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Hotspots of the European forests carbon cycle

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ABSTRACT

This paper is the outcome of a group discussion held at the Savonlinna meeting 'Management of forest ecosystems and its impact on the GHG budget'. The aim of this break-out group discussion was to 'Characterize forest management impacts on the GHG budget of forest ecosystems in different European regions'. In this paper we briefly characterize different options that a forest owner has in order to maintain or maximize forest carbon pools and carbon sequestration. These hectare scale descriptions of measures are then regarded in connection to the current state of European forests and how they can be combined with ongoing management trends and local issues. We point out the various possibilities that exist in European forests, where they are located, and where they could possibly be combined with adaptation. We identify these hotspots for largest growing stocks, largest peat areas, and, e.g. largest risks for loss of carbon due to fire or urban sprawl. We conclude that one common strategy cannot be designed. Within each region, local solutions have to be found that optimize goals and aim at integrated and sustainable land use.

1. Introduction

Forests are known to store large quantities of carbon, which was one of the reasons to include them into the Kyoto Protocol (UNFCCC, 1997). Forests can act as a carbon (C) source or sink, depending on the balance between uptake of carbon through photosynthesis and release of carbon through respiration, decomposition, fires, or removal by harvest activities. Both on a European as well as on a global scale, forests are generally estimated to have acted as sinks over the last decades (Nabuurs et al., 2003; IPCC, 2007). However, estimates for European forests still differ from a source of 100 Tg C year^{-1} to a sink of 460 Tg C year^{-1} (Lindner et al., 2004).

Management can influence the carbon balance in forests (Thornley and Cannell, 2000; Eggers et al., 2007). This is acknowledged in the Articles 3.3 and 3.4 of the Kyoto Protocol. Accounting of Article 3.3 (afforestation, reforestation, and deforestation) is mandatory, but under article 3.4, countries may choose to include management activities in existing forests to enhance the sink strength and account it within the emission reduction target during the first commitment period (2008–2012). By the end of 2006, Annex I countries had to decide whether to use this possibility for the first commitment period (2008–2012) or not. Currently (March 2007) 17 counties have elected forest management under Article 3.4, and eight have not elected it (Table 1).

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Table 1
Overview of election of forest management under Article 3.4 choice for EU countries (excluding Malta and Cyprus)

Country	Forest management	Country	Forest management
Austria	Not elected	Italy	Elected
Belgium	Not elected	Latvia	Elected
Bulgaria	Not Elected	Lithuania	Elected
Czech Republic	Elected	Luxembourg	Not elected
Denmark	Elected	Netherlands	Not elected
Estonia	Not elected	Poland	Elected
Finland	Elected	Portugal	Elected
France	Elected	Romania	Elected
Germany	Elected	Slovakia	Not elected
Greece	Elected	Slovenia	Elected
Hungary	Elected	Spain	Elected
Ireland	Not elected	Sweden	Elected
		United Kingdom	Elected

Source: http://unfccc.int/national_reports/initial_reports_under_the_kyoto_protocol/items/3765.php (25.04.08).

Clearly all countries with large expanses of forest have elected forest management under article 3.4, covering some 120 million ha of forest. Probably they expected a net benefit between the costs of forest management and reporting versus the achievable carbon credits (given the maximum assigned to them under forest management). The countries with smaller forest areas are divided; apparently they were not sure what the net benefit might be to them. E.g., Denmark with roughly 450,000 ha has elected forest management, while Slovakia with roughly 2 million ha of forest has not.

According to the exact text of Article 3.4, only "direct human induced changes since 1990" should be accounted for (UNFCCC, 1997). However, a separation into direct and indirect effects is very difficult, and currently no generally accepted methodology is available to achieve the separation. Therefore, each Annex I country agreed on a maximum accountable amount, so called CAP, approximately 15% of previously reported sink amounts (Decision 16/CMP.1[1]). Sinks as well as sources of carbon resulting from forest management under Article 3.4 can only be accounted by these countries within their assigned CAP.

E.g. wood products are a good example of the complex relations between management and the carbon balance. Wood products in use represent a small stock of carbon (Karjalainen et al., 1999). The important impact of an increased use of wood products on the mitigation of climate change, however, is the substitution of more energy-intensive products. Furthermore, forests can serve directly or indirectly as a provider of biomass for bio-energy. This can be in the form of harvest residues, fuelwood, waste within the production process, or discarded products. Through optimized use of forests to substitute non-woody materials and consistent re-use of discarded material for the efficient generation of heat and energy, forests can optimally contribute to the reduction of atmospheric CO_2 emissions (Werner et al., 2006). Using biomass for bio-energy will not increase carbon stocks in the forest, but will permanently reduce the emissions within the energy sector. Furthermore, increased harvesting from existing forests will lower the average growing stocks, and thus reduce susceptibility to storms, an adaptation measure. This increased attention for biomass for bio-energy will influence the strategy on how to make optimal use of the forest in combating the greenhouse effect. In turn, forest management will play an important role in achieving such a strategy (Schmid, 2005; Thürig, 2005).

This paper is the outcome of a group discussion held at the Savonlinna meeting 'Management of forests ecosystems and its impact on the GHG budget'. The aim of this break-out group discussion was to 'Characterize forest management impacts on the GHG budget of forest ecosystems in different European regions'.

In the paper we briefly characterize different options that a forest owner has in order to maintain or maximize forest carbon pools and carbon sequestration. These hectare scale and landscape scale descriptions of measures are then regarded in connection to the current state of European forests, and how they can be combined with ongoing management trends, and local issues. We point out the various possibilities that exist in European forests, where they are located, and where they could possibly be combined with adaptation.

2. Influencing carbon pools and fluxes by forest management

Various studies have shown different aspects of how forest management can be used to mitigate the increase of atmospheric CO_2 (Johnson and Curtis, 2001; Guo and Gifford, 2002; Freeman et al., 2005). Forest management activities influence carbon pools, fluxes, and productivity on-site, either directly by, e.g. transferring carbon from "live growing stock" to the "product" pools (e.g. thinning, final harvesting), or indirectly by altering growth conditions of trees (e.g. liming, fertilizing). The effects can be instantaneous (e.g. thinning) or slowly "evolving" (e.g. fertilization). Activities may affect the current stand (e.g. thinning regime) or future stands (e.g. regeneration), or they are transient (e.g. minimizing site preparation, planting). Furthermore, the impacts of an activity may be clear at the stand scale, but may be different at the landscape scale. In this section, we summarize the effect of management measures on carbon pools and fluxes in biomass, soil, and products (where appropriate), focused on the European situation. We ignore the use of any additional fossil fuels that may be needed to accomplish the change in management.

2.1. Harvesting effects

In general, a forest stand acts as a carbon source for some years after final harvest or thinning. In this period, the rate of decomposition of slash on the ground is higher than accumulation of carbon in the vegetation and soil (Mäkipää et al., 1999). Furthermore, the soil temperature may go up in the open spaces, and the decomposition of soil organic matter may increase. For the rest of the rotation period the stand is usually a carbon sink due to carbon sequestration of the growing vegetation and accumulation of carbon in the soil and addition of coarse woody debris (e.g. Janisch and Harmon, 2002). In determining harvesting effects, one should distinguish between effects at the stand level, and effects at the landscape level, and distinguish between which pool is meant. Carbon pools and fluxes at the regional scale are strongly determined by the applied rotation lengths, the thinning intensity, and the resulting age–class distribution of the forests.

2.1.1. Rotation length

Changes in rotation length affect the long-term average amount of carbon in trees and soil (Aber et al., 1978; Cooper, 1983). Generally, the shorter the rotation length the lower the average carbon stock in the biomass. Soil responses to altered rotation length are not trivial. A smaller tree biomass may produce less litter and decomposition of soil carbon (or peat) may accelerate in harvested sites. On the other hand, the fast growing young trees and the large quantity of harvest residues from frequent harvests can increase litter input (Liski et al., 2001). Furthermore, in an empirical study by Prescott et al. (2000) evidence on increased rate of decomposition on harvested stands was not found. Rotation length determines size and quantity of harvested timber, influen-

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[1] http://unfccc.int/resource/docs/2005/cmp1/eng/08a03.pdf#page=3 (25.09.06).

cing carbon stored in wood products (Karjalainen et al., 1999) and the amount of harvested biomass that can substitute fossil fuels (e.g. Eriksson, 2003).

In many studies, biomass and soil reacted in opposite directions with regard to changes in rotation length (Lasch et al., 2005), except Eriksson (2003) for Sweden. Most European studies indicate an increased total carbon accumulation in biomass and soil if rotation lengths are increased (Lasch et al., 2005). Only for Norway spruce in Finland, Liski et al. (2001) found a decrease, because a longer rotation meant smaller inputs of slash to the (mineral) soil. Kaipainen et al. (2004) reported that several European countries could accomplish their largest eligible carbon sink under Article 3.4 with the prolonged rotation length as the measure. However, at the landscape level, an increased rotation length also means that the total amount of wood to be harvested must be found in older forests. This means that more pressure is put on older forests (possibly elsewhere), and the average age of the forest at the landscape level may in some cases be reduced.

2.1.2. Regeneration regime

The regeneration regime describes how a stand is finally harvested and regenerated. Regeneration regimes can be characterized by the degree of canopy cover removed in one cut. This can range from single-tree selection systems (e.g. nature oriented management) to clearcut. The higher the share of standing stock that is cut, the higher is the input to forest floor C pools from residues. In most cases soil C stocks increase shortly after the harvest when slash is accounted as well (see review in Bergh et al., 2003). This period may be followed by a period of decrease, depending on the growth rate of new trees and the treeless time following harvest. Not fully understood however, is the role of the exact management activity and how it affects the soil C balance and the establishment of new trees. Overall it seems that the prevailing trend in Europe towards group and selective felling regimes, leads to maintenance of larger average stocks at the stand level. At the landscape level, the difference will be very small as in total the same amount of wood will be cut anyway.

2.1.3. Whole-tree harvesting

As an alternative to conventional harvesting where all needles, branches and non-merchantable timber remain on site, whole-tree harvesting removes almost all above-ground components from a site. While it increases the amount of harvested biomass by up to 40%, there are losses of nutrients from the forest which may also cause nutrient imbalance in trees (Olsson, 1999). Johnson and Curtis (2001) found in a meta-analysis an average decrease in soil C and N of 6%. Whole-tree harvesting leads to a decrease in mineralization, nitrification, nitrogen immobilization, and nitrogen accumulation (e.g. Lundborg, 1997). Reported losses in subsequent forest production range from 6% to 32% (Jacobson et al., 2000; Sterba, 2003) although the full successional effects may sometimes be different than expected (Brais et al., 2002). Some of the negative effects like nitrogen loss can be mitigated by the proper site-preparation (Jacobson et al., 2000). In areas where nitrogen deposition is relatively high due to anthropogenic influence, whole-tree harvesting can decrease nitrogen leaching by reducing the nitrogen load (Lundborg, 1997).

2.1.4. Tending (weed control)

We define tending here as all activities in forest plantations after planting up to the moment of the first (commercial) thinning. Trees and weeds cut in tending operations are not usually removed from the site. The decomposition of their foliage, stems, and roots increases soil C content (Paul et al., 2002). However, weed control by, e.g. soil scarification could result in the loss of soil carbon due to accelerated decomposition of organic matter and wind and water erosion (Paul et al., 2002). Tending in combination with thinning can have a beneficial effect of up to 10% on carbon sequestration, because the remaining trees will grow better (Kairiukstis and Juodvalkis, 2005).

2.1.5. Thinning

Thinning is an active reduction in stem number during the rotation of a stand. The aims of thinning include enhancing the growth of the remaining trees, obtaining early income from wood production, influencing the tree species composition or forest structure, and selecting for stem quality. Thinning can roughly be characterized by type (systematic or selective), direction of approach (from below or from above), recurrence interval, and intensity.

Various observations have indicated an optimum relationship between thinning intensity and production. Kramer (1988) found that light to medium thinning from below can increase overall production by 3–11% compared to un-thinned Norway spruce stands in central Europe. Kairiukstis and Juodvalkis (2005) found similar results in Lithuania. Pretzsch (2004) generalized the findings on thinning and production. According to his results the general pattern is an optimum interrelation which is more or less pronounced depending on the tree species, site conditions, and stand age. An experimental approach by Eriksson (2006), however, showed no significant difference in production between five different thinning regimes for Norway spruce.

Soil carbon may (temporarily) be enhanced due to increased litter input, but changes in microclimate could also lead to increased decomposition. Furthermore, decreased litter input afterwards or removal of thinning residues could lead to a decrease in soil carbon stocks (Bergh et al., 2003).

2.2. Forest fertilization

Fertilization is the artificial application of nutrients to the forest. Its aim is to increase biomass production, to compensate for nutrient losses due to the removal of logging residues for bio-fuel and nutrient leaching, to counteract imbalances caused by deposition, and to improve stress tolerance (Mandre, 2002). Depending on the situation and aim, fertilization can be done with pure N, mixtures of for example NPK, or in the form of liming or wood ash application.

The effect of fertilization depends on the nutrient state of the forests. Boreal forest ecosystems in Europe are usually N limited (Tamm, 1991) and a single N application of 0.15 Mg N ha^{-1} can effect an increase in carbon sequestration of 0.5–0.6 Mg C ha^{-1} year^{-1} (Saarsalmi and Malkonen, 2001). Bergh et al. (2005) calculated that the biomass production potential in Norway spruce forests in Sweden could be increased by 100–300%. In parts of Denmark, and Central and southern Europe other elements such as P, K and Mg can increase the growth rate of forests on mineral soils (Vejre et al., 2001). A meta-analysis by Johnson and Curtis (2001) showed that overall fertilization increased soil C storage due to increased litter production and reduced soil respiration.

2.3. Reducing risks to natural disturbances

2.3.1. Wind and insect damage

Management options to reduce wind damage are to increase the stability and to decrease the size of the stock at risk. Important options for increased stability are carefully designed thinning regimes (including no-thinning regimes in stands at high risk) and carefully planned fellings in order to minimize the length of exposed edges (Quine et al., 1995). Tree species choice also plays a decisive role in stand stability. Especially Norway spruce and Sitka spruce are known to be sensitive to wind throw. Increased stability would lead to higher average biomass carbon stocks, but could also mean a decrease in soil carbon stock due to lower litter input. Reducing the stock of the forest estate that is under risk would for example involve a choice for shorter rotations, where stands are harvested before they are exposed to wind risk. Avoiding wind damage clearly has not only stand level aspects, but also landscape level aspects. Schelhaas (2008) pointed at the combined effects of storm and insect damage, where insect populations can explode when large amounts of dead wood stay on site after a storm. Within Europe however, enormous explosions of insect populations as in Canada (Kurz et al., 2008) have not been seen yet.

2.3.2. Fire damage

The main influence forest management can have to decrease forest fire risk is by manipulating the fuel characteristics. A very important measure is to disrupt the continuity of the fuel, both within stands (open forest) and between stands (fire breaks, variation in stand characteristics). Planning at the landscape level is very important, but not much research has been done on this topic yet (Fernandes and Botelho, 2003), exceptions being Hirsch et al. (2001). The amount of fuel can be reduced by prescribed burning, or by active removal (Fernandes and Botelho, 2003). Other management options are to manage the forest to create an open structure (combined with removal of felling debris) or to change tree species to less flammable species. Tilman et al. (2000) found a fire suppression effect of 1.8 Mg C ha^{-1} $year^{-1}$ over a 35-year period in an oak savannah in Minnesota. This increase was mainly attributed to increased carbon stocks in woody vegetation and litter; effects on soil were not significant. Apart from these more direct effects of fire suppression, the long-term impacts on succession are more significant, but difficult to quantify.

2.4. Species mixture

Cannell (1996) pointed out that the choice of species and how they are arranged spatially could have an important role in the carbon stocks and production of the forests. He concluded that fast growing species accumulate carbon more rapidly than slow growing species, but that for long-term carbon storage, the slow growing species would be preferable. Replacing natural forests by plantations may lead to a loss of carbon in some cases due to the species substitution effect (Kowalski et al., 2004). Other studies indicate the importance of the choice of locally adapted species when abandoned agricultural lands are reforested (Lal, 2004).

A positive effect of species mixture on forest production may occur when species make different use of available resources, either in space or in time (Kelty, 2006). Differentiation in time can be achieved by mixing species with different growth patterns. Differentiation in space can be achieved by mixing species with different shade tolerance (Pretzsch, 2005) within a stand, or by mixing group-wise or stand-wise at the landscape level. In Central Europe productivity increases of 2–50% were reported for various combinations of common beech and Norway spruce (Assmann, 1970) relative to unmixed forests of these tree species. Investigations from boreal forests in Finland, Sweden, and Norway by Frivold and Kolström (1999) and Mielikäinen (1985) observed 10–15% increases in production in mixtures of Scots pine/silver birch and Norway spruce/silver birch. Even higher values are reported for the net primary production of coniferous/deciduous mixed stands in the northwest European part of Russia by Pristova (2003) and Karelian birch/aspen stands by Kazimirov et al. (1978). However, all studies report that effects were highly dependent on site conditions: positive effects might apply over larger areas.

3. Where are the carbon hotspots of the European forests?

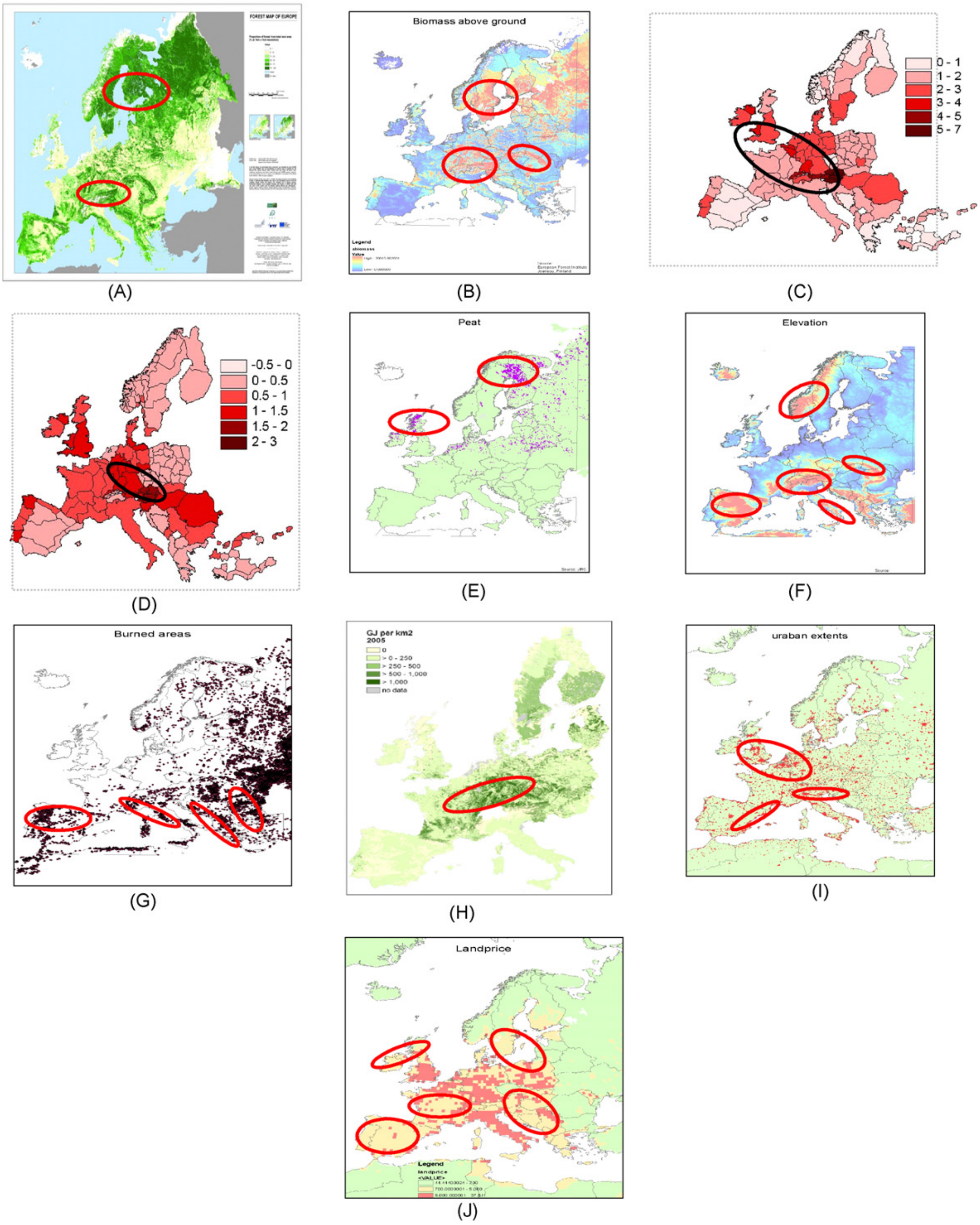
In relation to the description of management options (in existing forests) as described above, we now analyse where these management options could be applied in different regions of Europe. Fig. 1 shows relevant variables in European maps that indirectly address the mentioned mitigation options. In summary, the strategies consist of: (a) maximizing stock at low risk sites, (b) maintaining lower stocks or reducing the risks at high risk sites, and (c) maximizing biomass production either through changes in existing stands, or through forest area expansion. Fig. 1 illustrates in 10 different maps where best to apply a strategy.

Fig. 1A (Schuck et al., 2002) indicates where the main forested regions in Europe can be found and Fig. 1B where the highest average biomass can be found (Cox and Betts, 2005). Central Europe and southern parts of Scandinavia clearly stand out. The regions with high stocks, mainly concentrated in Central Europe, are the ones where we suggest concentrating effort to preserve existing stocks as much as possible, and gradually minimizing the risks of disturbances. This could be done by moderately regenerating the forests. This implies loss of carbon stock, but enhanced supply of wood as a raw material for products, and it keeps the forest estate in a state of vigorous growth. These are regions where the management options of reducing risks, changing stands to species mixtures, a careful regeneration regime, and a sustained production of wood for materials and bio-energy will apply.

Regions with lower carbon stock per km^2 of land (blue colour in Fig. 1B) are regions where higher stocks than at present could possibly be reached. One would have to look for regions where a combination of additional afforestations could be carried out, and/or where low growing stocks in existing forests are found. Suitable areas may be found in Ireland, southern England, northwestern France, Denmark, eastern Poland, and in the Hungarian and Romanian plains. Continuous build up of stocks is possible in these regions. One could think of decreasing the harvesting amount, or changes in tree species distribution towards more productive species. The first option may be attractive in regions where harvesting is technically difficult or ecologically harmful and uneconomical.

Fig. 1C (Nabuurs and Schelhaas, 2003) shows a northwestern to southeastern band over Europe where the Net Ecosystem Production (an approximate measure for net increment including harvesting amount) is highest. These are regions where currently the largest net carbon sinks can be observed. To some extent, the areas with the largest increment overlap with areas holding the large carbon stocks. This indicates that those highly stocked areas are not yet in a phase of saturation and still sequester a large amount of carbon (Carey et al., 2001). However, the question of the optimal growing stock in terms of long-term maximum carbon sequestration cannot be answered with this comparison. Due to the varying growing conditions, there is not one optimum growing stock for all regions. Each region therefore has to be treated differently to optimize the trade-off between increasing growing stock to create sinks accountable under the KP and maximizing the harvesting amount. Looking at the next figure at least gives an indicator, where harvesting could be increased without creating a carbon source in the forest growing stock.

Fig. 1D (Net Biome Production) indicates regions where currently the carbon stock in forests increases because the increment exceeds losses by natural mortality and harvesting. This figure indicates that harvesting levels might be increased without a long-term decrease of the growing stock. This goal can very well be in accordance with the goals of Fig. 1B, since keeping the forest estate at a high stock, and at the same time carrying out



(A) (B) (C) (D) (E) (F) (G) (H) (I) (J)

Fig. 1. Identification of the forest carbon cycle hotspots in European forests. (A) Forest area (Schuck et al., 2002), (B) aboveground biomass (Cox and Betts, 2005), (C) net ecosystem production (Mg C ha^{-1} year^{-1}) (Nabuurs and Schelhaas, 2003), (D) net biome production (Mg C ha^{-1} year^{-1}) (Nabuurs and Schelhaas, 2003), (E) peat (Jones et al., 2004), (F) elevation (ALTERRA CGI, 2005), (G) burned areas (Tansey et al., 2004), (H) available biomass for bio-energy (Lindner et al., 2005), (I) urban extent (CIESIN, 2006), and (J) land price (Obersteiner, personal communication).

sustainable harvest is very well possible (Kaipainen et al., 2004). This would also be in line with the industrial goal of a sustained high-level flow of raw material. The industry would not like to see stocks reaching an overmature status with high rates of mortality, and high risks of storm damage. Furthermore, the regions where Net Biome Production (NBP) is highest (i.e. the fastest increase of growing stock), are very well in line with the regions indicated in Fig. 1H, where the red circle indicates the region with the largest amount of biomass available for bio-energy.

Fig. 1E gives the peat soil map of Europe (Jones et al., 2004). This is relevant in respect to the carbon cycle also in terms of preservation of existing stocks. Northern Scandinavia and Ireland are hotspots in this respect. Here, forest management should be aimed at maintaining these stocks by careful drainage (if at all) and by careful or minimal soil preparation at regeneration.

Fig. 1F shows the elevation map of Europe (ALTERRA CGI, 2005). This is relevant in respect to the carbon cycle in different ways. High elevation often means steep slopes as well, and thus related to high risk of erosion (loss of soil C) after management measures, and possibly high storm risk. Depicted here as risk areas are parts of the Mediterranean, the Alps, Carpathians, and southern Norway. Elevation is also related to the carbon cycle in the sense that high elevation means lower biomass stocks and thus less impact of management measures on the carbon cycle. Furthermore high elevations usually mean higher costs for management measures and thus a low cost efficiency of harvesting. Combined with Fig. 1B this could indicate areas suitable for conservation of the current growing stock.

Fig. 1G indicates the burned areas (both forest and non-forest) in Europe (Tansey et al., 2004). Ignoring the steppe burns in the eastern Balkans and Ukraine, the main affected forest areas are in western Iberian Peninsula, southern Alps/Italy, Balkan and Romania/Bulgaria. These are the risk areas for high emissions, and high risk of losing stocks of carbon. With projected climate change predicting further increases in drought in the Mediterranean, these would not be the areas to aim at increased carbon stocks through forest management changes. These would be the areas to choose for more fire resistant species, to avoid multi-layered stands, and to concentrate on management that reduces fuel load. See Schelhaas (2008) for storm affected areas in North Western Atlantic Europe.

Fig. 1H (Lindner et al., 2005) depicts areas in Europe where forest biomass may be available for bio-energy. This is mostly the case stretching from southeastern France through Central Europe into some new accession countries. This clearly overlaps with areas in Fig. 1B, with the exception of Scandinavia. In the latter region, the authors found a rather high felling/increment ratio and several ecological constraints. Provided no competition is going to occur with traditional forest industries, the additional harvesting for bio-energy purposes could very well be combined with the strategy described under Fig. 1B, of moderate regeneration while maintaining average stocks at the forest estate level.

Fig. 1I (CIESIN, 2006) depicts the urban extent in Europe with concentrations in northwestern Europe, northern Italy, and eastern Spain. This variable is relevant in terms of a risk factor for existing stocks, namely urban sprawl always takes place in the vicinity of cities. Therefore, these are the locations where deforestation occurs in Europe. The emphasis should be on conservation in these regions.

Fig. 1J then finally depicts average land prices. This is relevant in terms of finding the most cost efficient sites for afforestation. Regions with large areas of relatively cheap land include Spain, Central France, Ireland, and some new accession countries.

4. Conclusion

Carbon sequestration will at most be only one of the goals that drive forest management decisions. Within each region, local solutions have to be found that strive to integrate goals, thereby aiming at sustainable forest use. Developing the optimal regional strategies for climate change mitigation (possibly with adaptation) involving forests will require complex analyses of the trade-offs (synergies and competition) between forest conservation (carbon storage) and harvesting forests, and the trade-offs among utilization strategies of harvested wood products aimed at maximizing the substitution of non-woody material through production, storage, and recycling of wood products and the (final) consumption for bio-energy.

The Kyoto Protocol created incentives to enhance the biomass stored in forests only through specific management actions. This system is limited and does not secure sustainable use of forests in climate change mitigation. Neither does it take into account the specific situation in each locality. Furthermore, the complex Protocol rules require intense monitoring and reporting. In the review process of the Kyoto Protocol for the next commitment periods, this should be taken into account, and possibly broader actions should be rewarded.

We show that local factors differ, and because of that local management strategies must differ as well. For each region local strategies can be defined and the optimal combinations found. We did this in a rather rough way by looking at relevant variables. In the future one can think of dynamically linking these overlays in combination with high resolution forest inventory data based on, for example, a 1 × 1 km grid. In this way relevant variables can be quantitatively combined to find optimal strategies. However, a drastic change in the current sink in European forests should not be expected. A large forest resource has a certain dynamic that it has inherited from the past 100 years of management. This cannot be changed from one year to the other, taking into account the many other demands placed on Europe's forests.

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