to the biomass dynamics. Theoretically, if vegetation cover functions in the same way for a long time, the biomass carbon and soil carbon reach a steady state. However, in practice this is never reached, because of fluctuations in tree dynamics, differences in weather conditions, disturbances, or land use changes. In the above case, the harvest causes a large input of organic matter (from harvesting slash) resulting in a short increase in forest floor stock. Afterwards, because of few trees producing litter, and because of enhanced soil disturbance and soil temperature, the litter layer looses carbon to the atmosphere through decomposition, but also through humification to the stable soil organic matter (Olsson et al. 1996). The soil C pool actually dampens the total system fluctuations in comparison to the strong fluctuations in the biomass pool. Later, the large dip in the forest floor as depicted here was disputed as well (Yanai et al. 2003).

1.4 The total system

Temporal carbon dynamics of forest ecosystems are characterised by long periods of gradual build-up of biomass (C sink), alternated with short periods of massive biomass loss (C source). Forests thus switch between being a source or a sink of carbon, depending on the succession stage, specific disturbance or management regime and activities (Figure 3). Large areas of undisturbed forest consist of a mosaic of patches in different successional stages. Averaged over the whole area, sources and sinks will be in balance. Although such areas do not capture new carbon, they represent large stocks. Harvesting or deforestation of such sites will therefore lead to large emissions in a short timeframe. In managed forests, trees are harvested at more or less regular intervals. Large parts of the European forest are managed in the traditional even-aged system. In this system, the main 'crop' consists of trees of equal age and species. During a rotation, several thinnings can be carried out, followed by a final harvest at the end of the rotation age. Harvests will decrease the amount of carbon in the living biomass, but increase the amount of carbon in the soil/deadwood compartment because of the slash (topwood, branches, foliage, roots) that is left after harvest (see also Figure 2). Rotation lengths can range from a few years for fast growing Eucalypt pulp plantations to well over 100 years for high quality sawlogs of slower growing species. Figure 3 illustrates the development of carbon stocks in a managed and an unmanaged stand.

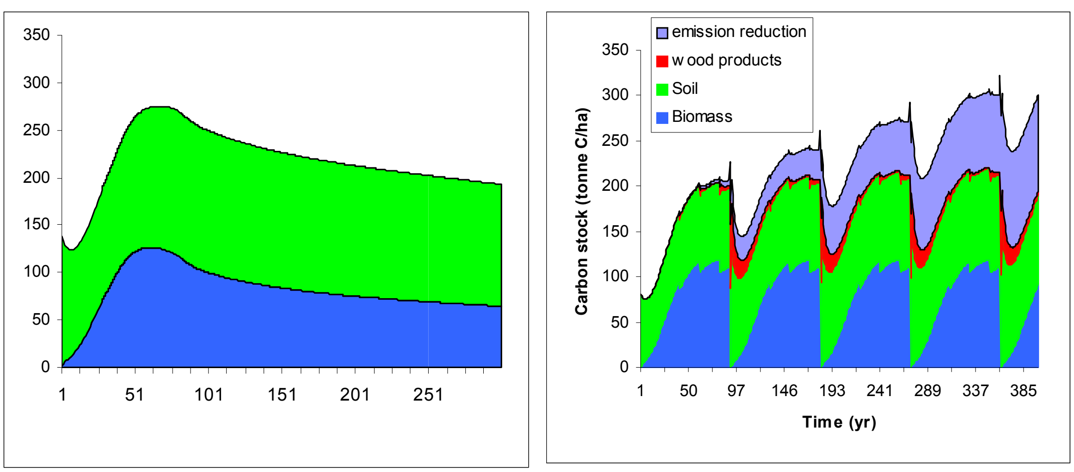

Figure 3. Comparison of carbon stocks in an unmanaged (left) and a managed (right) hypothetical forest stand.

1.5 Bioenergy

Bioenergy is energy derived from biomass. Biomass may be produced from energy crops (such as sugarcane or short rotation coppice) or forests, or as a by-product of forestry, sawmilling and agriculture. Biomass can be utilized directly for heat energy or can be converted into gas, electricity or liquid fuels.

With regard to CO_2 emissions, energy production from fossil fuels has very different implications compared to energy production from biomass. Burning fossil fuels releases CO_2 that has been locked up for millions of years. By contrast, burning biomass simply returns to the atmosphere the CO_2 that was absorbed as the plants grew and there is no net release of CO_2 if the cycle of growth and harvest is sustained (Figure 4). However, some input of (fossil) fuel is needed for harvesting and transportation. The bioenergy effect is thus only positive if energy inputs and associated emissions are (substantially) lower than the energy outputs and avoided emissions.

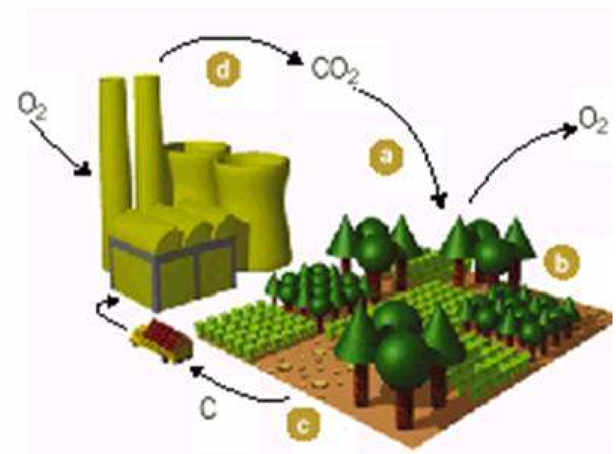

Figure 4. Carbon cycle of a bioenergy power plant (Source: IEA Bioenergy, 2001).

Substituting sustainably produced bioenergy for fossil fuels is a way of mitigating greenhouse gas emissions to the atmosphere. In contrast with carbon storage within the forest, the carbon benefits provided by bioenergy as a substitution for fossil fuels are irreversible, even if the bioenergy scheme only operates for a fixed period. This substitution effect is shown in Figure 3 as the emission reduction component.

1.6 The situation in Europe

In general, forest history in Europe can be characterised by a declining forest area since the Middle Ages, reaching a low in the 19th Century. Since then, the forest area has increased, either due to active afforestation or by natural means. Currently, the forest area in the EU25 is about 137 million hectares, and the net annual increase is 398 thousand ha (TBFRA 2000). Due to this recent expansion and quite intensive management, many countries show an age class distribution that is dominated by younger ages (Figure 5). The current harvest level is less than the increment, so growing stocks, and thus carbon stocks, are increasing (Figure 6). A large part of the forest is located on sites that do not have a long history of forest cover, so the soil carbon stock is also believed to increase. Without any changes in the current forest management, the forest is likely to act as a carbon sink for at least some decades.

Another factor contributing to increasing soil carbon sinks is climate change (Karjalainen et al. 2003, Nabuurs et al. 2002). The production increase that is foreseen under climate change is projected to lead to increased litterfall. This would not be fully compensated by increased decomposition. Figure 6 shows the annual carbon sink strength from 1950 to 1999, and Figure 1 shows the carbon stocks and fluxes for the year 1990.

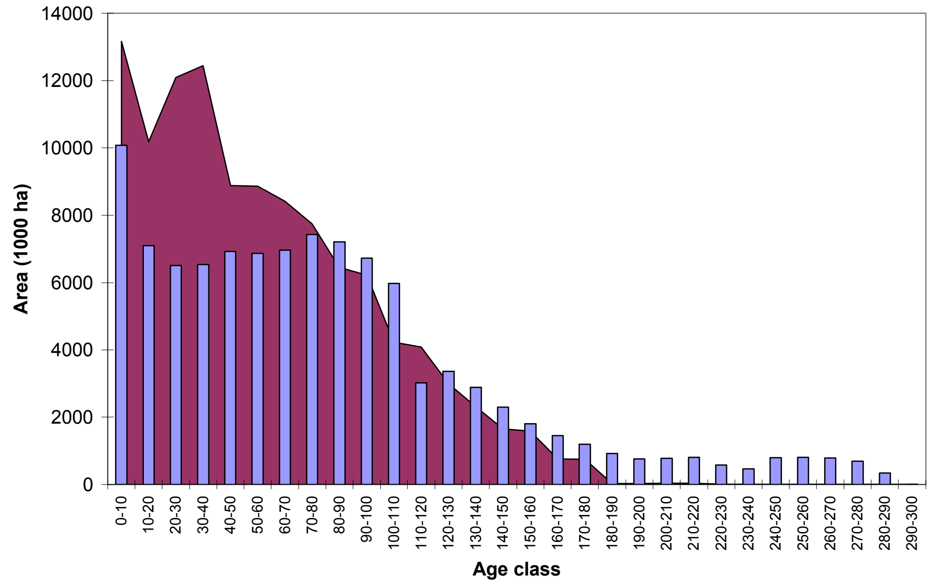

Figure 5. Current (about 1990, solid area) and projected (2090, bars) age class distribution of the European forest (Nabuurs et al. 2003).

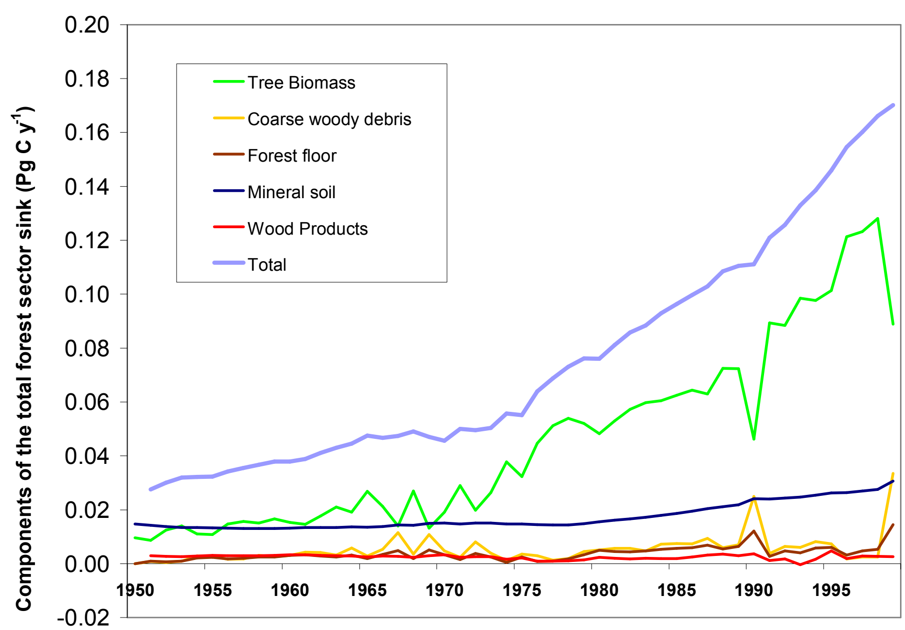

Figure 6. Sinks in the European forest sector, from 1950 to 1999, partitioned by compartments (Nabuurs et al. 2003)

2 Possible measures that can be taken in the forestry sector to contribute to the Kyoto Protocol

2.1 Introduction

In various ways, the forest sector could play a role in reaching the emission reduction targets as set in the Kyoto Protocol. Article 3.3 concerns Afforestation, Reforestation and Deforestation since 1990 (ARD). Reporting of these activities is obligatory for all Annex I countries (the industrialised countries). Article 3.4 concerns extra activities in agriculture and forestry. Countries are free to choose if they will include such activities or not. Most European countries are unlikely to choose the option of using the possibilities of Article 3.4. Apart from these specific Articles, forestry could play a significant role by providing biomass for the production of bioenergy. The use of bioenergy will not directly change the reporting in the Land Use, Land Use Change and Forestry (LULUCF) sector, but will show up as a reduction in the emissions due to fossil fuel use. In the following sections, we will discuss measures that can be taken in the forestry sector to contribute to the Kyoto Protocol and the implications they will have for both the greenhouse gas budget as well as for bioenergy. The measures are separated into measures under Article 3.3, Article 3.4, and other measures, such as bioenergy. The first (rough) screening of the measures followed the approach as described in the MECAP project guidelines. This approach consisted of ten different criteria that should be evaluated for each measure. However, the last three criteria (Monitoring and control parameters, Support and constraints in existing policies and Possible supporting political measures) would be covered in a later stage to those measures that were selected for further screening. Wherever information was readily available on these criteria, it was already included.

2.2 Article 3.3, Afforestation, Reforestation and Deforestation

2.2.1 Afforestation/Reforestation

Description: Afforestation is the direct human-induced conversion of other land uses to forested land through planting, seeding and/or human-induced promotion of natural seed sources. For specific purposes, the Kyoto Protocol recognizes the terms afforestation and reforestation (IPCC 2004). These terms differentiate land history; afforestation occurs on lands that did not contain forest for at least 50 years, while reforestation concerns forest land that did not contain forest by the end of 1989. Here, the term "afforestation" will represent the general term covering all cases of land conversion to forests. Since forests have higher carbon density than other ecosystems, afforestation represents a strong measure that increases carbon stock density on the land concerned, with likely attributable effects on large scale (e.g. Caspersen et al. 2000). Carbon sequestration is usually only one of the aims of afforestation.
Main potential: GHG mitigation through increase of forest area, increase of carbon stock density in biomass and soil pools.
Technical feasibility: Technically feasible throughout Europe, except for some regions where climate is restrictive, such as high elevation areas in Central Europe and tundras in northern Europe. However a land use change is a drastic change and a choice for a long term period. Therefore the changes are occurring at a slow pace. At present in the EU25 a net afforestation of some 0.4 million ha per year is occurring (TBFRA 2000).

Implication for GHG mitigation / biodiversity: The main implication of this measure for the GHG balance is an increased carbon stock in the longer term due to increased biomass and potentially increased soil carbon. The system changes from a low biomass system (where most of the NPP is harvested and removed) to a high biomass system with large amounts of litterfall. The usually intensive ploughing of agricultural soils ceases and a more moderate (moist) climate is created, which is beneficial for soil carbon. Furthermore, grassland emits N_2O, which will be stopped if it is afforested. It is clear that most profound effects are found in above-ground biomass and litter layers; the effects on the soil organic matter pool are much slower and smaller. Literature gives several overviews of impacts of land use change on the forest floor and soil organic matter (Post and Kwon 2000, Vesterdal et al. 2002, Paul et al. 2002). Results vary considerably; from reported losses during several decades after establishment to rather large increases in the long term. It is widely recognised that the net result of afforestation depends very much on the initial situation. If the initial stocks are low (for the soil type considered) then afforestation can yield considerable results in the soil C as well. Accumulation rates in the order of 0.3 to 0.4 Mg C ha^{-1} y^{-1} are frequently mentioned (see Figure 7).

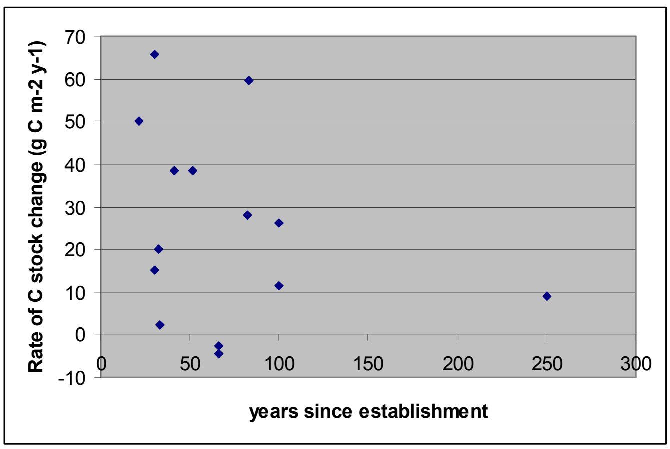

Figure 7. Average rates of soil carbon accumulation since forest establishment after agricultural use (Post and Kwon 2000).

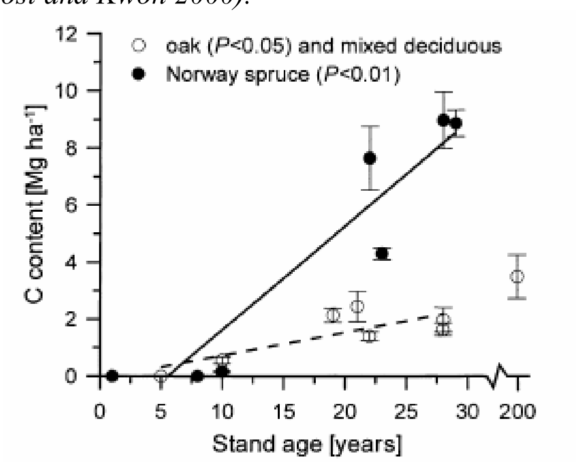

Figure 8. Forest floor C contents in afforestation chronosequences of oak and Norway spruce and of an adjacent ~200 years old mixed forest (Vesterdal et al. 2002).

Implications for biodiversity depend on the previous landuse, previous biodiversity values and on the surrounding landscape. Large scale afforestation of natural grasslands or culturally rich historical small scale landscapes could lead to the loss of specific species, while afforestation of intensively used agricultural areas could bring higher biodiversity. Similarly, afforestation of patches in an open landscape could increase biodiversity by creating additional habitats. Afforestation of open areas in a forested landscape could lead to a loss in biodiversity by destroying specific habitats. Open patches in the forest are known to be beneficial for many species. Effects of afforestation on biodiversity should therefore probably be judged by the diversity and structural heterogeneity of the newly created landscape. Effects on biodiversity also depend on the species that are used for afforestation. In Western Europe, earlier afforestations were aimed at production and often introduced coniferous tree species were used. Current afforestation is usually carried out with indigenous species, which is expected to be better for biodiversity (Larsson 2001). Furthermore, biodiversity could be enhanced through specific measures during afforestation. Such measures could include planting groups of species with different growth patterns to achieve a diverse structure or leaving parts of the area open, either permanently or to regenerate spontaneously. Furthermore, afforestation could be used to create corridors, e.g. in Natura 2000 frame.

<u>Revenues and costs (real as well as opportunity)</u>: Cost effectiveness of this measure is low if measured in terms of carbon sequestration in biomass only. Inclusion of soil carbon and reduction of N_2O emissions from former grassland will increase the cost effectiveness slightly. However, afforestation can serve many goals and can have many positive side-effects. A review study by Richards and Stokes (2004) suggests that secondary benefits of afforestation might actually be as great as the costs. Costs, revenues and secondary benefits will vary much across Europe, depending on land price, labour costs, and for secondary benefits (recreation), for example, distance to population centres.

A known obstacle for afforestation in at least some countries is the loss in land value when agricultural land is afforested. Conversion to forest land is usually permanent, since it is prohibited by law to change forest to another landuse. Revenues from forestry are usually less than those from agriculture, so the farmer would experience a loss in income. Therefore, afforestation occurs mostly on lands that are no longer used for agriculture.

<u>Constraints (Social, institutional, environmental etc.)</u>: Land use changes only take place slowly. These are drastic changes that are usually driven by other goals, or by developments in agriculture. Large-scale afforestation leads to losses in employment and abandonment of rural areas.

Some farmers oppose the idea of converting good agricultural land that often has been in family possession for centuries to forest. Further, afforestation can change the appearance of a landscape drastically. For example, the Northeast part of the Netherlands is known for its openness, caused by removal of the original peat layers and the cultivation of the area, where only agriculture was applied. Afforestation projects in these areas have led to protests because of the loss of the cultural identity of the landscape.

Furthermore, there are indications that specific types of afforestation could even enhance climate change. Claussen et al. (2001) concluded that afforestation with conifers in high altitudes leads to a net warming. Negative albedo effects were not compensated for by increased carbon storage.

Potential magnitude of technical measure: The potential of afforestation depends largely on the availability of abandoned agricultural land. Since these are usually marginal lands, the forest productivity would not be very high. On the other hand, the available area could be considerable and the increase in carbon stocks is for a large part permanent. The potential of new afforestation is recognized mostly in Eastern Europe, where both available land and low labour costs make afforestation feasible and attractive. On the contrary, a further major increase in forest land is unlikely in Western and Central Europe. Future availability of (marginal) agricultural lands is influenced by many factors, such as demand for agricultural products, (CAP) subsidies, openness of agricultural markets and possible competition with bioenergy crops. Different scenarios on land availability are provided by the ATEAM scenarios and the CLUE scenarios, for example, both based on the IPCC SRES scenarios. Depending on the scenario and the study, the forest area in Europe may either decrease by 4 million ha in total by 2030, or increase by 14 million ha over the same period.

Monitoring and control parameter (direct and indirect):

Forest area change can be detected with remote sensing techniques. Monitoring of C sinks would involve detailed repeated inventories. Direct and indirect effects are difficult to separate, unless the trees are planted.

Support and constraints in existing policies:

Land use changes are embedded in the Kyoto Protocol. Furthermore the CAP has provided subsidies for afforestation. Conflicts with local policies may arise in certain cases, for example with aims to keep certain areas open, or when maximum forest cover limits have been defined.

Possible political measure to support this technical measure: -

2.2.2 Avoiding deforestation

Description: Deforestation is the change of landuse from forest to some other landuse. Deforestation leads to an immediate loss of carbon in living biomass, and to a rapid decrease of soil carbon due to decreased litter input and increased decomposition due to soil disturbance and increased temperature (less shading). Avoiding deforestation is the prevention of the transition of forest to another land use that would contain less carbon.

Main potential: The main potential of this measure is avoiding carbon emissions from current stocks in both biomass and soil carbon, and to a lesser extent the safe-guarding of future potential for carbon sequestration.

Technical feasibility: No specific technology required.

Implication for GHG mitigation / biodiversity: The implication of avoiding deforestation on the greenhouse gas budget is avoiding large carbon emissions. Implications for biodiversity can generally be judged as positive; it would mean a prevention of loss of current biodiversity. This depends of course on the previous biodiversity values and the type of landuse transition. Some nature conservation organisations create open patches in large homogeneous forests to increase the diversity in forest structure and biodiversity, or remove spontaneously regenerated trees from heathland to keep or restore biodiversity on these lands. However, most deforestation in Western Europe occurs in the context of urbanization and infrastructure development, which is not beneficial for biodiversity.

Revenues and costs (real as well as opportunity): Direct costs of avoiding deforestation are minimal, but indirect costs could be high. If for example a road must be build around a forest to avoid going through it, costs might be very high.
Constraints (Social, institutional, environmental etc.): In many Western and Central European countries, deforestation is only allowed under very high restrictions. Deforestation that occurs is usually for road construction or house building, and under the provision that the forest area is compensated elsewhere. In such cases, interests are often high, and it is unlikely that this kind of deforestation could be prevented. Bauer et al. (2004) conclude in an overview of forest laws of 23 European countries that in general: "Changes of forest land into other forms of land use (agriculture/ urbanisation/ industrialisation) need a separate and specific regulation procedure by the national forest law." Despite the importance of deforestation in terms of carbon and the obligation to report it under the UNFCCCC, few countries are currently able to estimate gross deforestation. Despite the above-mentioned restrictions on deforestation, The Netherlands reported an annual gross deforestation of about 1500 ha (0.4% of the forest area) to the UNFCCC (Nabuurs et al. 2004).
Potential magnitude of technical measure: The potential magnitude is hard to assess, since figures on gross deforestation are not widely available. Most European countries report an increase in forest area (TBFRA 2000), but this is often the net result of a small deforestation and a larger afforestation. Moreover, gross deforestation figures need to be split according to the type of transition to assess whether it could have been prevented or not. The potential area will probably be rather small, but the potential per hectare is large.
Monitoring and control parameter (direct and indirect): Remote sensing techniques are available.
Support and constraints in existing policies: -
Possible political measure to support this technical measure: Subsidies for not carrying out a planned deforestation will be hard to implement, because it is difficult to prove that you have serious plans to cut down forests. Restricting possibilities for deforestation would probably be the best option. However, in most cases such restrictions already exist.

2.3 Article 3.4: Additional measures in agriculture and forestry

2.3.1 Application of fertilizer to increase productivity

Description: In many parts of Europe, forests are located on the least fertile soils. Application of fertilizer can lead to a significant increase in productivity, and thus to an increased carbon sink in the biomass (e.g., Nilsson 1993, Mäkipää et al. 1999). The limiting factor is often nitrogen. Currently, an increase in forest production has been reported throughout Europe, which can at least partly be attributed to an increased nitrogen deposition (Karjalainen et al. in press). However, other elements could also be or become limiting, specifically magnesium. Fertilisers have been extensively applied in Central and Northern Europe to offset acidification and nutrient degradation of forest soils.
Main potential: Increasing productivity of forests will lead to an increased carbon sink.
Technical feasibility: Feasible on sites with strong nutrient limitations, but not widely implemented. Implementation would not need any technological improvements. Many

experiments have been carried out in the past. However, the potential benefit has been significantly reduced by widespread N depositions. (Not widely used because of the relative high costs and long periods before returns).
Implication for GHG mitigation / biodiversity: GHG mitigation: positive, increased productivity, increased carbon sink, at least in the biomass, but probably also in the soil. However, some studies point to a decreasing soil carbon stock in response to fertilization (Jandl 2002). Furthermore, the production of traditional fertilizer is unfavourable for the GHG balance and would partly offset increases in carbon sinks. Chen et al. (2000) found the carbon costs of applying low rates of N fertilizer to be only 0.5% of the carbon gains. However, the background N deposition was very low (2.5 kg N ha^{-1} yr^{-1}), so small additions of N had large effects. Other sources of fertilizer could perhaps be considered. Biodiversity: mostly negative, many forest plants live on poor sites, fertilization leads to change in species composition of ground vegetation and apparently also to soil fauna.
Revenues and costs (real as well as opportunity): Costs are relatively high and revenues in terms of timber are late and unsure. Revenues due to increased biomass sinks depend on the price of carbon, type of fertilizer and increase in productivity.
Constraints (Social, institutional, environmental etc.): Conflicts with the 'natural' idea of forests, could lead to protests of local forest users, especially near urban areas and in Western Europe. Increased growth due to fertilization may affect stability of forest stand and increase the risk of windthrow. There is a risk of unpredictable effects to soil chemistry with long-term impact on production and hence carbon sequestration potential. Due to unclear site-specific responses of soils, forest fertilization is unlikely to be recommended for larger areas. As a result of N deposition, there are large forest areas in Europe no longer limited by N nutrition and on these sites, N fertilization would increase the risk of nitrogen leaching (cf. nitrogen saturation…).
Potential magnitude of technical measure: Most likely limited to a small fraction of European forests, mainly to sites with severe nutrient degradation and acidification of forest soils. Possible areas would include the Northern European countries and new accession countries.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.2 Improving genetic quality

Description: The production of forest trees can be enhanced by improving the genetic quality of the trees. This could either be done through traditional breeding and provenance research or using modern genetic engineering techniques. Encouraging breeding strategies or genetic modification fall outside the scope of the CAP, but forest owners can be stimulated to pay attention to genetic quality, for example by purchasing high-quality plants for regeneration.
Main potential: Increased carbon sink through increased forest production.
Technical feasibility: Throughout Europe, provenance trials have been carried out for at least a century. Also breeding programmes are common, as well as certifying the seed quality of selected forest stands. Thus, in general, high quality propagation material is available. Knowledge on planting and seeding procedures is common.
Implication for GHG mitigation / biodiversity: This measure may be beneficial for GHG mitigation in the biomass due to the increased productivity of the forest. It

might also be beneficial for soil carbon, through increased litterfall rates. Implications for biodiversity are most likely negative, since the genetic pool will be much smaller than in the natural situations. Another negative effect is that regeneration of the forest will be carried out by means of planting or seeding, leading to a more intensive management during the regeneration phase and less space for naturally appearing species. In general, the management will be more intensive, since higher investments are involved that need to be earned back. This will probably lead to monocultures of single species with severely limited age and spatial structure of such forest stands.
Revenues and costs (real as well as opportunity): Main costs for the forest owner are the costs for certified seed or planting material. These costs might be the full costs in case natural regeneration is otherwise used, or the additional costs relative to lower-quality propagation material that would have been used otherwise.
Constraints (Social, institutional, environmental etc.): A general trend in Europe is towards a more close-to-nature forestry, utilizing and mimicking natural processes. The traditional forest management, based on age classes and artificial planting, is slowly but steadily heading to a way of management that is closer to nature: stands with high age and spatial structure, rich and natural species composition and promoting continuous natural regeneration. This trend runs parallel with promoting the policy of multifunctional forestry, stressing other important functions besides production, like recreation and nature protection. It is not very likely that this trend can be reversed.
Another important trend to note is the focus on, and protection of, indigenous genetic resources, which conflicts with this measure as well.
Potential magnitude of technical measure: At present it is difficult to estimate this with any reliability. The major areas of application are existing plantation forests with pine or Eucalypt species.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure: Subsidies on purchasing certified propagation material.

2.3.3 Drainage

Description: In very wet soils, forest production is limited by the high ground water table. Drainage can lower the water table, leading to a higher production. This measure could also include measures to restore or maintain current drainage systems.
Main potential: The potential would be to increase the productivity of the forest, leading to an increased carbon sink in the biomass.
Technical feasibility: Technically feasible, applied in various regions, in peatland in the boreal zone, but also on other wet soils in other regions.
Implication for GHG mitigation / biodiversity: Increased productivity would be beneficial for the carbon sink in the biomass. However, drainage of forest soils, and specifically of organic soils like peatlands, may lead to substantial carbon loss from the soil due to enhanced respiration (e.g., Harden et al. 2000, Ikkonen et al. 2001). It is still unclear if this effect will offset the increased biomass uptake. Also, peat stores carbon for much longer timeframes than aboveground biomass. Apart from that, drainage means a disturbance of the natural situation, with imposed change of species composition of ground vegetation and negative consequences for biodiversity. Due to the recognized importance of peat, it is recommended that GHG inventories treat mineral and organic soils separately (IPCC 2004).

Revenues and costs (real as well as opportunity): Drainage of peatlands has been common practice (at least in the Scandinavian region), and can be probably cost effective if only timber production is regarded. Extra revenues from carbon would increase the profitability, but only if carbon in the soil is not affected. Main costs are for construction and maintenance which must be done regularly, but is less cost intensive.
Constraints (Social, institutional, environmental etc.): Drainage in general might conflict with the water protection function of the forest. E.g., in the Netherlands, the recent trend has been to raise the ground water table of forests restoring it to the older status. Ground water table declined due to extensive water extraction for drinking water and for use in agriculture. Due to the concerns of carbon loss from peatlands, peatland drainage is not to be supported by local environmental policies, which concerns mostly the Northern European countries.
Potential magnitude of technical measure: Unlikely to be applied on substantial areas
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure: Subsidy on construction and maintenance of drainage systems in forest.

2.3.4 Irrigation

Description: Part of the production in Europe's forest is limited by water availability. This is especially valid in the Mediterranean region, but at least partly also for the temperate zone of Europe. Irrigation is the artificial application of water during the growing season. This can be done either by pumping up groundwater or through the distribution of surface water. Surface water could be extracted from rivers or lakes, or from reservoirs that store rainwater. Another water source could be water from wastewater plants.
Main potential: The potential would be to increase the productivity of the forest, leading to an increased carbon sink.
Technical feasibility: Applied widely in agriculture and fast growing plantations (mainly Eucalypt in Spain and Portugal).
Implication for GHG mitigation / biodiversity: Increased productivity, leading to an increased carbon sink in the biomass. However, irrigation will probably be applied mostly to short rotation crops, so the effects on average biomass stocks will be low. Effects on soil are less obvious. Increased productivity could mean higher litterfall, which leads to higher soil and litter carbon stocks. On the other hand, increased water availability could lead to increased decomposition as well.
Effects on biodiversity are unclear, too. Irrigated plantations are likely to be managed intensively with negative impacts to biodiversity. On the other hand, the presence of trees in an otherwise probably open landscape could provide fauna shelter and nesting habitat.
Revenues and costs (real as well as opportunity): Investments costs are probably rather high. Intensive irrigation is currently only applied in crops with short rotations, with highly productive species. Discounted costs over longer rotations will probably be very high.
Constraints (Social, institutional, environmental etc.): The total amount of available water in the Mediterranean area is limited. Highly productive Eucalypt plantations are known to consume huge amounts of water, since they are not very water-efficient.

Irrigation water needs to be extracted from deep soil layers or from the surrounding area. In case of water shortage, public opinion will likely favour using water for drinking and food crops over biomass production.
Potential magnitude of technical measure: This measure would probably primarily be beneficial for the establishment of new plantations, or the conversion of existing extensively used forest to short rotation plantations. The potential magnitude is likely more limited by water availability rather than by land availability. This measure would be applicable especially in the Mediterranean area.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure: Subsidies on establishment of irrigated plantations.

2.3.5 Changing rotation lengths

Description: Large parts of the European forest are still managed in the traditional way using clear-cut and establishing even-aged, often monospecies stands. The time between regeneration and final harvest is called the rotation length. Increasing this rotation length would on average lead to a higher amount of biomass at the site, and thus to a larger carbon stock. However, growth at higher ages is generally smaller, so the actual carbon sink strength will decrease.
Main potential: GHG mitigation through increased carbon stocks.
Technical feasibility: No technical measures needed.
Implication for GHG mitigation / biodiversity: This measure will lead to a longer retention of carbon in the living biomass. However, the size of the annual carbon sink in the biomass will decrease, and there will be some repercussions on soil carbon (Kaipainen et al. 2004, Liski et al. 2001). Liski et al (2001) (Figure 9) in a modelling study looked at the effect of rotation length on all C pools. Generally, a rotation shortening led to increased soil C, because of logging slash being added to the soil at faster intervals.

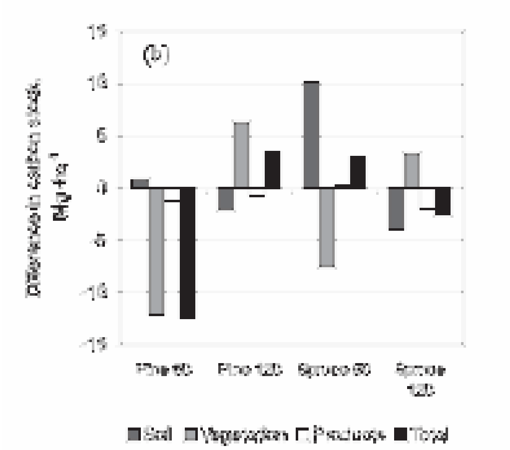

Figure 9: Difference in carbon stocks in soil, vegetation, and products compared to a 90 year rotation of the same species (Liski et al. 2001).

For biodiversity this measure will most likely be positive. Longer rotations will lead to trees with larger diameters, which is known to be positive for several bird and insect species. These trees are more likely to have holes for nesting and shelter and they provide stratum for mosses to grow on. Both the amount of deadwood in the forest as well as its size is likely to increase. This measure could also lead to a more diverse forest structure, which is beneficial for biodiversity as well (Larsson 2001). The general trend towards more close-to-nature forestry also propagates longer rotation lengths.
Revenues and costs (real as well as opportunity): Main costs associated with this measure are delayed revenues. Current rotation lengths are at least partly based on economic criteria and an increase will thus lead to less profitability. Harvesting costs will be somewhat different for larger trees. Longer rotations also mean a higher risk of quality loss and higher risks of unfavourable events, such as fire or windthrow.
Constraints (Social, institutional, environmental etc.): In some parts of Europe, rotation length is limited by natural factors, as for example windthrow in Sitka spruce plantations on peatlands in the UK and Ireland. Increasing rotation lengths in such situations is either impossible or involves very high risks. Furthermore, increased rotation lengths will lead to larger trees. The current woodworking industries are probably not capable of handling large amounts of much larger diameters.
In many tree species, longer rotations will lead to (for forest owners) unacceptable risks of quality losses. Although the physical rotation of beech could be much higher, risks of red heartwood formation limits it to about 120 years (Knoke 2003). Presence of this phenomenon will decrease the quality of the wood from excellent veneer quality to simple construction wood or less. Further, there is a risk that extending rotation lengths in one part of the forest (or region or Europe) leads to an increased harvest in other parts, since the same amount of wood is needed.
Potential magnitude of technical measure: The potential magnitude differs within Europe, depending on the tree species, current harvesting practices and intensity and current age class distribution.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.6 Changes in timing and intensity of thinnings

Description: During the rotation of a forest stand, usually several thinnings are carried out. A thinning is a reduction in the amount of trees per hectare. The aim of these thinnings is to increase the quality of the stand by removing the low quality trees, to concentrate the increment on fewer, carefully selected trees and to get early revenues. Thinnings reduce the amount of biomass in the stand, but could also stimulate the increment and thus carbon sink strength. Moreover, it provides extra litter input to the soil. Modern thinning schedules are strongly driven by economic considerations. First thinnings are often delayed to obtain larger revenues from the operation (cf. 4.2 pre-commercial thinnings). This leads to very dense overstocked forests which are not optimal for the C sink strength. Commercial thinnings are nowadays often done intensely with longer thinning intervals to obtain larger thinning volumes and to make the thinning more cost efficient. This leads to understocked stands which are not able to fully utilize the C sequestration potential. Optimum thinning strategies for C sequestration would aim to maintain a certain basal area in the forest which

maximizes volume production. This requires more frequent, but less intensive thinning interventions.
Main potential: GHG mitigation
Technical feasibility: No extra technical measures needed.
Implication for GHG mitigation / biodiversity: Changing timing and intensity of thinning provides the opportunity to influence stocks and fluxes in the forest system. Less thinnings will lead to higher carbon stocks in the biomass, but probably to lower net sinks due to decreased productivity or increased mortality in the dense stands. Associated changes in soil carbon are very subtle. Overall we can state that soil C impacts of changes in management are very small, hard to detect, rather uncertain, and depend very much on the initial state.
The implications for biodiversity are not easy to estimate, since it will depend on the situation before and the actual changes. Less thinnings or less intense thinnings would mean less human disturbance, which is more natural. However, some degree of disturbance is beneficial for biodiversity, since it will lead to the mobilisation of resources and create niches and habitats. Many plants that are associated with old forests are dependent on forest management. The dispersal mechanisms of some species have been linked to human activities (Bijlsma et al. 2001). Others decreased in abundance after management activities stopped because the tree canopies became too dense (Bijlsma et al. 2001).
Revenues and costs (real as well as opportunity): In most cases, C optimum management would cost more than the current practices, because of an earlier start of the thinning schedule and more frequent thinnings with low extracted volumes.
Constraints (Social, institutional, environmental etc.): Forest management aims at multiple goals. Carbon-optimal thinning regimes may conflict with other aims of the forest.
Potential magnitude of technical measure: Effects per hectare may be quite small, but the area under active management in Europe is fairly large.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.7 Continuous cover forestry/ selective logging

Description: Traditionally, large parts of the European forest have been managed using clear-cuts and planting. This created even-aged stands, often consisting of single tree species. Several alternatives exist, whereby trees can be mixed both in species and in age. Regeneration can be done gradually, either in a fixed period of several (tens of) years (shelterwood systems), or continuously in different parts of the forest (selective felling systems). A continuous presence of forest cover leads to less fluctuation of the carbon stocks and fluxes at the site, and probably to a higher average stock present at the site.
Main potential: Both GHG mitigation and biodiversity.
Technical feasibility: Similar systems are practiced and investigated in different parts of Europe. However, such systems are usually more complicated and demand more insight and knowledge of the foresters.
Implication for GHG mitigation / biodiversity: A continuous presence of forest cover leads to less fluctuation of the carbon stocks and fluxes at the site, and probably to a higher average stock present at the site. The micro-climate at the soil will fluctuate less, due to more constant shading. These systems lead to more diversity in forest

structure and are believed to better resemble the natural situation. Therefore, effects on biodiversity are believed to be positive (Larsson 2001).
Revenues and costs (real as well as opportunity): Costs and revenues are unclear. Even-aged systems can be managed more efficiently, but uneven-aged systems can take advantage of natural processes. Moreover, continuous cover systems might be less susceptible to natural disturbances, or can at least react more quickly to disturbances. More research is needed
Constraints (Social, institutional, environmental etc.): These systems are less easy to manage by foresters. Interactions between tree species are much more complex and reactions of (combinations of) species might differ per site type. In most parts of Europe, the area under such a kind of management is very small, and practical experience is therefore limited.
Potential magnitude of technical measure: The effect on a per hectare basis is largely unknown, and will probably vary with local site conditions and species combinations. The area where it could be applied is large, since most European forests are managed in an evenaged way (Nabuurs et al. 2003).
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies: A current trend in forestry is a more close-to-nature way of management. This trend coincides with this measure and will thus not be difficult to implement.
Possible political measure to support this technical measure:

2.3.8 Changes in tree species

Description: The choice of tree species influences the carbon cycle of a forest stand in various ways. Species differ in productivity, maximum attainable biomass stocks, associated management regimes, litterfall rates and litter quality. Changing the tree species composition could thus lead to changes in stocks and sinks, both in the biomass as well as in the soil compartment.
Main potential: GHG mitigation
Technical feasibility: Changing tree species is technically feasible.
Implication for GHG mitigation / biodiversity: Increased productivity could lead to higher sinks. A change to species with longer rotations could lead to higher average stocks, at least in biomass terms but probably also in the soil. Figure 10 shows carbon stocks of different forest types in Europe. Although these types grow on different soil types under different climatic conditions, it gives an indication as to what changes in species could do.

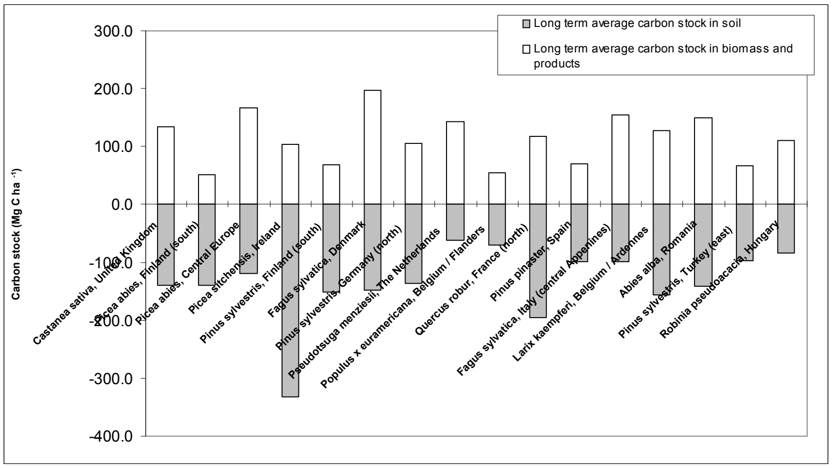

Figure 10. The long term average carbon stock in soil (below x-axis) and biomass and products (above x-axis) of 16 forest types throughout Europe. The negative sign for the stocks in soil was only used to display the soil stock below the x axis (Nabuurs and Schelhaas 2002).

In general, a change from introduced to indigenous species will be favourable for biodiversity, since indigenous species usually host specific organisms. Each tree species will have its own associated biodiversity, so changing from one species to another might lead to changes in biodiversity as well. If the same species has been growing at the site for a very long time, biodiversity might have adapted to this situation, so a species change will lead to a loss of biodiversity. In this case, a high sink strength would often conflict with biodiversity goals, especially when indigenous species are replaced with exotic species.

Revenues and costs (real as well as opportunity): To a large extent, revenues and costs will depend on the situation.

Constraints (Social, institutional, environmental etc.): A general trend in Europe is a shift from introduced to indigenous species. Introduced species are usually more productive, but have disadvantages regarding stability and biodiversity. It is not very likely that this trend could be reversed, if desired. The most appropriate point within a rotation to change tree species is when the stand is mature and will be harvested and regenerated. Earlier conversion leads to large economical losses because the harvested wood will have too small diameters to be sold on the market, or will yield much less than when the original dimensions would have been reached. This will limit the annual potential area, and at the same time make the process span over a long timeframe. Another option is planting the new species under the canopy of the existing forest. However, not all species can be handled in this way, and some kind of management needs to be applied to the existing forest.

Potential magnitude of technical measure: The potential area of application is the whole European forest area. However, tree species change will be feasible only on a certain fraction, depending on which tree species can be grown, protection status of the forest, productivity of different species, risks involved, etcetera. Quantification will be very difficult.

Monitoring and control parameter (direct and indirect): Coverage of different tree species.

Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.9 Protection of forests with high biomass carbon stocks

Description: Harvest of forest stands with a high amount of biomass will lead to a decrease in carbon stock in living biomass. Part of this biomass will be harvested and used for products; the rest will stay at the site and decompose. Not harvesting these stands would avoid a decrease in carbon stock in living biomass in these stands.
Main potential: GHG mitigation.
Technical feasibility: No technical measures needed.
Implication for GHG mitigation / biodiversity: Avoidance of decrease in biomass stocks, at least temporarily. In the longer term, stocks will probably decrease anyhow due to natural reasons (age-related mortality, natural disturbances). This measure might have implications for the soil carbon at the site, since fewer harvest residues are added to the litter layer. Moreover, leakage occurs as other stands will be harvested instead. If the products that would have been made from the harvested wood are made of other materials instead, the balance might even be negative. This might happen because other materials are generally more energy-intensive in production. Effects for biodiversity are probably positive, since the stands will not be harvested, and thus they can develop in a natural way (Larsson 2001). However, some degree of disturbance is thought to be positive for biodiversity, since it will create more diversity in forest structure, creating different habitats and niches.
Revenues and costs (real as well as opportunity): No direct costs are involved, only indirect costs in the form of lost revenues. These could be very large; the amount will depend on the species, quantity and quality of the wood available at the site.
Constraints (Social, institutional, environmental etc.): Some forest owners are probably not willing to leave high-quality wood in the forest until the trees die naturally. On the other hand, this measure is consistent with the current trend towards an increased awareness of the nature function of the forest.
In the longer term, the biomass will decrease again due to natural causes, such as age related mortality or disturbances. Per forest type and tree species the maximum attainable biomass and the period this amount can be sustained will differ significantly. Therefore, this measure will only work for a limited period of time, after which the stand will turn into a source. This uncertain behaviour will complicate the assessment and planning of this option.
Potential magnitude of technical measure: Currently the European forest is relatively young, and the increment rate is higher than the harvest. This has led to increasing growing stocks over the last decades. This trend is thought to continue for at least several decades (Schelhaas et al. in press, Nabuurs et al. 2003). The currently existing difference in many countries between increment and drain could be used to protect high biomass stands and to shift the harvest to younger age classes. However, it is not clear if this shift will increase the overall carbon stock.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.10 Minimising site preparation

Description: During the regeneration process forest soils are often disturbed in one way or another to prepare the site for seeding or planting. This can be done with many different techniques such as patch or row scarification, ploughing, disking or shearing. Minimising such preparation minimises the disturbance of the soil, and thus results in less soil carbon losses. A review of the effects of site preparation showed a net loss of soil C (Johnson, 1992). Several studies that compared different site preparation methods found that the loss of soil C increased with the intensity of the soil disturbance (Schmidt *et al.*, 1996, Mallik & Hu, 1997). At scarified sites, organic matter in logging residues and humus, mixed with- or buried beneath the mineral soil, decomposes more rapidly than on undisturbed soil surfaces of clear-cut areas. The soil moisture status of a site has great importance for the response to soil scarification. The increase in decomposition was more pronounced at poor, coarsely textured dry sites than on richer, fresh to wet sites (Johansson, 1994). Sandy soils are particularly sensitive to management practices, which result in significant losses of C and N (Carlyle, 1993). Intensive site preparation methods might result in increased nutrient losses and decreased long-term productivity (Lundmark, 1988). However, site preparation may also increase productivity and this effect may balance or even outweigh the loss of soil C in the total ecosystem response. The chosen technique of site preparation is important and will determine if the net C effect of the activity is positive or negative.
Main potential: GHG mitigation
Technical feasibility: Techniques which expose the mineral soil to less intensive soil disturbance exist. Moreover, nature-oriented silvicultural systems with natural regeneration require no, or only minimal, site preparation.
Implication for GHG mitigation / biodiversity: Reduction of carbon emissions from decomposing soil organic matter. Less disturbance of the soil favours existing plant species. However, soil disturbance also provides opportunities for new (pioneer) species.
Revenues and costs (real as well as opportunity): Choosing site preparation techniques with less soil disturbance creates no additional costs. If the silvicultural management system is changed, the whole cost structure of management operations changes. The economic consequences are difficult to assess.
Constraints (Social, institutional, environmental etc.):
Reduced soil disturbance has positive side effects on nutrient balances and water quality because nutrient leaching will be reduced.
Potential magnitude of technical measure: The application of site preparation has already been improved as a consequence of more environmental concerns in forest management, and the increase of nature-oriented forest management systems have reduced the need for site preparation. Because of the different impacts of alternative techniques and the site dependent impacts it is very difficult to assess on a larger scale the extent to which current practices can still be improved.
Monitoring and control parameter (direct and indirect): soil carbon monitoring is very difficult to implement because of large spatial variability and because there is not a well established methodology to assess stock changes in various soil types.
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.11 Decrease of (impact of) fires

Forest fires do not only release stored carbon to the atmosphere in the form of CO_2, they also produce other important greenhouse gasses, like CO and NO_x (Hoelzemann et al. 2004). Hoelzemann et al. estimate the emissions of NO_x for the year 2000 from Western Europe at 0.017 Tg (expressed as NO) and CO emissions at 0.49 Tg. Western Europe here includes those Mediterranean countries that dominate Europe's fire statistics: Spain, Portugal, Italy, Greece and France (see also Table 1). Barbosa et al. (submitted manuscript, cited in Hoelzemann et al. 2004) estimate emissions from these countries at 0.024 Tg and 0.46 Tg respectively. Schelhaas et al. (2003) estimate the annual damaged wood volume by forest fire at 4.9 million m^3 over the period 1950-2000. However, only a fraction of this volume will be totally burned, in most cases this wood volume will just die. However, the associated (smaller) branches, foliage and forest floor litter will be burned as well. Table 1 gives an overview of the annual burned areas in forest and forest and other wooded land throughout Europe (Schelhaas et al. 2001).

Fire suppression has different influences on the carbon cycle. First of all, prevention of fires means prevention of loss of carbon that is stored in the vegetation and the soil. Secondly, fire suppression could lead to increased carbon stocks, since the forest is allowed to reach older ages and thus to accumulate more carbon (Tilman et al. 2000). Moreover, fires lead to a net loss of nutrients in the system, which could slow down carbon accumulation afterwards (Rovira et al. 2004). Furthermore, changes in the fire regime will also affect the species composition of the forest, which in turn might influence carbon accumulation rates and maximum attainable stocks. For example, shrublands in the Mediterranean region are thought to be maintained by wildfires at 20-50 year intervals (Trabaud, 1991). If fires do not occur, these shrublands will convert to forest land in time.

Tilman et al. (2000) studied the effect of fire suppression on an oak savannah in Minnesota. They found an average carbon sink of 1.8 Mg ha^{-1} yr^{-1} over a 35-year period in unburned plots compared to periodically (annual or biannual) burned plots. This increase was mainly attributed to increased carbon stocks in woody vegetation and litter; effects on soil were not significant.

A possible negative effect of fire suppression is that fuel accumulates, and that the fire risk might increase. This accumulation might lead to very large, destructive fires that are difficult to manage. An effective fire strategy should therefore be not only to detect and fight fires at an early stage, but also to manage the forest in such a way that it is less susceptible to fires. Possible management measures aimed at reducing fire susceptibility are to reduce fuel loads (mainly litter and ground vegetation) by regular controlled burning or harvesting, keeping a forest structure that hinders the spread of fire, and by encouraging tree species that burn less easily. At the landscape level, the creation and maintenance of fire breaks might be an effective option, perhaps combined with a more effective fire detection and fighting system. Another important measure, but outside the scope of this project, might be to reduce the amount of ignitions; most fires are caused by humans, both intentional as well as by accident.

Table 1. Average annual fire area on the categories forest land and forest and other wooded land over the period 1991-2000 (source: DFDE database, Schelhaas et al. 2001). Data on total forest area and other wooded land from TBFRA 2000.

	Average annual forest fire area (ha)	Forest land area (1000 ha)	% of forest land (%)	Average annual fire area on forest and other wooded land (ha)	Forest and other wooded land area (1000 ha)	% of forest and other wooded land (%)
Spain	62348	13509	0.46	155695	25984	0.60
Portugal	43932	3383	1.30	104062	3467	3.00
Italy	43293	9857	0.44	93331	10842	0.86
Greece	26692	3359	0.79	59387	6513	0.91
Poland	11185	8942	0.13	10635	8942	0.12
France	3925	15156	0.03	17405	16989	0.10
Sweden	1926	27264	0.01	2482	30259	0.01
Germany	1240	10740	0.01	1240	10740	0.01
Finland	744	21883	0.00	833	22768	0.00
Czech Republic	713	2630	0.03	1108	2630	0.04
Latvia	620	2884	0.02	1605	2995	0.05
Cyprus	376	117	0.32	629	280	0.22
United Kingdom	343	2469	0.01	344	2489	0.01
Slovenia	335	1099	0.03	610	1166	0.05
Lithuania	254	1978	0.01	241	2050	0.01
Estonia	241	2016	0.01	503	2162	0.02
Ireland	189	591	0.03	513	591	0.09
Belgium	98	646	0.02	203	672	0.03
Slovakia	94	2016	0.00	210	2031	0.01
Austria	64	3840	0.00	65	3924	0.00
Netherlands	34	339	0.01	224	339	0.07
Denmark	15	445	0.00	59	538	0.01
Luxembourg	3	86	0.00	3	89	0.00
Hungary		1811	0.00		1811	0.00
Malta		0.347	0.00		0.347	0.00
Total	198664	137060	0.14	451386	160271	0.28

2.3.11.1 Decreasing fuel loads by prescribed burning

Description: One of the determining factors for forest fire risk is the fuel load. The more fuel present at the site, the higher the risk for (uncontrollable) fires. One way of decreasing the amount of fuel on the ground is by prescribed burning. In prescribed burning, the ground vegetation and litter on the ground is burned regularly in low-intensity fires under controlled circumstances. These fires will remove large parts of the fuel load, without killing the canopy trees. The application of prescribed burning will not lead to fire exclusion, but will reduce the intensity of a wildfire, and thus greatly enhance the fire fighting possibilities. A permanent reduction of the fine fuel load to levels below 5 t/ha will guarantee control by ground forces at very high fire

danger levels, while a fuel load of 9 t/ha will still allow wildfire control by aerial fire-fighting (Botelho et al. 2000).
Main potential: GHG mitigation through reduced fire risk
Technical feasibility: Prescribed burning has been used in many places in Europe in the past, and is commonly used in the US. However, prescribed burning is not widely applied in Europe at the moment and practical guidelines are lacking (Fernandes and Botelho, 2003).
Implication for GHG mitigation / biodiversity: A direct effect of prescribed burning is the emission of carbon sequestered in litter and ground vegetation, which is contradictory to the aim of GHG mitigation. Also the litter input to the soil might decrease by these burns. However, the risk for very intense fires is reduced, and thus the carbon stored in the remaining canopy trees is better protected. Effects on biodiversity are difficult to determine. Some fire-dependent species might benefit, others might be killed by the fires or may not be able to colonise the site. Large areas treated with prescribed burning might lead to unification and less biodiversity, but burning only certain patches might increase biodiversity by creating more habitats and a diverse landscape. Fire may also negatively affect individual animals. For example, slow moving animals may not be able to escape even low intensity fire fronts. Although ground nests may be lost in certain seasons, adult birds usually re-nest and benefit from the abundance of insects that follow a fire. Small animals that find cover in burrows or under logs, plants, or stumps may be much easier prey for predators, who truly benefit from fires (http://edis.ifas.ufl.edu/FR061).
Revenues and costs (real as well as opportunity): Revenues are difficult to assess, since there are no direct revenues. There are indirect revenues in the form of a larger chance that the trees will reach commercial proportions. Direct costs are planning costs and the costs of the crew to control the fire. Probably a rather large crew is needed to control a fire. Indirect costs might be the loss of a few trees and a loss of nutrients on the site.
According to Fernandes and Botelho (2004), prescribed burning is done in Northern Portugal by crews of 4-10 persons equipped with hand tools and led by a technical supervisor. The average burn is accomplished at a rate of 0.52 ha h^{-1}, which is two to five times faster than mechanical and chemical fuel management methods. Mean values vary from 0.12 – 1.03 ha h^{-1}.
Minimizing escapes is an important constraint which contributes to increase overall cost of the prescribed burning programme (González-Cabán 1997, cited in Baeza et al., 2002).
Constraints (Social, institutional, environmental etc.): (http://edis.ifas.ufl.edu/FR061)
Although the benefits of prescribed burning are clear, there are also notable concerns. Two of the most important are the possibilities of fire spreading to adjacent properties and smoke intrusions in populated areas. Good management can reduce these concerns, like limiting application to certain weather and fuel situations.
These restrictions may limit the opportunities to burn to just a few days each year. Given these limitations, many forest landowners do not have the staff or capability to burn all their land.
Another concern with prescribed burning, especially in plantations grown for timber production, is the potential for mortality or growth loss in trees. Even with older longleaf pines, long-term studies have demonstrated that repeated fires will reduce stand volume. The reductions are the result of individual trees killed by fires as well as productivity and growth losses due to needle scorch.

The spatial pattern of fire application is critical to reduce fire risk at the landscape level significantly (Fernandes and Botelho, 2003). This would involve a planning strategy at a higher level than the individual owner.
Potential magnitude of technical measure: Fire-prone areas, like Mediterranean area and Poland. According to Fernandes and Botelho (2003), best results are likely to be attained in climates where the likelihood of extreme weather conditions is low. This might not be the case in large areas in the Mediterranean basin.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies: Prescribed burning is not allowed in Greece and most of Italy (Botelho et al. 2000)
Possible political measure to support this technical measure:

2.3.11.2 Decreasing fuel loads by management activities

Description: Management can reduce fuel load or fuel structure in different ways, like cutting understory vegetation and leaving it on the site or removing it, chipping the understory vegetation, or the application of herbicides. In the short term, those options where the fuel is removed from the site are especially effective (Fernandes et al. 2000).
Main potential: GHG mitigation
Technical feasibility: This measure could be carried out manually or by machine. Manually would be very elaborate, but technically feasible. No special machines are designed for this task, but normal forest tractors and hand equipment will be sufficient. However, the chance to damage remaining trees is high, as well as the chances for soil damage (compaction).
Implication for GHG mitigation / biodiversity: Carbon stocks in litter and probably soils will be lowered, but the risk for intense fires is reduced, and thus the risk for loss of biomass carbon. This measure could be optimised by using the removed material for bioenergy production. Implications for biodiversity will depend on the species. It will be beneficial for pioneer species and others that need mineral ground for germination. If the removal cycle is shorter than the regeneration cycle of plant species, those species will disappear. This measure could also lead to smaller amounts of deadwood in the forest. However, of most importance in preventing fires is the removal of easily flammable material; logs will not burn too easily.
Revenues and costs (real as well as opportunity): Costs will be very high if the work is done manually. Even if carried out by machine, costs will probably be relatively high and recurring regularly. Indirect costs might be a loss of productivity due to removal of nutrients. Revenues are mainly indirect from reduced risks. Additional revenues could be created by using the removed material for bioenergy. Another indirect revenue (not at the owner level) would be an increase in labour opportunities in rural areas.
Constraints (Social, institutional, environmental etc.): This measure is very labour-intensive and thus costly. Application over large areas therefore seems to be unfeasible. However, this measure could be applied to certain carefully selected areas to create barriers, so forest fires will spread less easily. However, to make such an approach work, an integral planning for the whole area needs to be made, and all concerned landowners need to co-operate. Another opportunity could be to apply this measure close to settlements as additional fire protection. Another constraint for large-scale application might be concerns about the removal of nutrients out of the ecosystem.

Effects of treatment are short, so they need to be repeated on a very regular basis (2-4 years) (Fernandes and Botelho, 2003).
Potential magnitude of technical measure: Fire-prone areas, like Mediterranean area and Poland.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.11.3 Decreasing fire risk by adapting forest structure through management

Description: Not only the fuel load (quantity) is important in fire risk, but also the horizontal and vertical distribution of the fuel. The presence of a shrub layer might cause ground fires to evolve in crown fires. Fire might spread more easily in dense stands than in very open stands. Thinning the tree layer will influence the occurrence of ground and shrub vegetation, and influences the fuel structure of the canopy. Increased thinning might lead to more ground and shrub vegetation, which might increase fire risk again. Therefore this measure should include both thinning and shrub removal.
Main potential: GHG mitigation through reduced emissions
Technical feasibility: Thinning is a regular forest operation.
Implication for GHG mitigation / biodiversity: Thinning will lower the carbon stocks in the trees, but soil carbon might be enhanced through increased slash input. However, the influence of thinning on the carbon budget is in general limited. The main advantage of this measure is a reduced risk for loss of carbon stocks. This measure could be optimised by using the thinned trees and shrub material for bioenergy production, which would reduce the fire risk further. This measure will involve a rather intensive management which might not be beneficial for biodiversity. However, pioneer species will be favoured, leading to a different species composition compared to less intensively managed stands. Biodiversity effects will also depend on the scale of the measure. Perhaps this measure could already be effective if applied only in certain areas, effectively creating a kind of fire breaks, thereby creating a patchier biodiversity structure.
Revenues and costs (real as well as opportunity): Thinning is a regular forest operation and will not be too costly, and there might be some revenues. Thinning intensities could be higher than usual to create sparse stands, leading to some more revenues. Some extra revenues might be created by removing biomass for bioenergy. Indirect costs might be a loss of productivity due to removal of nutrients. Revenues are mainly indirect from reduced risks.
Constraints (Social, institutional, environmental etc.): The effectiveness of this measure is not entirely clear. Although it is commonly assumed that thinning will influence fuel characteristics, Silva et al. (2000) could not show differences in fuel characteristics and expected fire behaviour several years after the application of different thinning intensities, including a no-thin treatment.
Potential magnitude of technical measure: Fire-prone areas, like Mediterranean area and Poland.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.11.4 Decreasing flammability by changing tree species

Description: Large parts of the Mediterranean area are covered by vegetation that is very prone to fires, mainly pine species. Conversion of such species to less fire-prone species would reduce the chance of forest fires. Using strips of less susceptible species along streets and surrounding urban areas may reduce unintentional human induced fires. Strips can also be planted along fire breaks to reduce the fire spread (cf. fire break section).
Main potential: GHG mitigation
Technical feasibility: No special technical measures are needed.
Implication for GHG mitigation / biodiversity: The advantage for GHG mitigation is a reduced risk of carbon loss in biomass and litter due to fire. The productivity of such species might be less than that of pine species, which could lead to a somewhat smaller sink strength.
For biodiversity this measure might be beneficial, provided that species are used that would have occurred naturally. The current widespread occurrence of pine is unnatural. This measure could be used to restore the original vegetation types, and probably their associated biodiversity as well.
Revenues and costs (real as well as opportunity): Main direct costs are the costs for preparation and planting a site. If conversion is done before the optimal or usual rotation age, indirect costs occur as lost revenues. If productive, commercial pine plantations are converted to less productive stands, the owner will have decreased revenues in future. Besides productivity, the quality and commercial value of the new tree species could be lower as well. However, not all pine forest is commercially used. On the other hand, the risk for loss of timber is reduced as well.
Constraints (Social, institutional, environmental etc.): Species conversion of large areas will take a long time. It would be most logical to do the conversion at the end of the rotation length. The minimum time frame would be the longest rotation length in use, provided that all area is converted. However, not enough planting material or seed might be available, especially if the new species were until now not commercially interesting. Moreover, not all owners are probably willing to convert their land. Large parts of these forests might be managed as unevenaged stands, in which case the conversion could probably be done gradually. However, it is not sure if the knowledge to do so is widely available. Another constraint might be the willingness of owners to manage their land. Part of the land is not managed at all because of the low productivity.
Potential magnitude of technical measure: All flammable species in the Mediterranean basin.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.11.5 Improved fire detection and fighting

Description: The earlier a fire is detected, the larger the chance that it can be put out before it grows too large. Various measures could be taken to increase the chance that a fire will be detected in time. Such measures could include more intensive patrolling (land and/or air), automatic remote sensing fire detection systems, watchtowers, etcetera. However, such measures will probably fall outside the CAP, since it is not focussed on land and land management. We will therefore not evaluate this measure further.

2.3.11.6 Increased fire prevention (creation and maintenance of fire breaks)

Description: By maintaining fire breaks in strategic places, fires can be prevented from spreading over large areas. Fire breaks consist of a strip of land without vegetation (ploughed regularly to prevent establishment of flammable vegetation) or with vegetation that does not burn easily and that is wide enough to prevent the fire from reaching the other side. Fire breaks often consist of low vegetation that is kept short by grazing or mowing. This could be combined with measures to reduce the flammability on both sides of the fire break, like reducing the amount of understory vegetation and litter. Another possibility is the use of tree species that do not burn easily, like most broadleaved tree species. It is also possible to apply agriculture to such open strips, provided that the crops are not easily flammable. Fire breaks must be carefully planned on a regional level, taking into account the local circumstances and topography. Fire breaks could be planned in such a way so that optimal use is made of already open areas, like fields, roads and power lines.
Main potential: GHG mitigation
Technical feasibility: No specific new technology needed.
Implication for GHG mitigation / biodiversity: The main implication for GHG mitigation is a reduction of fire risk and size in the whole region. The carbon stocks in litter and biomass will be better protected, so the risk for carbon emissions will be lower, and probably also the average stock of carbon per hectare could increase. For the specific area where the fire breaks are made, the carbon stocks will be lower, but on a large area the carbon stocks will be higher. The effect on biodiversity will depend on the species. For species that have a limited dispersal capacity, fire breaks could be strong barriers. A well-maintained network of fire breaks would then effectively create isolated patches in the landscape. For other species this measure might be favourable, like large grazers. The fire breaks with short vegetation will provide grazing areas, while the adjoining forest provides shelter.
Revenues and costs (real as well as opportunity): The exact planning of where to make fire breaks will involve input from many people, like the local government and fire experts, and thus might be costly. The actual creation of the fire breaks is an event that takes place only once, and consists of the removal of the tree and shrub vegetation, and probably seeding or planting the new vegetation. Further costs will be the regular maintenance of the fire breaks, like ploughing, removing the vegetation, pruning adjoining trees, removing shrub vegetation, etc. Some revenues could be created by selling the first removal of biomass, either as timber or for bioenergy (chips or fuelwood). Other revenues depend on the type of vegetation in the fire breaks. Agriculture could provide some revenues, as well as selling hay or selling grazing rights on the fire breaks.
Constraints (Social, institutional, environmental etc.): An integrated plan for the whole area needs to be made, and all concerned landowners need to co-operate.
Potential magnitude of technical measure: All areas with a regular high fire risk
Monitoring and control parameter (direct and indirect): Length of fire breaks, spatial structure of fuel/fuel maps derived from remote sensing; indirect: burned area per fire, total fire area
Support and constraints in existing policies:
Possible political measure to support this technical measure:

Besides the possible effects of fire reduction on GHG mitigation inside the forest, there is an important side-effect of these measures on the whole community. Decreases in the frequency and severity of fires also lead to a reduction of damage risk of houses, farms and human lives. The reduction of economic risks on a larger scale should be incorporated in the economic analysis of all these measures.

Many of these measures can be used to make areas less easy to burn. However, decreasing the fire risk on some randomly located areas will not contribute much to the overall reduction of fire risk. A regional approach could be much more effective, identifying strategic areas or zones where these measures are most effective. Creation of a network of fire breaks and other zones which are less flammable could lead to the division of the area in compartments, which would facilitate fire fighting and would reduce the risk of very large fires. Application of such a regional approach would call for an integration of the CAP with local, regional and national policies.

2.3.12 Increased stability against wind

Wind damage frequently occurs in Europe. Damage can be caused by small-scale events such as thunderstorms and small cyclones, but also by major storms. Wind damage is most frequent in the Atlantic zone, with strong gales occurring every 2-3 years in the UK and Ireland. In Central Europe, high windspeeds are recorded less regularly, but the effects can be disastrous. Over the period 1950-2000, Schelhaas et al. (2003) estimated an average annual damage by storms of 18.7 million m^3. The damage in individual years can be much higher; in 1999, more than 180 million m^3, equal to about half of the normal harvest in the whole of Europe. In individual countries, damage was as high as 5 times the annual harvest. The amount of storm damage seems to have been increasing over recent decades. Although climate change is often referred to as a possible cause, it seems more likely that the increase is linked to developments in the forest resources. Forest area and wood volume per hectare has increased markedly since 1950, and thus the resource that can be damaged. Moreover, the average age of the forest has increased, which is generally linked to an increase in the susceptibility of the forest.

Various characteristics of a forest stand are known to increase the chance of storm damage. Such factors include tree species choice (conifers versus broadleaves, mixed versus monocultures), stand structure (even-aged versus uneven-aged), recent (heavy) thinnings, recent new stand edges, average tree height, height/diameter ratio, limited rooting possibilities (high groundwater table, impenetrable soil layers) and stand history (site preparation and planting techniques, fertilisation).

The influence of storm damage on carbon sequestration in forest is mainly on the biomass and soil pool. Storm damage decreases the amount of live biomass and increases the amount of litter on the ground. Usually not all storm damaged wood is removed from the forest, so the increased amount of litter will last for a few years at least. However, it is not clear if this will really affect the soil organic matter pool. The removal of (a large part of) the standing trees will cause a temporary reduction in biomass sink capacity, but could in the longer term lead to an increase in sink strength because old, slow growing trees are replaced with young ones.

Description: The management of stands in areas with a high risk of high wind speeds could aim at increasing stand stability by optimising the factors that influence stand stability. In the UK, a system has been developed to estimate the wind risk of individual stands (Miller, 1985). It is recommended that stands in high wind risk areas are not thinned. Besides the rather safe no-thinning option there are a variety of management practices that are recommended in the literature. Many of those options involve a gradual reduction of stem number with stand age in order to keep the height/diameter ratio of the trees low. Other recommendations include mixing trees of different species and ages. However, recommendations on optimal thinning regimes differ very much between different literature sources, and possibly also with species and location. Furthermore, there is no conclusive evidence that mixed stands are really more windfirm.
Recently, GIS based tools have been developed to calculate risks for new forest edges as a consequence of the harvest of adjacent stands (Talkkari, 2000, Blennow and Sallnäs, 2004). This would yield possibilities to carefully plan harvest areas to minimise damage to surrounding stands.
Main potential: GHG mitigation by preventing carbon losses from biomass.
Technical feasibility: Many options do not require new techniques. Tree species management and thinning are part of the normal forest management.
Implication for GHG mitigation / biodiversity: The implication for GHG mitigation is a reduced risk of carbon losses through storm damage. The average carbon stock per hectare on larger areas could be increased because of the reduced risk. The implication for biodiversity will be slightly negative, since less deadwood will become available. Furthermore, uprooting trees creates micro-relief in the soil which is known to be favourable for biodiversity. Windthrow patches also increase the structure of the forest and, if not cleared, can provide shelter and nesting for species.
Revenues and costs (real as well as opportunity): A no-thin regime will have fewer revenues early in the rotation, and not thinning will also negatively influence wood quality in the end. However, longer rotations are possible, which could compensate the lost revenues through larger trees. Costs and revenues of other options (thinning regime, mixtures) are very difficult to access and depend on the situation.
Constraints (Social, institutional, environmental etc.): The no-thinning option for stands at high risks seems to be rather well established. However, literature is not clear about other proposed measures at the stand level (for example Lekes and Dandul 2000 and Mason 2002 versus Quine et al. 1995 concerning evenaged forests). Wind risk is highly dependent on local conditions (wind climate, topography, surrounding stands), so it is not easy to give general guidelines on the most optimal management.
Potential magnitude of technical measure: In principle, the forest area where a storm could occur is large, but in many areas the return time (risk) is so low that measures will hardly be effective. On the other hand, in high risk areas (like parts of the UK and Ireland) forestry has already adapted to the wind regime, simply because it is economic. Such measures might be most effective in areas with intermediate risk, but especially in this intermediate risk zone it is not exactly clear how measures could contribute to stand stability.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.13 Decrease of impact and occurrence of pests and diseases

The occurrence of pest and disease outbreaks depends on many factors, such as weather, suitable conditions/material for breeding and dispersion and low enemy populations. For example, outbreaks of the bark beetle *Ips typographus* L. are often connected to the occurrence of storm damage. The large quantities of dead wood provide excellent breeding conditions for this species. Although it is a secondary pest insect (killing only weak trees) it can attack and kill healthy trees if the population density is high enough. Outbreaks are further favoured by warm and dry summers. After some five to ten years population densities decrease again because enemy populations will build up and the amount of breeding material will decrease. Many other secondary insect pests are known to become dangerous if trees are weakened by stress, for example due to severe droughts. The cause of such stresses is difficult to manipulate, but measures can be taken to reduce the negative effects. For example in the case of *Ips typographus* L., a timely removal of windblown wood can prevent large-scale outbreaks. In general, a healthy and diverse forest will have more possibilities to react to stress and insect occurrence than less healthy and diverse forests. Important for timely measures is a good information and monitoring system, but the development of such a system would fall outside the CAP and is therefore not considered here.

2.3.13.1 Decreased vulnerability

Description: For many pests and diseases it is known which conditions are favourable. For example, planting of certain conifers on former arable land is known to give high risks for Armillaria infections. Management could take measures to avoid such possible dangerous combinations. However, there are many different species that could be dangerous, all with specific requirements on stand structure and climate. Furthermore, there is always the possibility that new species will appear, either due to natural dispersion under changed climatic conditions or due to (human) introduction from other continents. In general, management can aim at a diverse and healthy forest, which would be more resistant to outbreaks and diseases.
Main potential: both GHG mitigation and biodiversity.
Technical feasibility: Health and diversity are influenced by many factors, of which some cannot be easily influenced by the manager, such as (artificially managed) groundwater levels. Measures within the manager's reach are common practice, such as tree species choice.
Implication for GHG mitigation / biodiversity: The implication for GHG mitigation would be less fluctuations in sink, because of less variations in growth rate due to insect infestations and fewer compulsory fellings. However, it is known that insect infestations can lead to increased availability of resources, which could cause the productivity to increase temporarily. A more diverse and healthy forest would be beneficial for biodiversity as well.
Revenues and costs (real as well as opportunity): Revenues of this measure are indirect as reduced costs for (chemical) treatment or sanitary fellings. Direct costs are costs aimed at increasing tree species and structure diversity, such as creating gaps or planting groups of other tree species.

Constraints (Social, institutional, environmental etc.): It is difficult to define what a healthy forest is. We can only refer to more or less natural conditions, but a healthy forest is also vulnerable to insect outbreaks.
Potential magnitude of technical measure: Basically all forest area in Europe, but especially those areas were the actual tree species deviate from the natural ones and where current insect and disease damage is high. However, there is no complete overview on a European scale with the occurrence of biotic damages.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

2.3.13.2 Improved treatment

Description: If an outbreak of a certain insect pest or disease is feared or happening, the area could be treated in certain ways: Removal of infested trees, spraying of chemicals, trapping of individuals, or increasing the population of natural enemies.
Main potential: GHG mitigation
Technical feasibility: Measures against pests are rather commonly applied.
Implication for GHG mitigation / biodiversity: Outbreaks will be less severe, with less effect on the growth rate (sink strength) of the forest. The effects on biodiversity depend on the type of application. Chemical treatments will in general not be beneficial for biodiversity, whereas biological treatment will have less adverse effects. However, insects and diseases are part of the ecosystem, and suppressing them might contradict biodiversity aims.
Revenues and costs (real as well as opportunity): In many European countries, insects and pests are monitored and treated if dangerous levels are being reached. Increasing treatments might have a marginal effect; large costs for little revenues in terms of carbon.
Constraints (Social, institutional, environmental etc.): The use of chemicals is largely restricted in forestry, and it is not likely that they will be applied again at a large scale. Improved treatment will depend also on more intensive monitoring, which will be costly as well.
Potential magnitude of technical measure: It is unclear how much effect improved insect and disease treatment would have on current growth rates. Probably the effect is rather marginal.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

3 Aiming at forest products

One carbon pool associated with forestry is the wood products pool. Wood is used in many different ways and in applications with sometimes very long residence times. Several measures can influence the size of the wood products pool, such as improved efficiency of wood, increased use of wood compared to other materials, longer lifespans or improved recycling. However, all these measures fall outside the CAP and are not taken into account in this overview.

4 Aiming at bioenergy

4.1 Increased use of logging residues for bioenergy purposes

Description: Harvest residues include all biomass that is not removed from the site after commercial or non-commercial operations, mainly small trees, crown mass and stumps. Harvest residues offer a huge and so far largely unutilized potential. Even in Finland, which is the European leader in generation of power from biomass, less than 10% of the technical potential was used in recent years (Hakkila 2003). Extraction of residues can be quite effective if it is combined with the roundwood removal.

Main potential: GHG mitigation

Technical feasibility: Technologies exist: highly mobile chippers which work in the terrain (chipping at the source), or a combination of forwarder/skidder and chippers for chipping at the landing, or the biomass is transported (loose or in bundles) to the power plant and chipped on site.

Implication for GHG mitigation / biodiversity: Removing biomass will result in slower accumulation of soil organic matter due to the decreased litter input to the soil. However, felling residues make up only a minor part of the total litter input over a rotation period (8-20% in a spruce forest in southern Sweden, (Lundborg 1998)), and stump and roots would remain on the site in most cases. Overall effect is most likely positive if generated bioenergy is used to substitute fossil fuels. The effect on biodiversity is more unclear; harvest residue removals means less deadwood on the site, but in practice at least 30% of the aboveground residues are left for technical reasons, and conifer residues are not very valuable as a substrate for plants and animals (Lundborg 1998). Experience indicates that residue extraction has little negative impact on biodiversity (IEA Bioenergy 2002). Regeneration will be faster after residue extraction, and the cleared site might offer a habitat for a larger variety of plants in the short term. Residue extraction can also help to counteract negative effects of high nitrogen deposition, such as eutrophication, acidification and the release of toxic aluminium, because the removal of nitrogen is three times higher in whole-tree harvesting than with conventional stemwood removal. The return of wood ash can help to prevent deficiencies of mineral nutrients (except nitrogen).

Revenues and costs (real as well as opportunity): The main barrier is the high price for production of forest chips from residues (Hakkila 2003). However, current high energy prices will make the revenues more attractive.

Constraints (Social, institutional, environmental etc.): Risk of nutrient depletion especially on nutrient poor sites. Concentration of nutrients is highest in foliage and bark, so nutrient depletion can be decreased by leaving the residues on site for one season in the case of conifers, and by harvesting in the winter months in the case of deciduous trees. However, the cost of residue chips increases in that situation, due to reduced biomass recovery and logistical disadvantages resulting from the delay in harvesting schedule (Hakkila 2003). On the other hand, high quantities of needles

may cause combustion problems (i.e. corrosion in boiler due to high chlorine concentration). Nutrient depletion with whole tree harvesting would in most cases create the need for fertilization to avoid productivity declines.
Potential magnitude of technical measure: All European countries. See EEA study by Lindner et al. (in press).
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

4.2 Pre-commercial thinnings aimed at harvesting biomass for bioenergy

Description: (Precommercial) thinnings are often neglected because of the high costs and the lack of demand for small-sized trees. Repeated light thinnings in young stands would have favourable effects on the yield compared to untended stands with late thinnings (Richardson et al. 2002).
Main potential: GHG mitigation
Technical feasibility: Technology exists, e.g. bundlers for whole-tree harvesting of young trees in thinning operations.
Implication for GHG mitigation / biodiversity: Reduction of CO_2 emissions if generated bioenergy is used to substitute fossil fuels. Increased utilization of existing forests decreases biomass carbon stock in the short term. Effects on biodiversity are probably small. There is some removal of nutrients as well as (possible) dead biomass while the forest structure is not affected.
Revenues and costs (real as well as opportunity): Pre-commercial thinnings are by definition not economic, due to the low revenues (small trees) and high costs (many trees to harvest). Revenues from current wood prices are not enough to cover the costs. Increasing energy prices may increase the revenues (even current level will make many pre-commercial thinnings cost efficient, if also CO_2 emission credits are utilized for substitution of fossil fuels). Early thinnings have a beneficial effect in the longer term, because the remaining trees will grow better.
Constraints (Social, institutional, environmental etc.): Risk of nutrient depletion with whole tree harvest from thinnings, due to high concentrations of nutrients in foliage and twigs relative to total tree biomass. Nutrient depletion can be minimized by topping trees before bundling or chipping in the case of conifers, and by cutting deciduous trees during winter.
Potential magnitude of technical measure: The effect of this measure on the hectare scale will probably be rather small, but it can be applied to all Europe's managed forests.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:
Subsidies for precommercial thinning operations

4.3 Complementary fellings

Description: In many European countries, wood harvests are considerably below growth rates. Felling levels could be increased up to a maximum sustainable level, and the balance could be used to generate bioenergy.

Main potential: GHG mitigation
Technical feasibility: No adaptations needed.
Implication for GHG mitigation / biodiversity: Reduction of CO_2 emissions if generated bioenergy is used to substitute fossil fuels. Increased utilization of existing forests probably decreases carbon stock in the short term, but could increase carbon sink capacity over the long term as overall yield will most likely increase due to the higher share of young, productive stands. For biodiversity this measure will probably be (slightly) negative, due to a more intensive felling regime. Furthermore, the share of old forests will be reduced because the harvest level will be higher.
Revenues and costs (real as well as opportunity): Depends on bio-energy price. With high energy prices and utilization of CO2 emission credits, the revenue will be similar to pulp and paper wood. If wood quality is high, forest owners may want to market the wood at higher prices (e.g. as sawlogs). This would create substantial opportunity costs. However, the current wood demand is not high enough to take up more saw logs.
Constraints (Social, institutional, environmental etc.): Risk of nutrient depletion with intensified biomass removal. Lack of awareness, expertise and necessary technology amongst forestry industry in many countries
Potential magnitude of technical measure: All forest area where harvest is lower than current annual increment, which is the case in almost all Europe.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

4.4 Changing management system to pure bioenergy production

Description: Conversion of unmanaged/less productive forests to management systems that aim only at bioenergy production, such as short-rotation coppice. Management for pure bioenergy production would allow for shorter rotation lengths than in conventional forestry, i.e. soon after the period of highest productivity around canopy closure. It might also involve a tree species change to fast growing species.
Main potential: GHG mitigation
Technical feasibility:
Implication for GHG mitigation / biodiversity: If the initial standing stock of the forest is large, the conversion to a biomass production system can require several harvest cycles to balance the carbon lost during the removal of the initial carbon stock (Huston and Marland 2003). Conversion of close-to-natural existing forests to a biomass production system can have a net negative effect on biodiversity (Huston and Marland 2003), because in many cases, species rich and partly uneven-aged forests will be replaced by mono-specific even-aged stands. The effect on biodiversity will strongly depend on the species and management system applied. Many natural forests in Europe in the past have been managed for bioenergy and some of these systems e.g. coppice with standards can have high biodiversity values.
Revenues and costs (real as well as opportunity):
Constraints (Social, institutional, environmental etc.): A high rate of nutrients is removed in coppice systems due to the harvest of almost all above-ground biomass at frequent intervals, which might require compensatory fertilization in later rotations (Richardson et al. 2002). Such fertilisation requirements may compromise the overall

GHG balance of such systems as industrial fertiliser manufacture is energy intensive. Utilisation of wood ash may be a suitable alternative.
Potential magnitude of technical measure: Unknown
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

4.5 New short rotation plantations for bioenergy production

Description: Utilization of set-aside agricultural land for energy-crop plantations (e.g. with fast growing tree species as *Salix, Alnus, Populus, Eucalyptus*, etc.); these sites can also be used for waste water irrigation from municipal waste water treatment plants; certain species have the capabilities to bind heavy metals.
Main potential: GHG mitigation, biodiversity
Technical feasibility: Technology and harvesting schemes have been established over the last decade and are in use (e.g. Enköping, Sweden).
Implication for GHG mitigation / biodiversity: Energy crop plantations reduce CO_2 emissions if the generated energy is used to substitute fossil fuels. Soil carbon stocks probably increase compared to the former agricultural use. Woody energy crop plantations can offer shelter for wildlife in predominantly arable land, thus increasing biodiversity (Skärbäck and Becht 2005). Biofuel plantations of native species on formerly arable land have a higher animal biodiversity than the annual agricultural system they replace (Cook and Behea 2000). On the other hand, woody bioenergy plantations are intensively managed mono-species plantations, sometimes growing exotic species like Eucalyptus, which may not be very favourable for biodiversity. Furthermore, genetic engineering is often used to produce more productive clones; and gene flow between the crop and wild relatives may pose a risk to the native vegetation (James et al. 1998).
Revenues and costs (real as well as opportunity): Depends on bio-energy price. Opportunity costs form agriculture are rarely relevant as the land was not used anymore for agriculture.
Constraints (Social, institutional, environmental etc.): At low energy prices, biomass plantations require productive sites to be economically viable, which may result in a competition with traditional agricultural use (Huston and Marland 2003).
Potential magnitude of technical measure: Most bioenergy plantations will be established on agricultural set-aside lands. The potential magnitude of this measure will therefore depend on the availability of such lands, as well as on the development of energy prices and subsidies for biomass crops.
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure:

5 Other

5.1 Decrease fossil fuel energy use of forest machinery

Description: Forest machinery (chainsaws, harvesters, forwarders etcetera) could be designed to use less (fossil) fuel. Old, less efficient equipment could be replaced by new, more efficient equipment.
Main potential: GHG mitigation
Technical feasibility: New technology development needed, except for replacement of old equipment.
Implication for GHG mitigation / biodiversity: Fewer emissions due to more efficient fuel use, a more positive GHG balance for the produced wood or biomass.
Revenues and costs (real as well as opportunity):
Constraints (Social, institutional, environmental etc.): For cars, about 85% of the emissions are connected to the production, and only 15% are related to the use. Probably for machinery the same kind of figures are applicable. So early replacement of machinery could actually lead to higher total emissions.
Potential magnitude of technical measure:
Monitoring and control parameter (direct and indirect):
Support and constraints in existing policies:
Possible political measure to support this technical measure: Subsidies for replacement of energy inefficient machinery; subsidies on efficient machinery.

Ranking of measures

All of the previously mentioned measures can be judged according to various aspects, such as cost effectiveness, GHG potential, etcetera. We evaluated the measures according to the following criteria:

- GHG mitigation potential per ha
- potential area of application
- technical feasibility
- environmental added value
- cost effectiveness
- social acceptance
- state of technology knowledge
- robustness under changing climate
- biodiversity effects
- effect on other forest functions
- leakage risk (i.e. undesired carbon effects outside the area)
- short term effectiveness
- medium term effectiveness
- long term effectiveness

Each of the measures was given a score for each of the aspects mentioned above. Scores ranged from 0-5, where 0 would mean a "killing assumption" and 5 the best score. A "killing assumption" would mean a very negative impact on a certain aspect, overruling any other benefits. For all measures an average score over all aspects was calculated, which allows a ranking of the measures. For the aspect leakage, a 5 would mean no risk of leakage, while a 1 would mean a high leakage risk. Table 2 contains the scoring of the different measures for all aspects.

Table 2. Scores for all aspects for all measures.

		GHG mitigation potential per ha	potential area of application	technical feasibility	environmental added value	cost effectiveness	social acceptance	state of technology knowledge	robustness under changing climate	biodiversity effects	effect on other forest functions	leakage risk	short term effectiveness	medium term effectiveness	long term effectiveness	**Average**	**Rank**
2.2	**Article 3.3**																
2.2.1	Afforestation/ Reforestation	5	4	5	4	3	3	4	4	3	5	5	1	3	5	**3.86**	**3**
2.2.2	Avoiding deforestation	5	2	5	5	2	4	5	5	4	5	3	5	5	5	**4.29**	**1**
2.3	**Article 3.4**																
2.3.1	Application of fertilizer	3	4	5	2	2	2	4	3	1	2	1	2	3	3	**2.64**	**24**
2.3.2	Improving genetic quality	3	5	4	2	2	3	4	3	2	3	5	1	2	3	**3.00**	**22**

2.3.3	Drainage	4	3	4	1	2	3	5	3	1	3	5	2	3	3	**3.00**	**22**
2.3.4	Irrigation	4	2	4	1	1	1	4	4	1	2	3	2	3	3	**2.50**	**26**
2.3.5	Changing rotation lengths	4	5	5	4	3	4	5	4	5	5	3	2	4	3	**4.00**	**2**
2.3.6	Changes in timing and intensity of thinnings	3	5	5	3	3	4	4	4	3	4	3	3	3	2	**3.50**	**13**
2.3.7	Continuous cover forestry/ selective logging	3	4	4	4	4	4	3	4	4	4	4	3	4	2	**3.64**	**8**
2.3.8	Changes in tree species	3	4	4	3	3	4	4	3	3	3	5	2	4	3	**3.43**	**15**
2.3.9	Protection of forests with high biomass carbon stocks	5	3	4	4	3	5	4	3	5	4	3	4	3	2	**3.71**	**5**
2.3.10	Minimising site preparation	3	4	4	4	3	4	4	5	4	3	5	3	3	3	**3.71**	**5**
2.3.11.1	Decreasing fuel loads by prescribed burning	4	1	3	2	2	3	3	4	3	3	5	3	3	4	**3.07**	**21**
2.3.11.2	Decreasing fuel loads by management activities	4	2	4	3	3	4	4	4	3	4	5	3	3	4	**3.57**	**10**
2.3.11.3	Decreasing fire risk by adapting forest structure through management	4	2	4	3	3	4	3	4	3	3	5	3	3	4	**3.43**	**15**
2.3.11.4	Decreasing flammability by changing tree species	5	2	4	4	3	4	4	4	3	4	5	1	2	4	**3.50**	**13**
2.3.11.6	Increased fire prevention (creation and maintenance of fire breaks)	5	2	4	3	3	5	4	5	3	4	5	2	4	4	**3.79**	**4**
2.3.12.1	Increased stability to wind	2	3	3	4	2	4	3	4	4	3	5	2	3	3	**3.21**	**19**
2.3.12.2	Decreased vulnerability to wind	2	3	4	3	3	4	4	4	2	3	5	2	3	3	**3.21**	**19**
2.3.13.1	Decreased vulnerability for insects	2	3	3	4	2	5	3	4	4	4	5	2	3	3	**3.36**	**18**
2.3.13.2	Improved treatment of insects	2	2	4	1	1	2	4	3	2	3	5	2	3	3	**2.64**	**24**
4	**Aiming at bioenergy**																
4.1	Increased use of logging residues	2	5	4	2	3	3	4	5	2	3	5	3	5	5	**3.64**	**8**
4.2	Pre-commercial thinnings aimed at harvesting biomass for bioenergy	2	5	4	2	2	3	4	5	2	3	5	3	5	5	**3.57**	**10**
4.3	Complementary fellings	3	5	4	2	3	3	4	5	2	3	5	3	5	5	**3.71**	**5**
4.4	Changing management system to pure bioenergy production	4	2	4	1	3	3	4	5	2	2	5	3	5	5	**3.43**	**15**
4.5	New short rotation plantations for bioenergy production	5	2	4	1	3	3	4	4	2	3	5	4	5	5	**3.57**	**10**
5	**Other**																

5.1	Decrease fossil energy use of forest machinery	1	4	4	5	3	5	3	5	3	3	0	4	5	5

All measures that have a rank from 1 to 10 are selected as a potential measure to be included in the CAP. Because several measures have the same rank, a total of 12 measures are selected in this way. The selected measures and their rankings are shown in Table 3.

Table 3. Selected measures for the CAP

Measure	Average score	Rank
Avoiding deforestation	4.29	1
Changing rotation lengths	4.00	2
Afforestation/Reforestation	3.86	3
Increased fire prevention (creation and maintenance of fire breaks)	3.79	4
Protection of forests with high biomass carbon stocks	3.71	5
Minimising site preparation	3.71	5
Complementary fellings	3.71	5
Continuous cover forestry/ selective logging	3.64	8
Increased use of logging residues	3.64	8
Decreasing fuel loads by management activities	3.57	10
Pre-commercial thinnings aimed at harvesting biomass for bioenergy	3.57	10
New short rotation plantations for bioenergy production	3.57	10

Some measures are self-standing and straightforward, such as afforestation. Other measures are linked, or could be combined with others. For example the creation of fire breaks should partly be supported by management activities as mentioned under other measures, such as the use of prescribed fire. In the further detailing process of the selected measures, we might therefore include some measures that were initially not selected. In the further process within MEACAP, the selected measures will be more closely examined and quantified wherever possible.

The carbon cycle in forests is often characterised as ‘slow in, fast out’. Avoiding the ‘fast out’ would generally offer the best options for carbon management, since it will take a long time to recover the lost carbon (‘slow in’). This is reflected in many of the selected measures, such as avoiding deforestation, not harvesting stands with high carbon contents, increased fire prevention and minimising site preparation. Some measures are a kind of derivative to this and aim at creating higher average carbon stocks per hectare. A good example is afforestation: in grasslands, harvest takes place every year, resulting in no stock build-up. After afforestation, harvest will be postponed for many decades, allowing the stock to build up. Changing rotation lengths and conversion to continuous cover forestry are other examples, but their effectiveness will be lower, because the initial (or baseline) stock is much higher. Manipulating the ‘slow in’ process is also possible, but the manoeuvring space is generally limited, since there is a maximum to the production per hectare. This is reflected by the fact that the pure input-based measures have not been selected, such as fertilisation, improving genetic quality, drainage and irrigation. The last group of measures do not aim at maximising carbon storage in the forest, but aim at replacing fossil fuel by bioenergy. This is generally seen as a very effective option, since the effect of avoided emission will last forever, but stocks in the forest will eventually be released to the atmosphere again.

In general, the measures that are finally selected match well with measures that have been proposed earlier (Houghton 1996; Thornley and Cannell 2000). However, no study addressed, quantified and compared all possible options. Most studies concentrated on only one (Kaipainen et al. 2004; Liski et al. 2001; Tilman et al. 2000) or a few options (Chen et al. 2000), and others just listed some measures that might be of relevance (Houghton 1996).

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